

V I S U A L S O I L A S S E S S M E N T

WSA

Field Guides

BioAgriNomics



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DEGLI STUDI
DI TERAMO



Annual Crops



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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
CO ₂	Carbon dioxide
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of annual cropping. A decline in soil quality has a marked impact on plant growth and yield, grain quality, production costs and the increased risk of soil erosion. Therefore, it can have significant consequences on society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of annual cropping are important tasks for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the character and quality of annual cropping and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing crops, and to make informed decisions that will lead to sustainable land and environmental management. To this end, Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for annual crops. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a scorecard. With the exception of soil texture, the soil indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and as such provide an effective monitoring tool.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality observed when comparing the soil sample with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil indicators are relatively more important in the assessment of soil quality than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index score for the sample you are evaluating. Compare this with the rating scale at the bottom of the scorecard to determine whether your soil is in good, moderate or poor condition.

The VSA tool kit

PLATE 1 The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in fields is site specific. Avoid areas that may have had heavier traffic than the rest of the field and sample between wheel traffic lanes. However, VSA can also be used to assess the effects of high traffic on soil quality by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

Format of the booklet

The soil scorecard is given in Figure 1 and lists the ten key soil ‘state’ indicators required in order to assess soil quality. Each indicator is described on the following pages, with a section on how to assess each indicator and an explanation of its importance and what it reveals about the condition of the soil.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in annual crops

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Date: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
 Moisture condition: Dry Slightly moist Moist Very moist Wet
 Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 2	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 1	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

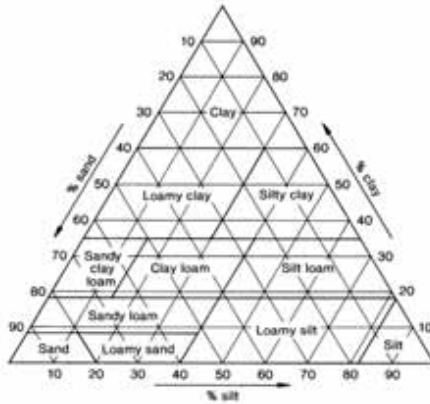


Importance

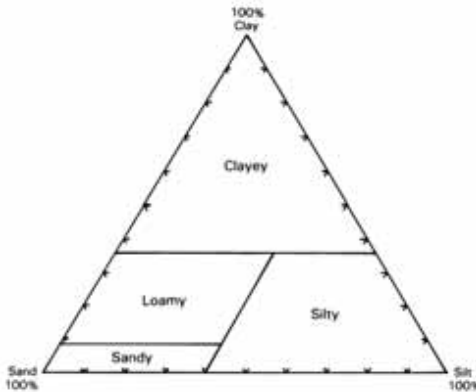
SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil workability and trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- 1 Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- 2 Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- 3 Transfer the soil onto the large plastic bag.
- 4 For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- 5 Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- 6 Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for arable cropping. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and indicates whether the soil is functioning as a carbon 'sink' or as a source of greenhouse gases. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of crops increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot in soils prone to waterlogging.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.

Assessment

- Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S and Cu. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. In addition, decay and dieback of roots can occur as a result of fungal diseases such as *Rhizoctonia*, *Pythium* and *Fusarium* root rot, foot rot and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

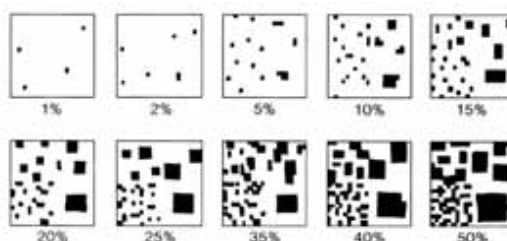


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (>50%) medium and coarse orange and particularly grey mottles.



Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 7) and compare with the class limits in Table 2. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to $1/25 \text{ m}^2$, and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in cropping soils and can increase growth rates, crop yield and protein levels significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their

PLATE 6 (a): earthworm casts under crop residue; (b): yellow-tail earthworm (*Octolasion cyaneum*)

biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes can increase crop production markedly while at the same time reducing fertilizer requirements.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the crops grown, the amount and quality of surface residues (Plate 6a), the use of cover crops and the method of tillage. Earthworm populations can be up to three times higher under no-tillage than conventional cultivation. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

Earthworms species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 6b) can indicate adverse soil conditions.

PLATE 7 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present (Plate 8), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also whether there is an over-thickening of roots (a result of a high penetration resistance), and whether the roots are being forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan (pp 16–17). An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated crops. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the crop. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ❖ an abrupt textural change;
- ❖ pH;
- ❖ aluminium (Al) toxicity;
- ❖ nutrient deficiencies;
- ❖ salinity;
- ❖ sodicity;
- ❖ a high or fluctuating water table;
- ❖ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Crops with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce, promote soil structure, porosity, water storage, soil aeration and drainage at depth. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on frequent and high application rates of fertilizer and N to generate growth, and available nutrients are more likely to be taken up, so reducing losses by leaching into the environment.

PLATE 8 Hole dug to assess the potential rooting depth



The potential rooting depth extends to the bottom of the arrow, below which the soil is extremely firm and very tight with no roots or old root channels, no worm channels and no cracks and fissures down which roots can extend.

TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

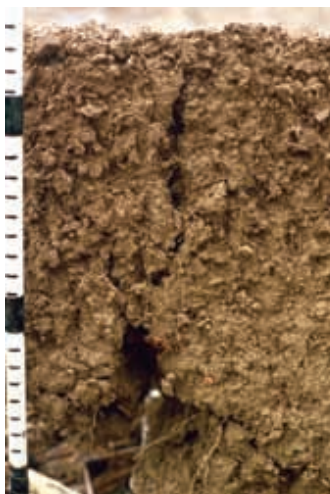
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given in Plate 10.

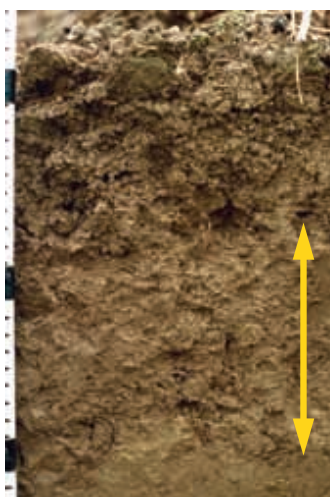
PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth of roots. Roots need oxygen for respiration. They are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are actively growing at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the crop is transpiring actively causes leaf desiccation and the plant to wilt. Prolonged waterlogging also increases the likelihood of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Plant stress induced by poor aeration and prolonged soil saturation can render crops less resistant to insect pest attack such as aphids, armyworm, cutworm and wireworm. Crops decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, become discoloured and die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of the root system to surface ponding and waterlogging is dependent on a number of factors, including the time of year and the type of crop. Tolerance of waterlogging is also dependent on: soil and air temperatures; soil type; the condition of the soil; fluctuating water tables; and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate.

Prolonged surface ponding makes the soil more susceptible to damage under wheel traffic, so reducing vehicle access. As a consequence, waterlogging can delay ground preparation and sowing dates significantly. Sowing can further be delayed because the seed bed is below the crop-specific critical temperature. Increases in the temperature of saturated soils can be delayed as long as water is evaporating.

PLATE 11 Surface ponding in a field



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤1	No surface ponding of water evident after 1 day following heavy rainfall on soils that were at or near saturation.
1 [Moderate]	2–4	Moderate surface ponding occurs for 2–4 days after heavy rainfall on soils that were at or near saturation.
0 [Poor]	>5	Significant surface ponding occurs for longer than 5 days after heavy rainfall on soils that were at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER after harvesting and prior to canopy closure of the next crop helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of conservation tillage can reduce soil erosion by up to 90 percent and water runoff by up to 40 percent. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of soils through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be water eroded by gullying, rilling and sheet wash. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability of water through the soil;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

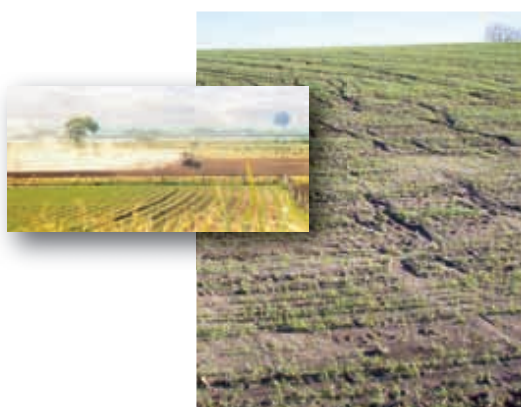
The loss of organic matter and soil structure as a result of overcultivation can also give rise to significant soil loss by wind erosion of exposed ground.

PLATE 13 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no *water erosion*. Topsoil depths in the footslope areas are <150 mm deeper than on the crest.

Wind erosion is not a concern; only small dust plumes emanate from the cultivator on a windy day. Most wind-eroded material is contained in the field.

**MODERATE CONDITION VS = 1**

Water erosion is a moderate concern with a significant amount of rilling and sheet erosion. Topsoil depths in the footslope areas are 150–300 mm greater than on crests, and sediment input into drains/streams may be significant.

Wind erosion is of moderate concern where significant dust plumes can emanate from the cultivator on windy days. A considerable amount of material is blown off the field but is contained within the farm.

**POOR CONDITION VS = 0**

Water erosion is a major concern with severe gully, rilling and sheet erosion occurring. Topsoils in footslope areas are more than 300 mm deeper than on the crests, and sediment input into drains/streams may be high.

Wind erosion is a major concern. Large dust clouds can occur when cultivating on windy days. A substantial amount of topsoil can be lost from the field and deposited elsewhere in the district.

Soil management of annual crops

Good soil management practices are needed in order to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximize water and nutrient utilization. Good soil structure also promotes infiltration and movement of water into and through the soil, minimizing surface ponding, runoff and soil erosion.

Conservation tillage practices, including no-tillage and minimum tillage that incorporate the establishment of temporary cover crops and crop residues on the surface (Plates 14–16), provide soil management systems that conserve the environment, minimize the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface, reducing water runoff and soil erosion. It reduces wheel traffic, which lessens wheel traffic compaction and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimize sowing time, being less dependent on climate conditions in spring and autumn. It improves soil physical characteristics, encourages soil life and biological activity (including earthworm numbers), and increases micro-organism biodiversity. Unlike conventional tillage, conservation tillage also enables the soil to retain a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO_2), enabling the soil to act as a sink for CO_2 . Consequently, soil organic matter levels build up and, therefore, the potential to gain carbon credits. Moreover, conservation tillage uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

On the other hand, conventional tillage can have a negative impact on the environment, with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases greenhouse gas emissions (including the release of 5–times more CO_2), and uses more fossil fuels (i.e., 6–times more consumption of fuel). It degrades soil structure, increases soil erosion, and alters microflora and microfauna adversely by reducing both the number of species and their biomass. The fundamental difference between conventional tillage and conservation tillage is their relative environmental and economic sustainability. The long-term effects of conventional tillage are cumulatively negative whereas the long-term effects of conservation tillage are cumulatively positive.

PLATE 14 No-till drilling an annual crop into an erosion-prone field protected by herbicided pasture [BAKER NO-TILLAGE LTD]



PLATE 15 Strip-tillage planting of an annual crop protected by good residue cover



PLATE 16 Harvesting an annual grain crop followed immediately by no-till seeding the next crop into stubble [BAKER NO-TILLAGE LTD]



References

Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for annual crops*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Olive Orchards



Olive Orchards

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Cover photograph: M. Pastor, CiFA-IFAPA.

List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
CO ₂	Carbon dioxide
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of orchards. A decline in soil quality has a marked impact on tree growth, olive production and the character and quality of olive oil, production costs and the risk of soil erosion. Therefore, it can have significant consequences on society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of olive orchards are important tasks for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance of olive orchards, and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing olives, and to make informed decisions that lead to sustainable land and environmental management. To this end, Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for olives. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a scorecard. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant scorecard. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, the soil quality

assessment is not a combination of the ‘soil’ and ‘plant’ scores. Rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate or poor condition.

Placing the soil and plant assessments side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.

PLATE 1 The VSA tool kit



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the orchard. The condition of the soil in olive orchards is site specific. Sample sites that have had little or no wheel traffic (e.g. near the olive tree). The VSA method can also be used to assess compacted areas by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS rankings in the right-hand column.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required in order to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil and about plant performance.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in olive orchards

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Date: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
 Moisture condition: Dry Slightly moist Moist Very moist Wet
 Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 2	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 1	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 2	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

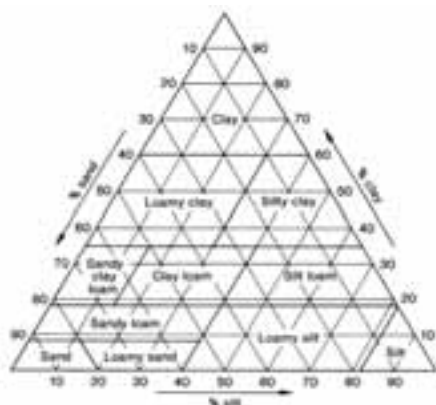


Importance

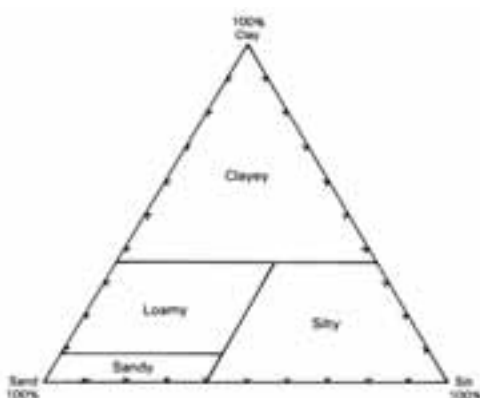
SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for olive orchards. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and maintains the soil carbon 'sink'. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of trees increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of fungal diseases such as *Phytophthora* root and crown rot in soils prone to waterlogging. Trees exhibit reduced growth, have thin canopies, and eventually die.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.



Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.



Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure decreases and blocks the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K and S. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. Decay and dieback of roots can also occur as a result of fungal diseases such as *Phytophthora* root and crown rot in strongly mottled, poorly aerated soils. Root rot and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. Trees exhibit reduced growth, have thin canopies, and eventually die. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

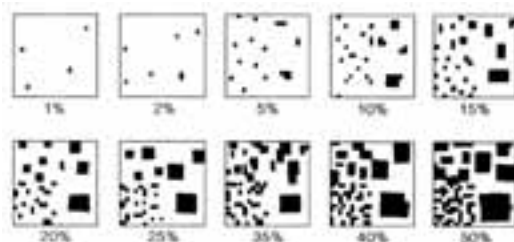


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (>50%) medium and coarse orange and particularly grey mottles.



Assessment

- ① Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 6) and compare with the class limits in Table 2. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to $1/25 \text{ m}^2$, and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in olive orchards and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in

the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes reduce fertilizer requirements and improve trees and olive production.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue, the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 6 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present, and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots (Plates 7 and 8) and old root channels, worm channels, cracks and fissures down which roots can extend. Note also the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan. An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting, gully, slip, earth slump or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated olive orchards. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the olives. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases crop yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ❖ an abrupt textural change;
- ❖ pH;
- ❖ aluminium (Al) toxicity;
- ❖ nutrient deficiencies;
- ❖ salinity;
- ❖ sodicity;
- ❖ a high or fluctuating water table;
- ❖ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Olive trees with a deep, dense, vigorous root system raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce promote soil structure, porosity, water storage, soil aeration and drainage at depth. The soil depth should preferably not be less than 600 mm. Heavy clay soils are not recommended. Stony soils are acceptable under artificial irrigation. Furthermore, olive trees need a sufficient rooting depth to provide adequate anchorage for the trees at maturity.

PLATE 7 Root system of an olive tree



PLATE 8 Generic drawing of an olive tree [L. DRAZETA and A. LANG]



TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

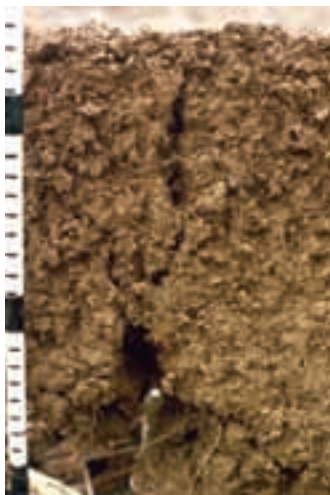
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given Plate 10.

PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Olive trees generally require free-draining soils. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth and development of roots. Roots need oxygen for respiration. While olive trees transpire all year round and do not have a dormant period, they are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are growing actively at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging cause the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the tree is transpiring actively causes leaf desiccation and tip-burn. Prolonged waterlogging also increases the likelihood of infections and fungal diseases such as *Phytophthora* root rot and crown rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Trees decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, have thin canopies, and eventually die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of olive trees to waterlogging is dependent on a number of factors, including the time of year, the rootstock, soil and air temperatures, soil type, the condition of the soil, fluctuating water tables and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the amount of entrapped air and the oxygen consumption rate by plant roots.

Prolonged surface ponding increases the susceptibility of soils to damage under wheel traffic, so reducing vehicle access.

PLATE 11 Surface ponding in an olive orchard [J. GOMEZ]



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤ 1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–4	Moderate surface ponding occurs for 1–3 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	> 5	Significant surface ponding occurs for longer than 3 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare with Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of managed cover crops has in some cases reduced sediment erosion rates from 70 tonnes/ha to 1.5 tonnes/ha during single large rainfall events. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $> 30\%$ and $< 70\%$.

POOR CONDITION VS = 0

Surface crusting is > 5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Photos of surface cover: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and, more importantly, on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of an olive orchard through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation of interrows can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be removed by slips, flows, gullying and rilling, or it can be relocated semi-intact by slumping. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation between rows can also give rise to significant soil loss by wind erosion of exposed ground where the tree spacing is quite large.

PLATE 13 How to score soil erosion



GOOD CONDITION VS = 2

Little or no evidence of soil erosion. Little difference in height between the mounded row and interrow. The root system is completely covered.



MODERATE CONDITION VS = 1

Moderate soil erosion with a significant difference in height between the interrow and the soil around the base of the tree trunk. Part of the upper root system is occasionally exposed.



POOR CONDITION VS = 0

Severe soil erosion with deeply incised gullies or other mass movement features between rows. There is a large difference in height between the interrow and the soil around the base of the tree trunk. The root system is often well exposed and sometimes undermined.

FIGURE 3 Plant scorecard – visual indicators for assessing plant performance in olive orchards

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Canopy volume pg. 26		x 2	
Canopy density pg. 28		x 3	
Shoot length pg. 30		x 3	
Flowering pg. 32		x 3	
Leaf colour pg. 34		x 3	
Yield pg. 36		x 2	
Variability of tree performance along the row pg. 38		x 2	
PLANT PERFORMANCE INDEX (sum of VS rankings)			

Plant Performance Assessment	Plant Performance Index
Poor	< 10
Moderate	10–25
Good	> 25

SUMMARY

Comparison of soil & plant assessments		Do the soil and plant assessments differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:



Assessment

- 1 Assess canopy volume in the late spring to early summer at flowering by comparing the olive tree with Plate 14 and the criteria given. In making the observation, consideration must be given to choosing a representative olive tree in terms of variety, pruning and age. In some cases, orchards are composed of trees of different age and cultivars. Corrections can be made on the basis of previously known annual growth rates as a function of age and cultivars, assigning a hypothetical common age for all trees and subtracting that part of the growth in the canopy volume. Canopy volume can be calculated approximately by applying the simple formula: canopy volume = $w \times b \times h$, where w is the width, b is the breadth and h is the height of the canopy.



Importance

CANOPY VOLUME at the flowering stage is dependent on: the age of the tree, cultivar, pruning, orchard management, disease, and climate factors (including frost damage). However, it can be a useful visual indicator of production and soil quality. Indeed, poor soil structure and soil aeration, limited movement and storage of water, and soil erosion as a result of structural degradation can reduce plant growth and vigour. Canopy volume is a particularly useful assessment of soil quality where climate factors have not limited crop development.

PLATE 14 How to score canopy volume

**GOOD CONDITION VS = 2**

Canopy volume is greater than 100 m^3 (varying from 4–5 m high by 5–6 m wide or more) for mature trees planted at spacings of 5x5 or 6x6 m. Trees have a good distribution of leaves.

**MODERATE CONDITION VS = 1**

Canopy volume is about 50 m^3 (varying from 3–4 m high by 4 m wide) for mature trees planted at spacings of 5x5 or 6x6 m. Trees have a moderate distribution of leaves.

**POOR CONDITION VS = 0**

Canopy volume is less than 23 m^3 (i.e. $\leq 2\text{--}2.5 \text{ m}$ high by 3 m wide) for mature trees planted at spacings of 5x5 or 6x6 m. Trees have a poor distribution of leaves.



Assessment

- 1 Assess the canopy density by comparing with Plate 15 and the criteria given.
- 2 The assessment can be made at any stage after the new growth in the spring and before harvest. In making the assessment, consideration must be given to the pruning and variety of the tree, the presence of pests and diseases, and the weather conditions at bud break (i.e. whether warm and dry, or cold and wet). Poor weather during bud break will promote a high number of leaf buds rather than flowering buds and give rise to many shoots and leaves.



Importance

CANOPY DENSITY is a good indicator of the health and vigour of the tree as reflected by the number of shoots, the number of leaves per shoot and the age of the leaves. In addition to the weather, tree vigour is related strongly to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy, sandy or gravelly). Moreover, soils in good condition with good structure and porosity, and having a deep, well-aerated root zone, enable the unrestricted movement of air and water into and through the soil and the development and proliferation of superficial (feeder) roots. Furthermore, soils with good organic matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, the growth and vigour of the tree. The amount of photosynthate produced by the tree is proportional to the number of leaves and, therefore, influences strongly the growth of the tree and the production and quality of olives.

PLATE 15 How to score canopy density

**GOOD CONDITION VS = 2**

Good canopy density with abundant shoots and leaves per shoot. Many of the leaves are more than two years old.

**MODERATE CONDITION VS = 1**

Moderate canopy density with a moderate number of shoots and leaves per shoot. Most leaves are less than two years old.

**POOR CONDITION VS = 0**

Poor canopy density with few shoots and few leaves per shoot. The canopy appears sparse and spindly. The tree sheds its older leaves prematurely, with only one-year-old leaves being present.



Assessment

- 1 Measure or visually assess shoot length (each month if possible starting from mid-spring to the end of summer) on the mature part of the aerial part of the plant and compare it with Plate 16 and the criteria given. In making the assessment, consideration must be given to the pruning and variety of the tree, and to the weather conditions at bud break and during the spring.



Importance

SHOOT LENGTH determines the number of buds, some of which will bear flowers. It is also strongly related to the physical properties and chemical fertility of the soil, which in turn is influenced by soil management. Shoot length is an expression of plant vigour and general plant growth, which are regulated by the availability of water, nutrients and the aeration status of the soil. Soils in good condition with a deep vigorous root system, good structure, porosity, organic matter levels and soil life show an active chemical and biological process, favouring the release and uptake of nutrients and water, and consequently shoot growth.

PLATE 16 How to score shoot length



GOOD CONDITION VS = 2
Shoots are at least 200 mm (depending on variety) on the external part of the plant.



MODERATE CONDITION VS = 1
Shoot length is moderately below maximum (depending on variety) on the external part of the plant.



POOR CONDITION VS = 0
Shoot length is significantly below maximum (depending on variety) on the external part of the plant.



Assessment

- 1 Assess by visual estimation the number and distribution of flowers at full flowering by comparing with Plate 17 and the criteria given. In making the assessment, consideration must be given to the pruning management of the tree and the weather conditions at bud break and in spring (i.e. whether warm and dry, or cold and wet). Poor weather will promote a high number of leaf buds rather than flowering buds and give rise to lots of shoots and leaves rather than flowers.



Importance

The number and distribution of **FLOWERS** affects fruiting behaviour. The presence of a large number of flowers is also a good indicator of high yields. Flower induction starts in the preceding year of the olive production cycle. Its intensity depends on: weather conditions at the time (e.g. whether wet and cold, or dry and hot); the production of carbohydrate; and the presence of specific hormones necessary to drive the bud apex toward inflorescence production. Carbohydrate production depends on climate conditions, including: the amount of energy from the sun, the number of leaves on the tree, the cultivar, diseases, the availability of water and nutrients, and the physical status of the soil. Once again, soil fertility (physical, chemical and microbiological conditions) is crucial in determining high plant productivity.

PLATE 17 How to score flowering



GOOD CONDITION VS = 2
High number of flowers per shoot and well distributed over the tree.



MODERATE CONDITION VS = 1
Moderate number of flowers occur.



POOR CONDITION VS = 0
Low number of flowers and poorly distributed over the tree.



Assessment

- 1 Assess the colour of the leaves by comparing with Plate 18 and the criteria given. The assessment must be made after the first flush of new growth at the end of the first annual growing period and on leaves exposed to the sunlight. Olive trees have leaves of different ages, varying from one to three years old. Assess only the young leaves, avoiding the deteriorating and immature leaves at the extremities of branches. Consideration must also be given to: the cultivar, the stage of growth, pests and diseases, and recent weather conditions. Prolonged cold and cloudy days with little sunlight can give rise to chlorosis (or yellowing of the leaf) owing to the inadequate formation or loss of chlorophyll.



Importance

LEAF COLOUR can provide a good indication of the nutrient status and condition of the soil. The higher the soil fertility, the greener the leaf colour. Leaf colour is related primarily to water and nutrient availability and especially N. Leaf colour can also be related to a deficiency or excess in phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and boron (B). Chlorosis can further occur as a result of low N, K, S, Fe, Mg and Cu levels in the soil, low soil and air temperatures, and poor soil aeration caused by compaction and waterlogging.

Sulphur is an important element for plant growth and leaf colour and can only be utilized by plants in the sulphate (SO_4^{2-}) form. Under poorly-aerated conditions caused by compaction or waterlogging, S will reduce to sulphur dioxide (SO_2) and sulphides (e.g. H_2S , FeS). Sulphides and SO_2 cannot be taken up by the plant, are toxic to plant roots and micro-organisms, and suppress the uptake of N. Plants can only utilize N where S is present in the oxygenated (sulphate) form. Nitrogen can also only be utilized by the plant in the nitrate (NO_3^-) and ammonium (NH_4^+) forms under aerobic conditions. Under poorly-aerated conditions, N will reduce to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and become plant-unavailable.

PLATE 18 How to score leaf colour



GOOD CONDITION VS = 2
Canopy has an intense green colour.



MODERATE CONDITION VS = 1
Leaves are a medium-green or yellowish-green colour.



POOR CONDITION VS = 0
Leaves are a distinct yellowish colour or turn opaque green.



Assessment

- ❶ Assess relative crop yield by visually estimating the yield per tree and by comparing fruit number and size with Plate 19 and the criteria given. Compare also the percentage of olive oil extracted with that from an ideal crop.
- ❷ In making your assessment, consideration must be given to the amount and type of fertilizer used, disease, and the cultivar, pruning and age of the olive tree. While olive trees can be rejuvenated by good pruning, the greatest yield potential of trees occurs from tree maturity to about 40 years of age on average. Olive trees generally mature in 10 years in humid temperate climates and 15 years in drier Mediterranean climates.
- ❸ Consideration must also be given to the weather conditions (e.g. whether warm and dry, or cold and wet) at pollination, fertilization, flowering and fruit-set. Pollination and fertilization are best when the weather is dry and warm. Cold and wet weather during flowering can give rise to poor fruit-set. Warm weather at fruit-set will give good yields while cold wet weather will give poorer yields. Yield is also influenced by the amount of photosynthate produced by the tree, which is proportional to the number of leaves. Because olive trees are generally biennial bearing, consider the average yield over a 3-year or 4-year period.



Importance

YIELD can be a good visual indicator of the properties and condition of the soil. Olive trees can come under stress from drought (especially during the crucial flowering stage) and from a decline in soil quality caused by reduced water storage and plant-available water, nutrient deficiencies, poor aeration, and restricted root development as a result of soil compaction, a hardpan, a fluctuating water table, etc. This results in disease attack, shorter bud length, a lower number of flowers and poor yield production. Plant stress induced by soil structure degradation during harvesting time also affects the quality of the fruit by changing the amount and type of organic acids and polyphenols.

Appropriate soil management, including the adoption of a managed cover crop between rows and avoiding wheel traffic when the soil is wet, helps to promote the physical condition and overall fertility of the soil, minimize soil erosion, and promote sustainable long-term production.

PLATE 19 How to score yield



GOOD CONDITION VS = 2

Average yield is >0.5 kg of olives/ m^3 of mature trees (10–15 years old).



MODERATE CONDITION VS = 1

Average yield is 0.3 – 0.5 kg of olives/ m^3 of mature trees (10–15 years old).



POOR CONDITION VS = 0

Average yield is <0.3 kg of olives/ m^3 of mature trees (10–15 years old).



Assessment

- 1 Cast your eye along the rows and observe any variability in tree performance (in terms of tree height, trunk thickness, canopy volume, canopy density, leaf colour, etc.) and compare with the class limits in Table 5. In making the assessment, consideration must be given to the variety, pruning and age of the olive tree.



Importance

VARIABILITY OF TREE PERFORMANCE ALONG THE ROW is a good visual indicator of the properties and condition of the soil (Plates 20 and 21). In particular, the linear variability in tree performance is often related to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy, sandy or gravelly). Moreover, soils in good condition with good structure and porosity, and with a deep, well-aerated root zone, enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic-matter levels and soil life (including mycorrhiza) show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, the growth and vigour of the tree.

The spatial variability of tree performance along the row is also a useful indicator because it highlights those trees that are underperforming compared with the majority, enabling a specific investigation as to why those are struggling and what remedial action may be taken.

TABLE 5 **Visual scores for variability of tree performance along the row**

Visual score (VS)	Variability in tree performance along the row
2 [Good]	Tree performance is good and even along the row
1 [Moderate]	Tree performance is moderately variable along the row
0 [Poor]	Tree performance is extremely variable along the row

PLATE 20 Effect of soil texture and available water on tree performance along the row [M. GREVEN]



Variable tree performance along the row owing to differences in soil texture and water-holding capacity. Poor-performing trees occur on gravelly (droughty) soils, while well-performing trees are situated on deeper siltier soils (in the background).

PLATE 21 Effect of soil aeration and drainage on tree performance along the row



Variable tree performance along the row in a four-year-old orchard owing to differences in the aeration and wetness status of the root zone. Poor-performing trees occur in the hollows with a shallow water table, while healthier trees are situated on the humps with a deeper, better-aerated root zone owing to a deeper water table.

Soil management in olive orchards

Olive trees with satisfactory production develop shoot of optimal length, promote flower-bud induction, give good percentage fruiting, and stimulate fruit development. Therefore, it is essential to maintain the availability of water, nutrients and carbohydrate during the crop cycle, avoiding any shortages.

Good soil management practices are needed in order to maintain good growth conditions and productivity to safeguard olive tree functionality especially during the crucial periods of plant development and fructification. To achieve this, management practices need to maintain and promote the condition and, therefore, functionality of the soil, particularly in regard to its aeration status and the supply of nutrients and water to the plant. To this end, the soil needs to have a good rooting environment, including an adequate soil structure to allow an effective root system to develop in order to maximize the utilization of water and nutrients, and to provide sufficient anchorage for the plant. Good soil structure also promotes infiltration and movement of water into and through the soil, so minimizing surface ponding, runoff and soil erosion. The maintenance of good soil health through the implementation of sound management practices further safeguards the environment and minimizes the ecological footprint of olive orchards on a region. A decline in soil quality through soil tillage, compaction, increased fertilizer and chemical inputs, and the loss of soil through erosion contribute to the food eco-footprint of a region and the country.

Where rainfall is not a limiting factor for plant growth, the establishment of cover crops is the most suitable soil management practice to protect the soil surface from erosion, to preserve the environment, to reduce production costs and to enhance the quality of the olive oil. Cover cropping not only helps in reducing water runoff and soil erosion, but it also improves the soil physical characteristics, enriches soil organic matter content, and suppresses soil-borne diseases by increasing micro-organism biodiversity. On the other hand, cover crops compete with olive trees for minerals, water and fertilizer where they are not well managed. In the absence of irrigation in the hottest months in those regions characterized by dry summers, competition for water could occur during flowering, fruit formation and development, so limiting the final yield. To avoid this competition, a temporary cover crop or natural vegetation can be grown during the wetter months and can be controlled during the hottest period by herbicide application or mowing 2–3 times during the period of major nutrient demand.

Different mixes of cover crops, including leguminous species that supply N, should be evaluated in different areas. In addition to legumes, the mix could comprise annual or perennial species, grasses and other broadleaf plants. Winter annuals can be grown to protect the soil from erosion in winter and to improve the ability of the soil to resist compaction when wet. Grasses, with their fibrous root system, are also more effective at improving soil structure, and generally add more organic matter to the soil than do legumes. If allowed to seed in early summer, a seed bank for subsequent regeneration is built up. Where possible, the grass in the interrows and within rows could be kept short by grazing sheep, provided the tree trunks

have protective plastic screens to shield them from strip and ring barking. The advantages of managing a grass cover crop using sheep compared with mowing and herbicide strips include: reduced use of synthetic (herbicide) chemicals, reduced fossil fuel usage, lower CO₂ emissions and, therefore, greater market acceptance. Other advantages include: lower labour and material costs; less compaction along wheel traffic lanes; and improved soil nutrient status and greater soil life (including earthworm numbers) as a result of the dung and urine applied. Stock tend to rest, urinate and defecate most within the tree row, translocating and concentrating nutrients to where the tree roots are greatest. Sheep can also graze grass very short, thereby reducing not only the competition for water and nutrients but also reducing insect and bird numbers and the possibility of fungal diseases.

The traditional management of the interrow is based on one or two cultivations with discs and tine harrows during the hot period following natural weed cover and could be satisfactory in limiting, principally, competition for water. The cultivation should be shallower than 100 mm in order to de-vigorate the cover crop but not to modify the canopy/root ratio of the trees by damaging the root system. The cultivation operations can also be useful for incorporating organic and mineral fertilizers as well as controlling diseases caused by fungi and bacteria in the soil.

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Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for olive orchards*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Orchards



Orchards

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of orchards. A decline in soil quality can have a marked impact on tree growth, yield, fruit quality and the operation and running of the orchard. A decline in soil physical properties in particular can take considerable time and cost to correct. Safeguarding soil resources for future generations is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the production performance of orchards and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing orchard crops, and to make informed decisions that will lead to sustainable land and environmental management. To this end, Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. The VSA method can also be used to assess the suitability and limitations of a soil for pipfruit, stonefruit and vine crops. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' indicators of soil quality, presented on a scorecard. With the exception of soil texture, the soil indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and as such provide an effective monitoring tool.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality observed when comparing the soil sample with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil indicators are relatively more important for soil quality than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index score for the sample you are evaluating. Compare this with the rating scale at the bottom of the scorecard to determine whether your soil is in good, moderate or poor condition.

The VSA tool kit

PLATE 1 The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in orchards is site specific. Sample sites that have had little or no wheel traffic (e.g. near the tree). The VSA method can also be used to assess compacted areas by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required. Note that the VSA can be used to assess the suitability of a soil for growing pipfruit and stonefruit trees and vine crops before the orchard is established.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test**Initial observation**

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

Format of the booklet

The soil scorecard is given on Figure 1 and lists the ten key soil ‘state’ indicators required in order to assess soil quality. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in orchards

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Date:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 2	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 1	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 2	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

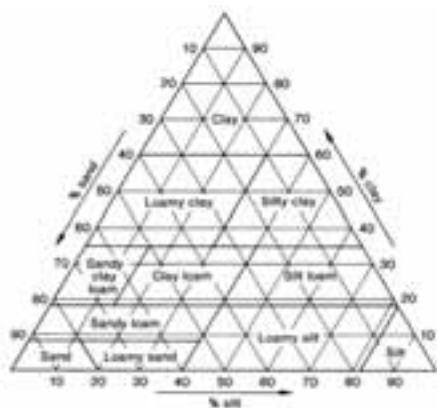


Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for orchards. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and maintains the soil carbon 'sink'. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of trees increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, methane and ethanol that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of fungal diseases such as *Phytophthora* root and crown rot in soils prone to waterlogging. Trees exhibit reduced growth, have thin canopies, and eventually die.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.

Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure decreases and blocks the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K and S. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. In addition, decay and dieback of roots can occur as a result of fungal diseases such as *Phytophthora* root and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. Trees exhibit reduced growth, have thin canopies, and can eventually die. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

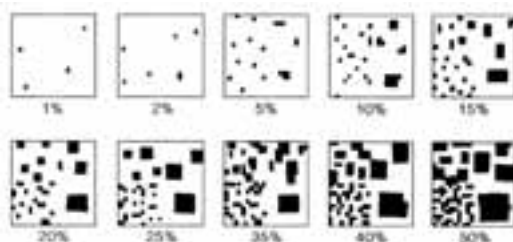


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (> 50%) medium and coarse orange and particularly grey mottles.



Assessment

- ① Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 6) and compare with the class limits in Table 2. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in orchards and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in

the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes reduce fertilizer requirements and improve the health of the trees and fruit production.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue, the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of:

- (i) surface feeders that live at or near the surface to breakdown plant residues and dung;
- (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and
- (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 6 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- 1 Dig a hole to identify the depth to a limiting (restricting) layer where present (Plate 7), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan (pp 16–17). An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting, gully, slip, earth slump or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated orchards. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the fruit. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Trees with a deep, dense vigorous root system raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce promote soil structure, porosity, water storage, soil aeration and drainage at depth. Soil depth should preferably not be less than 600 mm. Heavy clay soils are not recommended. Stony soils are acceptable under irrigation systems, particularly if the depth of the soil is less than 1 m. An adequate rooting depth is also needed to provide adequate anchorage of the tree at maturity.

PLATE 7 Generic drawing of the root system of a tree [L. DRAZETA and A. LANG]



TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

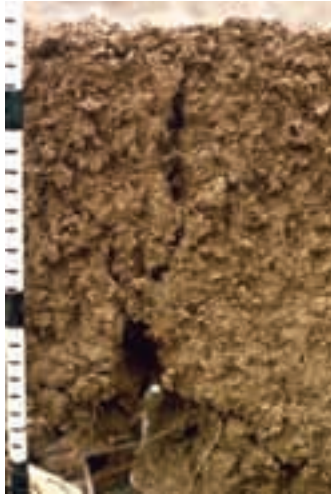
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 8). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 9).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given Plate 9.

PLATE 8 Using a knife to determine the presence or absence of a hardpan



PLATE 9 Identifying the presence of a hardpan



NO HARDPAN

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .



MODERATELY DEVELOPED HARDPAN

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).



STRONGLY DEVELOPED HARDPAN

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 10) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Orchard crops generally require free-draining soils. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth and development of roots. Roots need oxygen for respiration and are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are actively growing at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the tree is transpiring actively causes leaf desiccation and tip-burn, particularly in the outer canopy. Prolonged waterlogging also increases the likelihood of infections and fungal disease such as *Phytophthora* root rot and foot rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Trees decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, have thin canopies, and can eventually die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and manganese to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N, S and Zn. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of trees to waterlogging is dependent on a number of factors, including the time of year, the rootstock and type of tree crop, e.g. pear trees are generally more tolerant than apple trees of saturated soils. Tolerance of waterlogging is also dependent on soil and air temperatures, soil type, the condition of the soil, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate by plant roots.

Prolonged surface ponding increases the susceptibility of soils to damage under wheel traffic, reducing vehicle access.

PLATE 10 Surface ponding in an orchard [A. TOPP]



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤ 1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–4	Moderate surface ponding occurs for 2–4 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	> 5	Significant surface ponding occurs for longer than 5 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare with Plate 11 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of managed cover crops has in some cases reduced sediment erosion rates from 70 tonnes/ha to 1.5 tonnes/ha during single large rainfall events. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 11 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $> 30\%$ and $< 70\%$.

POOR CONDITION VS = 0

Surface crusting is > 5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and, more importantly, on your knowledge of what the site looked like in the past relative to Plate 12.



Importance

SOIL EROSION reduces the productive potential of an orchard through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation of interrows can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be removed by slips, flows, gullying and rilling, or it can be relocated semi-intact by slumping. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation between rows can also give rise to significant soil loss by wind erosion of exposed ground where the tree spacing is quite large.

PLATE 12 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no evidence of soil erosion. Little difference in height between the mounded row and interrow. The root system is completely covered.

**MODERATE CONDITION VS = 1**

Moderate soil erosion with a significant difference in height between the interrow and the soil around the base of the tree trunk. Part of the upper root system is occasionally exposed.

**POOR CONDITION VS = 0**

Severe soil erosion with deeply incised gullies or other mass movement features between rows. There is a large difference in height between the interrow and the soil around the base of the tree trunk. The root system is often well exposed and sometimes undermined.

Soil management in orchards

Trees with satisfactory production develop buds of optimal length, promote flower-bud induction, give good percentage fruiting, and stimulate fruit development. Therefore, it is essential to maintain the availability of water, nutrients and carbohydrates during the crop cycle, avoiding any shortages.

Good soil management practices are needed in order to maintain good growth conditions and productivity to safeguard the functionality of the tree, especially during the crucial periods of plant development and fructification. To achieve this, management practices need to maintain and promote the condition and, therefore, functionality of the soil, particularly in regard to its aeration status and the supply of nutrients and water to the plant. To this end, the soil needs to have a good rooting environment, including an adequate soil structure, to allow an effective root system to develop and so maximize the utilization of water and nutrients, and also provide sufficient anchorage for the plant. Good soil structure also promotes infiltration and movement of water through the soil, minimizing surface ponding, runoff and soil erosion.

Where rainfall is not a limiting factor for plant growth, the establishment of cover crops is the most suitable soil management practice to protect the soil surface from erosion, to preserve the environment, to reduce production costs, and to enhance the quality of the fruit. Cover cropping not only helps in reducing water runoff and soil erosion but also improves soil physical characteristics, enriches soil organic matter content and soil life (including earthworm numbers), and suppresses soil-borne diseases by increasing micro-organism biodiversity. However, cover crops compete for minerals, water and fertilizer where they are not well managed. In the absence of irrigation during the hottest months, competition for water could occur during flowering, fruit formation and development, thereby limiting the final yield. To avoid this competition, a temporary cover crop or natural vegetation can be grown from early autumn to mid-spring (often the wettest period), and it can be controlled during the hottest period by herbicide application or mowing 2–3 times during the period of major nutrient demand.

Different mixes of cover crops, including leguminous species that supply N, should be evaluated in different areas. In addition to legumes, the mix could include annual or perennial species, grasses and other broadleaf plants. Winter annuals can be grown to protect the soil from erosion during the winter and to improve the ability of the soil to resist compaction when wet. With their fibrous root system, grasses are also more effective at improving soil structure, and generally add more organic matter to the soil than do legumes. Where allowed to seed in early summer, a seed bank for subsequent regeneration is built up. Where possible, the grass in the interrows and within rows could be kept short by grazing sheep, provided the tree trunks have protective plastic screens to shield them from strip and ring barking. The advantages of managing a grass cover crop using sheep compared with mowing and herbicide strips include: lower use of synthetic (herbicide) chemicals; reduced fossil fuel use; and lower carbon dioxide emissions and, therefore, greater market acceptance. Other advantages include: lower labour and material costs; less compaction along wheel traffic lanes; improved soil nutrient

status; and greater soil life (including earthworm numbers), as a result of the dung and urine applied. Stock tend to rest, urinate and defecate most within the tree row, translocating and concentrating nutrients to where the tree roots are greatest. Sheep can also graze grass very short, reducing not only the competition for water and nutrients but also reducing insect and bird numbers and the possibility of fungal diseases.

The traditional management of the interrow is based on one or two cultivations with discs and tine harrows during the hot period following natural weed cover and it could be satisfactory in limiting, principally, competition for water. The cultivation should be shallower than 100 mm so as to de-vigorate the cover crop but not to modify the canopy/root ratio of the trees by damaging the root system. The cultivation operations can also be useful for incorporating organic and mineral fertilizers as well as controlling diseases caused by fungi and bacteria in the soil.

The application of mulches along the row in the form of compost, bark chips, cereal straw and grass clippings (spread during mowing) shades the soil, so reducing temperature and soil evaporation in summer. Mulches also encourage biological activity, especially earthworms. They suppress weeds and prevent the breakdown of the soil structure under the impact of rain, thereby enhancing water infiltration.

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Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for orchards*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Vineyards



Vineyards

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of vineyards. A decline in soil quality has a marked impact on vine growth, grape quality, production costs and the risk of soil erosion. Therefore, it can have significant consequences on society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of viticulture are important tasks for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the character and quality of wine, and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing grapes, and to make informed decisions that lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for viticulture. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a scorecard. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant scorecard. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, the soil quality assessment is not a combination of the 'soil' and 'plant' scores. Rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate or poor condition.

Placing the soil and plant assessments side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.

PLATE 1 The VSA tool kit



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the vineyard. The condition of the soil in vineyards is site specific. Sample sites that have had little or no wheel traffic (e.g. near the vine). The VSA method can also be used to assess compacted areas by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS rankings in the right-hand column.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required in order to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil and about plant performance.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in vineyards

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Date:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 2	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 1	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 2	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

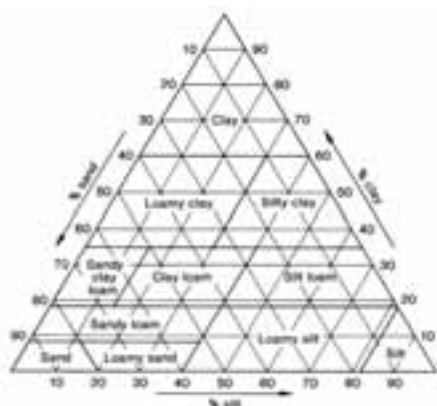


Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size > 0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is < 0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and the potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for vineyards. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Vine roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and maintains the soil carbon 'sink'. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of vines increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of the *Phylloxera* aphid and fungal diseases such as *Phytophthora* root rot and black foot rot in soils prone to waterlogging.

In general, dark-coloured soils are more favourable for red wine quality (owing to an increase in polyphenol and terpens).

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.



Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.



Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure decreases and blocks the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K and S. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. Decay and dieback of roots can also occur as a result of the *Phylloxera* aphid and fungal diseases such as *Phytophthora* root rot and black foot rot in strongly mottled, poorly aerated soils. Root rot and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

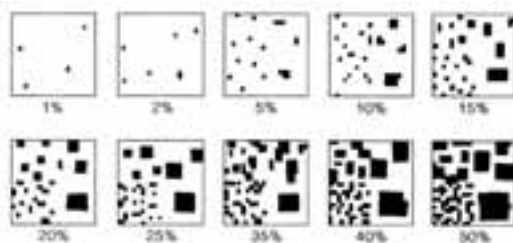


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (> 50%) medium and coarse orange and particularly grey mottles.



Assessment

- ① Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 6) and compare with the class limits in Table 2. Pay particular attention to the turf mat. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in vineyards and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in

the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes reduce fertilizer requirements and improve vine and grape quality.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue, the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 6 Sample for assessing earthworms

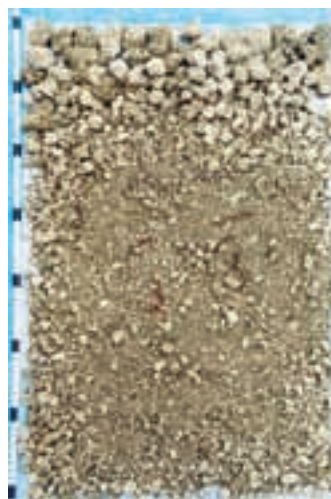


TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present (Plates 7 and 8), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also whether there is an over-thickening of roots (a result of a high penetration resistance), and whether the roots are being forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan (Plate 8), or a natural pan such as an iron, siliceous or calcitic pan. An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting, gully, slip, earth slump or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated vineyards. Under irrigation, the majority of roots are in the top 1 m of soil. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the grapes. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Grapevines with a deep, dense, vigorous root system raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce promote soil structure, porosity, water storage, soil aeration and drainage at depth. For rainfed vineyards, the depth of a restricting layer should ideally be deeper than 2.5 m, with a soil depth of preferably not less than 600 mm. Stony soils are acceptable under irrigation systems, particularly where the depth of the soil is less than 1 m. Furthermore, grapevines need a sufficient rooting depth to provide adequate anchorage for the vines at maturity.

PLATE 7 Potential rooting depth

[L. VAN HUYSTEEN in VAN ZYL 1988]



PLATE 8 Restricted root penetration through plough pan at 25 cm [L. VAN HUYSTEEN]



TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

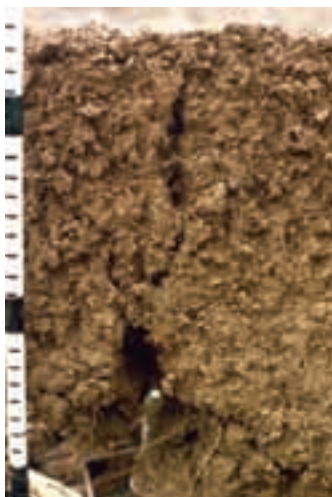
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) rapidly with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given in Plate 10.

PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Grapevines generally require free-draining soils. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth and development of roots. Roots need oxygen for respiration. They are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are growing actively at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the vine is transpiring actively causes leaf desiccation and tip-burn. Prolonged waterlogging also increases the likelihood of pests and diseases, including the *Phylloxera* aphid and *Phytophthora* fungal root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Vines decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, and eventually die.

Waterlogging and deoxygenation also result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of vine roots to waterlogging is dependent on a number of factors, including the time of year, the rootstock, soil and air temperatures, soil type, the condition of the soil, fluctuating water tables and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the amount of entrapped air and the oxygen consumption rate by plant roots. Prolonged surface ponding increases the susceptibility of soils to damage under wheel traffic, so reducing vehicle access.

PLATE 11 Surface ponding in a vineyard [CWi Technical Ltd]



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤ 1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–3	Moderate surface ponding occurs for 2–3 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	> 4	Significant surface ponding occurs for longer than 4 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare with Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of managed cover crops has in some cases reduced sediment erosion rates from 70 tonnes/ha to 1.5 tonnes/ha during single large rainfall events. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Photos of surface cover: courtesy of A. Leys;
Photo of severe crusting: courtesy of M. Speyer



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and, more importantly, on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of a vineyard through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation of interrows can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be removed by slips, flows, gullying and rilling, or it can be relocated semi-intact by slumping. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

PLATE 13 How to score soil erosion



GOOD CONDITION VS = 2

Little or no evidence of soil erosion. Little difference in height between the mounded row and interrow. The root system is completely covered.



MODERATE CONDITION VS = 1

Moderate soil erosion with a significant difference in height between the mounded row and interrow. Part of the upper root system is occasionally exposed.



POOR CONDITION VS = 0

Severe soil erosion with deeply incised gullies or other mass movement features between rows. The root system is often well exposed and the vine trunk totally undermined in places.

FIGURE 3 Plant scorecard – visual indicators for assessing plant performance in vineyards

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Wood production pg. 26		x 3	
Shoot lenght pg. 28		x 3	
Leaf colour pg. 30		x 3	
Yield pg. 34		x 2	
Variability of vine performance along the row pg. 36		x 2	
Production costs pg. 38		x 1	
PLANT PERFORMANCE INDEX (sum of VS rankings)			

Plant Performance Assessment	Plant Performance Index
Poor	< 10
Moderate	10–20
Good	> 20

SUMMARY

Comparison of soil & plant assessments		Do the soil and plant assessments differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:



Assessment

- 1 Estimate wood production per metre cord by assessing fresh wood weight at pruning (Plate 14). In making the observation, consideration must be given to the cultivar, pruning and age of the vine.

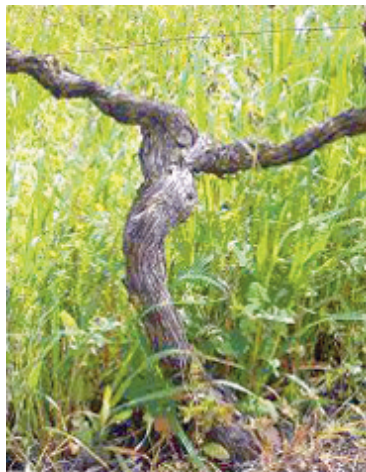


Importance

While climate factors, cultivar and agricultural practices all influence **WOOD PRODUCTION**, wood production at flowering is a good indicator of plant vigour and the fertility and physical condition of the soil (including its nutrient and water status). Therefore, it is a useful indicator of soil quality.

Soil degradation resulting from the loss of organic matter, soil compaction, poor aeration or soil erosion restricts root growth and limits the movement and storage of water, the cycling of nutrients and the efficient uptake of fertilizers. Plant roots either cannot reach the fertilizer, or the applied nutrients remain unavailable in the compacted soil because of impaired water movement or preferential flow through the soil, by-passing much of the soil volume. As a result, plant growth and vigour are poor.

PLATE 14 How to score wood production

**GOOD CONDITION VS = 2**

Depending on the cultivar, vineyards of seven years of age have 0.8 kg of vine-shoots per metre cord at pruning.

**MODERATE CONDITION VS = 1**

Depending on the cultivar, vineyards of seven years of age have 0.6–0.8 kg of vine-shoots per metre cord at pruning.

**POOR CONDITION VS = 0**

Depending on the cultivar, vineyards of seven years of age have <0.6 kg of vine-shoots per metre cord at pruning.



Assessment

- 1 Measure or visually assess shoot length and compare with the criteria given (Plate 15) at veraison. In making your assessment, consideration must be given to the cultivar, pruning and age of the vine, and the weather conditions at bud break. Poor weather will promote a high number of leaf buds rather than flowering buds and give rise to many shoots and leaves rather than flowers.



Importance

SHOOT LENGTH is also influenced by the bud position on the trunk and cordon, and by bud orientation with respect to the vertical direction. It is related strongly to the physical and chemical fertility of the soil, which in turn is influenced by soil management. Shoot length is an expression of plant vigour and general plant growth, which are also regulated by the availability of water and nutrients and by the aeration status of the soil. Waterlogging and poor drainage can restrict spring growth and give rise to poor shoot growth and dieback. Soils in good condition with good structure and porosity, and with a deep, well-aerated rootzone, enable the unrestricted movement of air and water into and through the soil and the development and proliferation of superficial (feeder) roots. Furthermore, soils with good organic-matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, shoot growth.

PLATE 15 How to score shoot length

**GOOD CONDITION VS = 2**

Vine-shoots are at or near the maximum length, with a little variability depending on the position of the shoot on the branch.

**MODERATE CONDITION VS = 1**

Vine-shoot length is moderately below maximum and shows moderate variability depending on the position of the shoot on the plant.

**POOR CONDITION VS = 0**

Vine-shoot length is significantly below the maximum length.



Assessment

- 1 Assess the colour of the mature leaves at the base of the vine-shoots by comparing with Plate 16 and the criteria given. In making the observation, consideration must be given to the cultivar, the stage of growth, pests and diseases, and recent weather conditions. Prolonged cold and cloudy days with little sunlight can give rise to chlorosis (or yellowing of the leaf) owing to the inadequate formation or loss of chlorophyll.



Importance

LEAF COLOUR can provide a good indication of the nutrient status and condition of the soil. The higher is the soil fertility, the greener is the leaf colour. Leaf colour is related primarily to water and nutrient availability, especially N. Leaf colour can also indicate a deficiency or excess of P, K, S, Ca, Mg, Fe, Mn, zinc (Zn), copper (Cu) and boron (B). Chlorosis can further occur as a result of low N, K, S, Fe, Mg and Cu levels in the soil, low soil and air temperatures, and poor soil aeration caused by compaction and waterlogging. A deficiency or excess of one or more essential elements in a plant can also produce visual symptoms of necrosis of leaf margins, stunted growth of shoots, irregular fruit-set and small berries. Premature leaf senescence can further indicate plant stress.

Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of Zn and Cu. Excess N can suppress B and Cu and cause the plant to luxury feed on K, which in turn can suppress the utilization of Ca and Mg. Sulphur can also only be utilized by plants in the sulphate (SO_4^{2-}) form. Under poorly aerated conditions, S will reduce to sulphur dioxide (SO_2) and sulphides (e.g. hydrogen sulphide [H_2S], and ferrous sulphide [FeS]). Sulphides and SO_2 cannot be taken up by the plant, are toxic to plant roots and micro-organisms, and suppress N uptake. Plants can only utilize N where S is present in the oxygenated (sulphate) form. Like S, N can also only be utilized by the plant under aerobic conditions in the nitrate (NO_3^-) or ammonium form (NH_4^+).

Plate 17 shows some of the most common symptoms of nutrient deficiencies.

PLATE 16 How to score leaf colour



GOOD CONDITION VS = 2

Leaves have an intense dark green colour.



MODERATE CONDITION VS = 1

Leaves have a yellowish-green or medium green colour.



POOR CONDITION VS = 0

Leaves have a distinct yellowish colour or turn opaque green.

PLATE 17 Visual symptoms of nutrient deficiency in vines



Phosphorus



Potassium



PLATE 17 Visual symptoms of nutrient deficiency in vines *(continued)*



Boron



Iron



Zinc





Assessment

- 1 Assess relative crop yield by visual estimation of fruit number and size and by comparing with Plate 18 and the criteria given, or alternatively estimate or measure the weight of grapes per metre cord. In making your assessment, consideration must be given to the cultivar, pruning and age of the vine. Consideration must also be given to the weather conditions (e.g. whether warm and dry, or cold and wet) at pollination, fertilization, flowering and fruit-set. Pollination is best when the weather is dry, while fertilization is most successful when temperatures are warm. Poor weather during flowering can give rise to poor fruit-set. Warm weather at fruit-set will give good yields while cold wet weather will give poorer yields. Compare your assessment or measurement against the mean of the last 3 or 4 years.



Importance

YIELD can be a good visual indicator of the properties and condition of the soil. The physical condition of the soil (in terms of its texture, structure, porosity, aeration and drainage) has a significant effect on the root system, aeration status and water and nutrient availability at critical times of the year. It also plays an important role in vine growth and vigour, grape quality and yield.

Appropriate soil management, including the adoption of a managed cover crop between rows, and avoiding wheel traffic when the soil is wet, helps to promote the physical condition and overall fertility of the soil and sustainable long-term production.

PLATE 18 How to score yield



GOOD CONDITION VS = 2

Depending on the cultivar, pruning and age of the vine, yields are good.



MODERATE CONDITION VS = 1

Depending on the cultivar, pruning and age of the vine, yields are moderate.



POOR CONDITION VS = 0

Depending on the cultivar, pruning and age of the vine, yields are poor.

Assessment

- 1 Cast your eye along the rows and observe any variability in vine performance (in terms of vine height, stem thickness, canopy volume and density, leaf colour, early senescence of leaves, etc.) and compare with the class limits in Table 5. In making the assessment, consideration must be given to pruning and to diseases that are not soil-related (Plates 19–22).

Importance

VARIABILITY OF VINE PERFORMANCE ALONG THE ROW can be a very good visual indicator of the properties and condition of the soil. In particular, the linear variability of vine performance is often related to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy, sandy or gravelly). Moreover, soils in good condition with good structure and porosity, and with a deep, well-aerated rootzone, enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic-matter levels and soil life (including mycorrhizae) show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, the growth and vigour of the vine.

The spatial variability of vine performance along the row is also a useful indicator because it highlights those vines that are underperforming compared with the majority, enabling a specific investigation as to why those are struggling and what remedial action may be taken.

PLATE 19 Effect of soil texture, organic matter and mycorrhizae on vine performance [D. MUNDY]



Poor-performing vines on the left are on coarse-textured soils with low organic matter and a low mycorrhizal colonization of 40%. Well-performing vines on the right are the result of better utilization of water and nutrients on a siltier soil with more organic matter and a 90% colonization of mycorrhizae.

PLATE 20 Effect of soil aeration and drainage on vine performance [D. MUNDY]

Poor-performing vines in the hollows are due to root (black foot) rot associated with poor drainage, while the better-performing vines on higher ground further along the row are on freer-draining, better-aerated soil.

PLATE 21 Effect of soil-borne pathogens on vine performance [D. MUNDY]

Poor-performing vines in the centre row owing to a soil-borne pathogen.

PLATE 22 Variable crop vigour and leaf colour [S. GREEN]

Variable crop vigour and leaf colour along the row owing to differences in water and nutrient availability associated with differences in soil texture and soil depth.

TABLE 5 Visual scores for variability of vine performance along the row

Visual score (VS)	Variability of vine performance along the row
2 [Good]	Vine performance is good and even along the row
1 [Moderate]	Vine performance is moderately variable along the row
0 [Poor]	Vine performance is extremely variable along the row



Assessment

- 1 Assess whether production costs have increased because of increased tillage/subsoiling, fertilizer requirements and pesticide application over the years (Figure 4 and Table 6). This assessment can be based on perceptions, but reference to annual balance sheets will give a more precise answer.



Importance

Continuous tillage between rows using conventional cultivation techniques can give rise to a marked decline in soil structure, porosity and organic matter. The result is a reduction in root growth owing to a decline in soil aeration, an increase in penetration resistance to root development, a reduction in water storage and plant-available water, and a reduction in soil fertility and the ability of the soil to supply nutrients. Higher amounts of fertilizer are required in order to compensate for the loss of these nutrients and the decline in soil quality. Higher and more frequent applications of chemical sprays are also needed because of increased disease and pest attack in vineyards with degraded soils. The quantity and quality of the final product can often be reduced, with a lower income as a consequence.

Soil compaction under wheel traffic between rows increases the size, density and strength of soil clods, and increases the penetration resistance to lateral root development. Apart from decreasing infiltration and increasing runoff, the increased tillage resistance of compacted lanes often requires a greater number of passes and careful timing with the cultivator in order to break down the large clods. Subsoiling may also be necessary to ameliorate compaction in the subsoil in order to improve aeration and root development.

FIGURE 4 Assessment of production costs

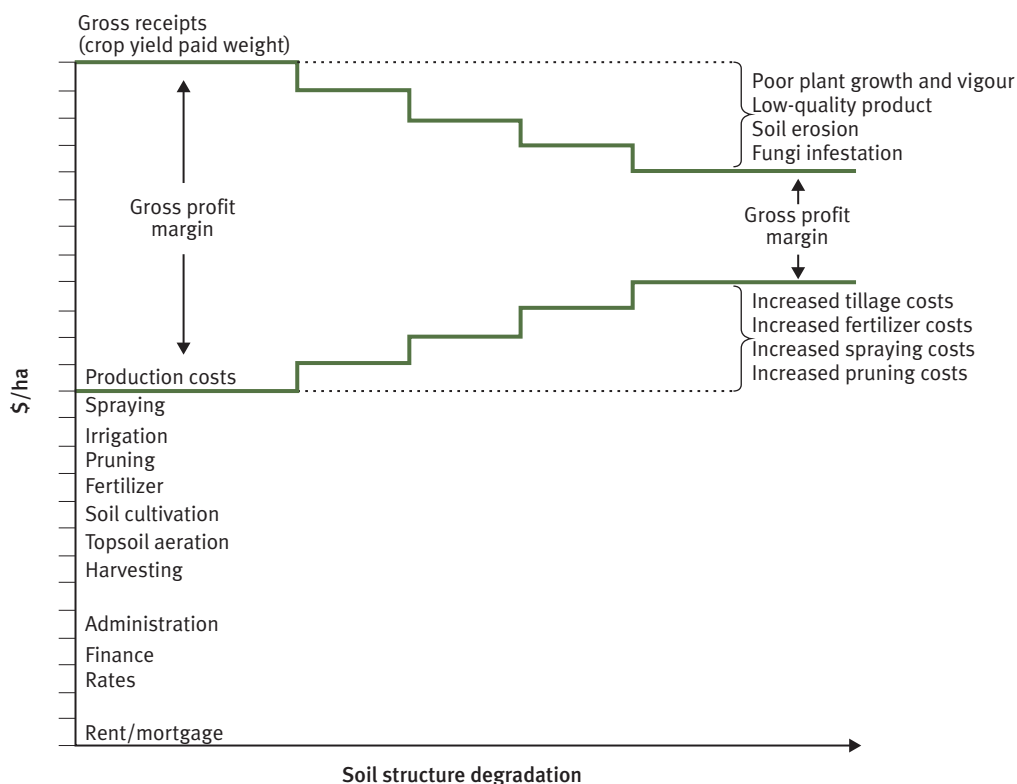


TABLE 6 Visual scores for production costs

Visual score (VS)	Production costs
2 [Good]	Spraying, fertilizer and tillage/subsoiling requirements have not increased significantly
1 [Moderate]	Spraying, fertilizer and tillage/subsoiling requirements have increased moderately
0 [Poor]	Spraying, fertilizer and tillage/subsoiling requirements have increased greatly

Soil management in vineyards

Soil management plays a key role in achieving good high-quality vineyard production while at the same time safeguarding the environment and minimizing the ecological footprint of viticulture on a region and the country.

One of the aims of the farmer should be soil conservation. This does not only mean having healthy plants and high grape quality, but achieving this with less fertilizer, chemical input and soil tillage. In general, conventional soil management in vineyards can have a negative impact on the environment. It enhances chemical residues, alters microflora and microfauna by reducing both the number of species and their biomass, reduces soil organic matter content and exposes the soil to accelerated soil erosion. Thus, the loss of soil and soil quality in vineyards contributes to the food eco-footprint.

Cover crops play an important role in protecting the soil surface and enhancing soil quality, so preserving the environment, reducing production costs and enhancing the quality of wine. Recent experiments have shown that the nutritional status of vineyards can have a strong influence on the chemical and organoleptic characteristics of wine.

Cover cropping not only helps in reducing water runoff and soil erosion but also improves soil physical characteristics, enriches soil organic matter content, reduces inorganic fertilization and root mortality, and suppresses soil-borne disease by increasing micro-organism activity and biodiversity.

One of the limiting factors of cover crops in vineyards is the competition for nutrients and plant-available water where the management is inadequate. This can affect the amount of available N to the plant and the N content and alcoholic fermentation of the wine. In order to solve this problem, a different mix of cover crops including leguminous species such as clover and lucerne that supply N (fixed from the atmosphere) should be evaluated in different areas, reducing the problem of N deficiency. The input of biologically fixed N is also an important component of the N cycle.

In addition to legumes, the mix of cover crops in the interrows could include annual and perennial species, grasses and other broadleaf plants. Winter annuals can be grown in order to protect the soil from erosion during winter and to improve the ability of the soil to resist compaction when wet. Grasses, with their fibrous root system, are also more effective at improving soil structure, and generally add more organic matter to the soil than do legumes. Where allowed to seed in early summer, a seed bank for subsequent regeneration is built up. In order to reduce competition, cover crops or natural weeds can be controlled by herbicide application or by mowing 2–3 times during the period of major water and nutrient demand. Grass should also be kept short in order to reduce insect and bird numbers. Where the grass cover crop extends along and under the vine row, ensure that the length of grass is kept short in order to reduce not only the competition for water and nutrients but also the possibility of fungal diseases.

In addition to the adoption of managed cover crops, the physical condition and overall fertility of the soil can be promoted by avoiding wheel traffic between rows when the soils are wet.

The application of mulches along the vine rows in the form of grass mowings, compost, bark chips and cereal straw shade the soil, so reducing temperature and soil evaporation during the summer. Mulches also encourage biological activity, especially earthworms. They suppress weeds and prevent the breakdown of the soil structure under the impact of rain, so enhancing water infiltration. The application of crushed glass as a 'mulch' enhances the availability of understorey light, so providing more energy from the rays of the sun to the ripening fruit, lifting the flavour, and ripening the fruit earlier. However, glass mulch does nothing to enhance the biological life of the soil.

References

Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for vineyards*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Wheat



Wheat

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
CO ₂	Carbon dioxide
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of wheat cropping. A decline in soil quality has a marked impact on yield and grain quality, production costs and the risk of soil erosion, and can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of cropping wheat is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance of wheat cropping and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for growing crops, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for wheat. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil ‘state’ and plant performance indicators of soil quality, presented on a scorecard. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant scorecard. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the ‘soil’ and ‘plant’ scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate or poor condition.

Placing the soil and plant assessments side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.

PLATE 1 The VSA tool kit



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the 'worm test'. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in wheat fields is site specific. Avoid areas that may have had heavier traffic than the rest of the field and sample between wheel traffic lanes. VSA can also be used however, to assess the effects of high traffic on soil quality by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS rankings in the right-hand column.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required in order to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil and about plant performance.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in wheat

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Date:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 2	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 1	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

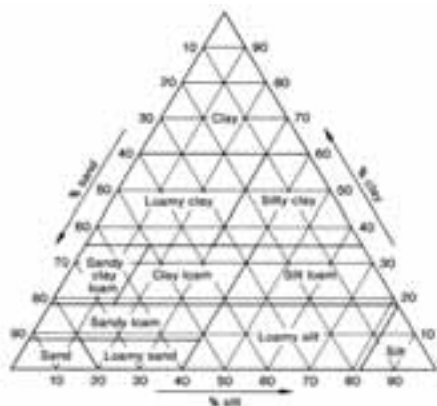


Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil workability and trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and the potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for grain crops. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till, controlled traffic or conventional cultivation under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and indicates whether the soil is functioning as a carbon 'sink' or as a source of greenhouse gases. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of crops increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe³⁺) and manganic (Mn³⁺) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe²⁺) and manganous (Mn²⁺) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot in soils prone to waterlogging.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.



Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.



Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S and Cu. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. In addition, decay and dieback of roots can occur as a result of fungal diseases such as *Rhizoctonia*, *Pythium* and *Fusarium* root rot, foot rot and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

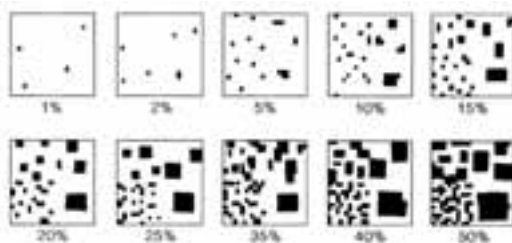


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (> 50%) medium and coarse orange and particularly grey mottles.



Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 7) and compare with the class limits in Table 2. Pay particular attention to the turf mat. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in arable cropping and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that

PLATE 6 (a): earthworm casts under crop residue; (b): yellow-tail earthworm (*Octolasion cyaneum*)



stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases, and promote a more rapid breakdown of organic herbicides. The collective benefits of microbes can increase crop production markedly while at the same time reducing fertilizer requirements.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue (Plate 6a), the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 7 Sample for assessing earthworms

Earthworms species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 6b) can indicate adverse soil conditions.



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present (Plate 8), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also whether there is an over-thickening of roots (a result of a high penetration resistance), and whether the roots are being forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan (pp 16–17). An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated crops. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the crop. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Crops with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce, promote soil structure, porosity, water storage, soil aeration and drainage at depth. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on frequent and high application rates of fertilizer and N to generate growth, and available nutrients are more likely to be taken up, so reducing losses by leaching into the environment.

PLATE 8 Hole dug to assess the potential rooting depth



The potential rooting depth extends to the bottom of the arrow, below which the soil is extremely firm and very tight with no roots or old root channels, no worm channels and no cracks and fissures down which roots can extend.

TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

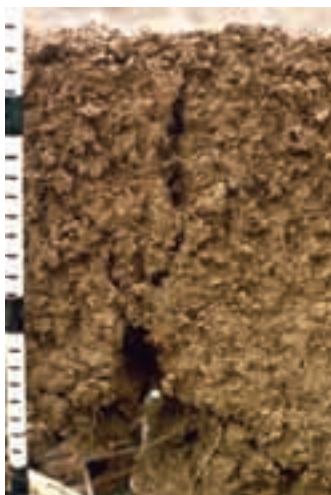
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given in Plate 10.

PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth of roots. Roots need oxygen for respiration. They are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are actively growing at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the crop is transpiring actively causes leaf desiccation and the plant to wilt. Prolonged waterlogging also increases the likelihood of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Plant stress induced by poor aeration and prolonged soil saturation can render crops less resistant to insect pest attack such as aphids, armyworm, cutworm and wireworm. Crops decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, become discoloured and die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of the root system to surface ponding and waterlogging is dependent on a number of factors, including the time of year and the type of crop. Tolerance of waterlogging is also dependent on: soil and air temperatures; soil type; the condition of the soil; fluctuating water tables; and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate.

Prolonged surface ponding makes the soil more susceptible to damage under wheel traffic, so reducing vehicle access. As a consequence, waterlogging can delay ground preparation and sowing dates significantly. Sowing can further be delayed because the seed bed is below the crop-specific critical temperature. Increases in the temperature of saturated soils can be delayed as long as water is evaporating.

PLATE 11 Surface ponding in a wheat field



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–3	Moderate surface ponding occurs for 2–3 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	>5	Significant surface ponding occurs for longer than 5 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER after harvesting and prior to canopy closure of the next crop helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of conservation tillage can reduce soil erosion by up to 90 percent and water runoff by up to 40 percent. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of soils through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be water eroded by gullyng, rilling and sheet wash. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability of water through the soil;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation can also give rise to significant soil loss by wind erosion of exposed ground.

PLATE 13 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no *water erosion*. Topsoil depths in the footslope areas are <150 mm deeper than on the crest.

Wind erosion is not a concern; only small dust plumes emanate from the cultivator on a windy day. Most wind-eroded material is contained in the field.

**MODERATE CONDITION VS = 1**

Water erosion is a moderate concern with a significant amount of rilling and sheet erosion. Topsoil depths in the footslope areas are 150–300 mm greater than on crests, and sediment input into drains/streams may be significant.

Wind erosion is of moderate concern where significant dust plumes can emanate from the cultivator on windy days. A considerable amount of material is blown off the field but is contained within the farm.

**POOR CONDITION VS = 0**

Water erosion is a major concern with severe gullying, rilling and sheet erosion occurring. Topsoils in footslope areas are more than 300 mm deeper than on the crests, and sediment input into drains/streams may be high.

Wind erosion is a major concern. Large dust clouds can occur when cultivating on windy days. A substantial amount of topsoil can be lost from the field and deposited elsewhere in the district.

FIGURE 3 Plant scorecard – visual indicators for assessing plant performance in wheat

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Crop establishment pg. 26		x 2	
Tillering pg. 28		x 3	
Leaf colour pg. 30		x 3	
Variability of crop performance along the row pg. 34		x 3	
Root development pg. 36		x 3	
Root diseases pg. 38		x 2	
Crop growth & height at maturity pg. 40		x 2	
Kernel size pg. 42		x 2	
Crop yield pg. 44		x 3	
Production costs pg. 46		x 1	
PLANT QUALITY INDEX (sum of VS rankings)			

Plant Quality Assessment	Plant Quality Index
Poor	< 15
Moderate	15–30
Good	> 30

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Land use management & history:

Total available water-holding capacity:



Assessment

- 1 Assess the degree and uniformity of crop establishment within a month of sowing by comparing the number and height of established plants with the three photographs provided (Plate 14).



Importance

GOOD SEED GERMINATION, PLANT EMERGENCE AND CROP ESTABLISHMENT depend on factors that include the quality of soil tilth at the time of sowing and during the weeks immediately following. Soils that have poor structure through compaction and over-cultivation can resettle and consolidate rapidly after the seed bed has been prepared. Impeded water and air movement through the soil can give rise to increased soil-borne pathogens and areas low in oxygen (anaerobic zones). Anaerobic zones produce chemical and biochemical reduction reactions, the by-products of which are toxic to plants. Poor soil aeration and soil-borne pathogens can give rise to poor germination, poor pre- and post emergence, poor plant vigour and even death. While emergence may be slow, recovery can also be limited and plants often appear sickly. Poor plant emergence, bare patches and poor and uneven early leaf and tiller growth are commonly observed throughout paddocks and result in crop thinning and low plant populations. Young plants can also show discolouration of leaves, leaf blemishes and moisture stress.

The loss of soil condition can reduce crop establishment from 300 to 130 plants/m² and grain yields from 8 to 5 tonnes per hectare. Seedling mortality can be high if the soil is waterlogged for more than 3 to 4 days between germination and emergence.

PLATE 14 How to score crop establishment

**GOOD CONDITION VS = 2**

Good emergence and crop establishment, with few gaps along the row and crop showing a good even height.

**MODERATE CONDITION VS = 1**

Moderate emergence and crop establishment, with a significant number of gaps along the row and a significant variation in seedling height. Emergence may also be moderately slow but recovers somewhat.

**POOR CONDITION VS = 0**

Poor emergence and crop establishment, with a large number of gaps along the row and a large variation in seedling height. Emergence may also be slow with limited recovery and plants often appear sickly.



Assessment

- 1 Measure the number of tillers at the end of the tillering stage and compare with the photographs (Plate 15) and class limits below.



Importance

THE NUMBER OF TILLERS play a fundamental role in determining the number of ears (spikes) per square metre and consequently the final yield. The potential number of tillers varies with the genotype, particularly among winter genotypes which have the greatest number. The new semi-dwarf wheat varieties normally have 2–3 tillers per plant to permit the development and grouping of tillers and ears that are contemporary, i.e. are equal in all vegetative, reproductive and ripening stages in order to maximise yields. Although this character is genetically determined and strongly influenced by planting density, it is also an expression of plant vigour and general plant growth which are firstly regulated by nutrient and water availability and the condition of the soil.

Soils in good health with good structure, porosity, organic matter levels, soil life, soil fertility and rooting depth favour the release and uptake of water and nutrients and subsequently the development of a greater number of tillers and their contemporary development.

PLATE 15 How to score tillering

**GOOD CONDITION VS = 2**

Depending on the cultivar the plant has 3 well developed tillers with little variability compared to the main stem (i.e., main culm).

**MODERATE CONDITION VS = 1**

Depending on the cultivar the plant has 2–3 tillers with moderate variability compared to the main stem (or culm).

**POOR CONDITION VS = 0**

The plant has 1 or no tillers at all with significant differences in terms of development to the main stem (or culm).



Assessment

- 1 Assess the leaf colour of the crop when all other factors favour rapid growth, and compare with the three photographs (Plate 16). In making the assessment, consideration must be given to the cultivar, the stage of growth, the soil moisture and temperature conditions, and the presence of pests and diseases (e.g. nematodes). The assessment can be done at any time prior to leaf senescence but ideally from four to six weeks after plant emergence to grain filling, avoiding very cold and wet weather.



Importance

LEAF COLOUR prior to completion of grain filling can provide a good indication of the water and nutrient status and condition of the soil. Under normal environmental conditions the higher the soil fertility, the greener the crop. Plant vigour and colour is strongly related to soil water and nutrient availability, especially nitrogen (N). Discolouration of the foliage and blemishes on the leaf can also result from a deficiency or excess of phosphorus (P), potassium (K), sulphur (S), magnesium (Mg), manganese (Mn), zinc (Zn), copper (Cu) and boron (B) – Plate 17. Chlorosis (or yellowing of crops) due to the inadequate formation of chlorophyll, commonly occurs as a result of low N, K, S, Fe, Mg and Cu levels in the soil, low soil and air temperatures, prolonged cloudy days and poor soil aeration due to compaction and waterlogging.

Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of Zn and Cu. Excess N can suppress B and Cu and cause the plant to luxury feed on K. Sulphur can also only be utilised by the plant in the sulphate (SO_4^{2-}) form. Under poorly aerated conditions sulphate-S will reduce to sulphur dioxide (SO_2) and sulphides (eg. hydrogen sulphide [H_2S], and ferrous sulphide [FeS]). Sulphides and SO_2 cannot be taken up by the plant, are toxic to plant roots and micro organisms, and suppress the uptake of N. Plants can also only utilise N if S is present in the oxygenated (sulphate) form. Like S, N can only be utilised by the plant in the oxygenated nitrate (NO_3^-) and ammonium (NH_4^+) form under aerobic conditions.

The aeration status of the soil can further affect the uptake of nutrients. Phosphorus, copper and cobalt for example cannot be efficiently utilised by the plant under anaerobic conditions.

PLATE 16 How to score leaf colour



GOOD CONDITION VS = 2

Leaf colour is uniformly deep green. The odd colour blemish on leaves may be apparent within a broad area.



MODERATE CONDITION VS = 1

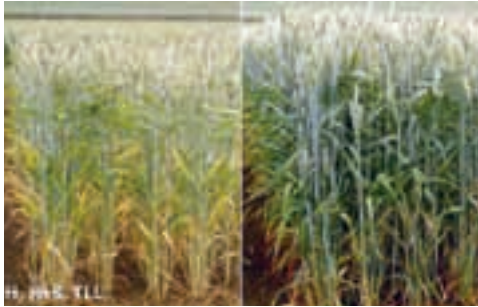
Leaf colour is yellowish green; i.e. has a distinct yellowish tinge. Few colour blemishes on leaves may occur within a wide area.



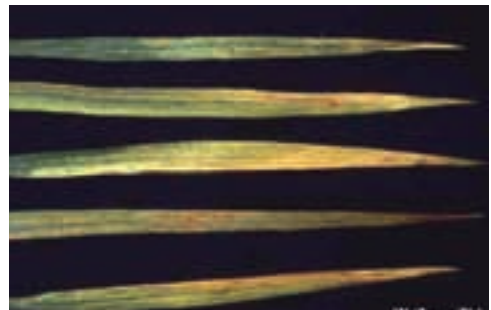
POOR CONDITION VS = 0

Leaf colour is quite yellow over a wide area. Colour blemishes on leaves may commonly occur.

PLATE 17 Common symptoms of leaf discolouration due to nutrient deficiencies in wheat



Nitrogen deficiency on the left



Phosphorus deficiency

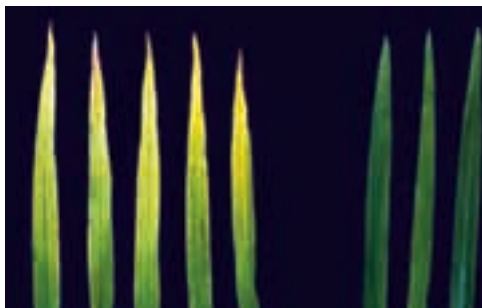


Potassium deficiency



Sulphur deficiency on the right

PLATE 17 Common symptoms of leaf discolouration due to nutrient deficiencies in wheat (*cont'd*)



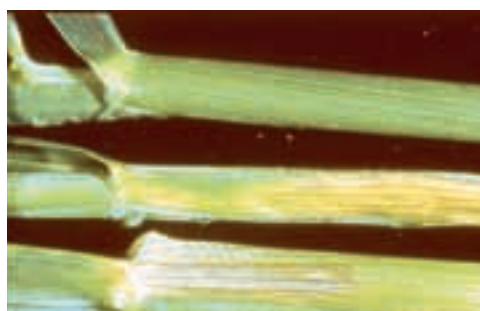
Magnesium deficiency on the left



Manganese deficiency



Copper deficiency



Zinc deficiency



Assessment

- Cast your eye along the row and observe any variability in crop performance (in terms of crop height, plant and leaf density, stem thickness, leaf colour) and compare with the class limits in the Table 5. In making the assessment, consideration must also be given to other factors that may affect the performance of a crop such as pest and disease attack that are not related to the condition of the soil.



Importance

VARIABILITY OF CROP PERFORMANCE ALONG THE ROW can be a good visual indicator of the condition of the soil (Plates 18–21). In particular, the linear variability in crop performance can be strongly related to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy or sandy). Also, soils in good condition with good structure and porosity, and have a deep, well aerated root zone enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and consequently the growth and vigour of the crop.

The spatial variability of crop performance along the row is also a useful indicator because it highlights those areas of the field that are under-performing enabling a site specific investigation as to why and what remedial action may be taken. This may include variable rate application of fertiliser by GPS guided ground spreaders.

PLATE 18 Variable crop performance due to soil aeration and wetness



Variable crop performance due to differences in soil aeration and soil wetness.

PLATE 19 Variable crop performance due to soil compaction



Variable crop performance due to differences in soil compaction.

PLATE 20 Variable crop performance due to an iron pan



Variable crop performance due to differences in rooting depth to an iron pan.

PLATE 21 Variable crop performance due to water repellency



Concentric rings of poor wheat growth due to severely water repellent (hydrophobic) soils. Areas of stronger wheat growth occur on non-water repellent soils.

TABLE 5 Visual scores for variability of crop performance along the row

Visual score (VS)	Variability of crop performance along the row
2 [Good]	Crop performance is good and even along the row
1 [Moderate]	Crop performance is moderately variable along the row
0 [Poor]	Crop performance is extremely variable along the row



Assessment

- 1 Examine the upper part of the hole dug to assess the potential rooting depth of the soil. With the help of a knife, carefully loosen the soil around the roots to expose the root system *in-situ* (Plate 22). Alternatively, dig out a 250–300 mm deep slice of soil around a group of plants and gently tap the sample against the edge of the hole to expose the root system. Use a knife to help loosen the soil if required. Assess both the length and the density of the roots and compare with the class limits in the Table 6. Root length and root density is best assessed at or just prior to crop maturity.



Importance

THE ROOT LENGTH AND ROOT DENSITY provides a good indication of the condition of the plant root system. Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared to crops with a shallow, thin root system. Tillering, ear development and grain filling is therefore likely to be greater, crops are less likely to suffer wind throw, and they will be less susceptible to drought stress. Crops with a dense, deep, vigorous root system are also more likely to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna, and the glues they produce promote the development of soil structure, soil aeration and drainage.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up reducing losses by leaching into the groundwater and waterways.

Root length and density can be restricted by the mechanical impedance of roots and the lack of soil pores due to soil compaction or a hardpan. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, nutrient deficiencies, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and low oxygen levels. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions (see pg 18).

PLATE 22 Root development



Photo showing good root development in the upper 150 mm of soil only. The root distribution and root density in the 150–300 mm zone is poor.

TABLE 6 Visual scores for root development

Visual score (VS)	Root development
2 [Good]	Good root length and root density in the upper 250–300 mm of soil
1 [Moderate]	Moderate root length & density in the upper 250–300 mm of soil
0 [Poor]	Poor root length & density in the upper 250–300 mm of soil with the root system being restricted to limited areas



Assessment

- 1 Assess the presence of root diseases by pulling a number of stems out of the soil and carefully examining the root system for visual evidence of root diseases at or any time before crop maturity. Make your assessment based on the class limits in Table 7.
- 2 Consider also how commonly root diseases occur in a particular field from season to season.



Importance

ROOT DISEASES encouraged by the degradation of soil quality include take-all (*G. graminis* var. *tritici*), dryland root rot (*Fusarium graminearum* and many others), *Rhizoctonia* root rot (*Rhizoctonia solani*) and *Pythium* root rot (*Pythium* spp.) (Plates 23–26). Their presence can cause severe yield loss and reduction in grain quality. Symptoms of root diseases include pre- and post emergence plant death in seedlings resulting in crop thinning, stunting and reduced tillering, discolouration of and blemishes (lesions) on stems, tillers and leaves, bleached heads and premature death. Infected plants have sparse root development and characteristically a brown-black rot can be seen at the crown and extending to the base.

Poor soil aeration, soil saturation and high penetration resistance to root development due to soil structural degradation can increase root rot and soil-borne pathogens. They can also reduce the ability of the root system to overcome the harmful effects of pathogens resident in the topsoil.

The conservation of soil moisture, amelioration of soil compaction, the build up of organic matter and the promotion of good soil life (in terms of microbial biomass, diversity and activity) are factors that contribute to the development of healthy plants and the suppression of soil-borne diseases. They also help enable the plant to better resist the pressure of disease and insect attack. Soil biota and especially those micro-organisms that enhance cellulytic breakdown and decomposition of straw residues further limit pathogen survival.

PLATE 23 *Pythium* root disease [from Compendium of Wheat Diseases by M.V. WIESE]



Wheat seedlings damaged by *Pythium* species in wet soil.

PLATE 24 **Take-all root disease** [from Compendium of Wheat Diseases by M.V. WIESE]

Root rot and darkened stem bases due to take-all (*G. graminis* var. *tritici*).

PLATE 25 ***Fusarium* root disease** [from Compendium of Wheat Diseases by M.V. WIESE]

Secondary root emerging from crown and invaded by *Fusarium culmorum*.

PLATE 26 **Root rot** [from Compendium of Wheat Diseases by M.V. WIESE]

Wheat crown on the left damaged by common root rot; healthy crown (right).

TABLE 7 **Visual scores for root disease**

Visual score (VS)	Occurrence of root diseases due to soil conditions
2 [Good]	Root disease are rare
1 [Moderate]	Root disease are common
0 [Poor]	Root disease are very common



Assessment

- 1 Assess crop growth and crop height when the crop has reached maturity and preferably two weeks after ear emergence (Plate 27). Compare with the class limits in Table 8. Your observations of crop growth and vigour during the growing season may also provide a useful indication of seedbed conditions. In a good season under non-limiting conditions, a particular cultivar should grow to a certain height with about a 10–15% variation. Allowances should be made for exceptionally good seasons and for poor seasons.



Importance

CROP GROWTH AND CROP HEIGHT AT MATURITY can be useful visual indicators of soil quality. They are also dependent on a number of other factors including climate, cultivar, nitrogen application and soil fertility, time of sowing, fungicide applications and the use of plant growth regulators to reduce straw length. Crop growth and crop height are however particularly helpful indicators of soil quality if agronomic factors have not limited crop emergence and development during the growing season. The growth and vigour of grain crops depend in part on the ability of the seedbed to maintain an adequate tilth throughout the growing season. Poor soil aeration and resistance to root penetration as a result of structural degradation reduce plant growth and vigour, and delay maturity.

PLATE 27 Crop height at maturity

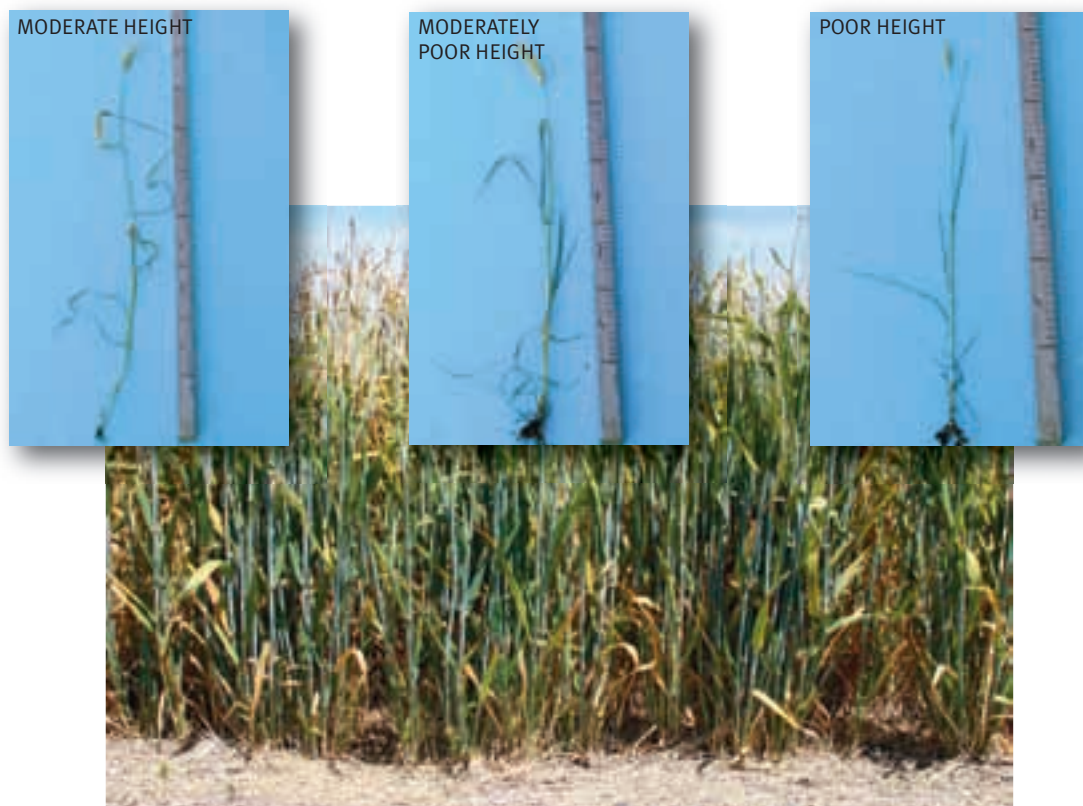


TABLE 8 Visual scores for crop growth and height at maturity

Visual score (VS)	Crop growth and crop height at maturity
2 [Good]	Crop growth is good and crops are at or near maximum height, with little variability in height at maturity. Semi-dwarf varieties commonly have a crop height at maturity of >1000 mm
1 [Moderate]	Crop growth is moderate. Crops show moderate variability in height at maturity and are significantly below maximum (700–900 mm)
0 [Poor]	Crop growth is poor and plants can appear sickly. Crop height is uneven and patchy and well below maximum at maturity (400–600 mm)



Assessment

- 1 Measure the size of the kernels just before harvesting and compare them with the photographs and criteria given (Plate 28).

While there is a strong association between kernel number and yield, kernel size and dry weight are also strong determinants of the final yield. In making the assessment, consideration must be given to the plant population, tiller density and weather conditions and in particular the rainfall and sunlight hours. High plant populations and tiller densities will reduce the size of the kernel, and dry conditions and prolonged cloudy weather will reduce photosynthesis and subsequently the formation of carbohydrates and starch.



Importance

KERNEL development starts immediately after floret fertilization with cellular division during which the endosperm cell and amyloplasts are formed. This period is known as the lag phase and lasts for about 20 to 30 percent of the grain filling period. This is followed by a phase of cell growth, differentiation and starch deposition in the endosperm which takes 50 to 70 percent of the grain filling period. Good availability of carbohydrate is essential to be maintained during the crop cycle avoiding any shortage especially during the grain filling period. Soils in good condition with good structure, porosity, organic matter levels, soil life, soil fertility and rooting depth help ensure the supply and availability of water and nutrients. The grain filling period is prolonged as a result and an increase in kernel size is achieved. Good crop management practices including the adoption of widely spaced rows and good residue cover between rows to conserve water in dry zones also help to maximise the size of the kernel.

KERNEL SIZE is a useful determinant of grain quality by measuring the weight of unscreened grain, the screening loss and the weight of 1000 grains of clean seed.

PLATE 28 How to score kernel size

**GOOD CONDITION VS = 2**

Depending on the variety, kernels are large, completely filled and well shaped with few or no moisture stress features apparent.

**MODERATE CONDITION VS = 1**

Kernels are of moderate size, may show occasional incomplete grain filling and stress features are often apparent.

**POOR CONDITION VS = 0**

Kernels are generally very small with an irregular shape and stress features are very common.



Assessment

- 1 Assess relative crop yield based on the class limits in Table 9. Assessments can be made for all varieties of crops by counting or estimating the number and size of ears (spikes) per square metre, the number of kernels (grains) per ear, and the degree of grain filling. Harvested yield monitors could also be employed. Compare these with an 'ideal' crop (Plates 29). In making the assessment, consideration must be given to the variety of wheat, the number of plants per square metre, the soil moisture, air temperature and sunshine hours during the growing season, and pests and diseases not associated with the condition of the soil.



Importance

WITH A DECLINE IN SOIL QUALITY, crops can come under stress as a result of poor soil aeration, water-logging, moisture stress (due to either soil saturation or a reduced available water-holding capacity), a lack of available nutrients (Plates 30–31), and adverse temperatures. Toxic chemicals can also build up and root growth be impeded owing to chemical reduction reactions and a high penetration resistance to root development. This results in poor germination and emergence, poor plant growth and vigour, the need for redrilling, delays in drilling, root diseases, pest attack, and consequently lower crop yields. Plant stress induced by structural degradation can further affect the quality of grain by changing the amount and type of protein and starch formed, and the enzymic potential. These affect the amount of fermentable carbohydrate, the baking quality of wheat and the malting potential of barley. Under good soil conditions with adequate water and nutrients, the ripening period is prolonged and the starch accumulation inside the kernel is delayed and more gradual. This increases yield with a higher starch and protein percentage and quality.

PLATE 29 Crop yield



Good crop yield with large ear development and complete grain filling.

PLATE 30 Effect of boron deficiency on crop yield



Small ear development on the left due to boron deficiency.

PLATE 31 Effect of copper deficiency on crop yield



White tipping and incomplete ear development due to copper deficiency.

TABLE 9 Visual scores for crop yield

Visual score (VS)	Crop yield
2 [Good]	Crops have >500 ears per square metre. The ears are large with a spike length >90% of maximum for the variety. Ears have >50 kernels (grains) per ear and show complete grain filling with few signs of stress, pests or diseases. Harvested yield is greater than 8 tonnes per hectare
1 [Moderate]	Crops have 300–400 ears per square metre. The ears are of medium size with the spike length varying from 60–80% of maximum for the variety. Ears have 30–40 kernels (grains) per ear and show moderate and occasional uneven grain filling. Stress, pest and disease evidence is moderately common. Harvested yield is 6–7 tonnes per hectare
0 [Poor]	Crops have <200 ears per square metre. The ears are generally small and vary in length. Spike length is commonly <50% of maximum for the variety. Ears have <20 kernels (grains) per ear and grain filling is poor and often uneven. Stress, pest and disease features are very common. Harvested yield is less than 5 tonnes per hectare



Assessment

- 1 Assess whether production costs have increased because of increased tillage/fertilizer requirements and herbicide/fungicide application over the years (Figure 4 and Table 10). This assessment can be based on perceptions, but reference to annual balance sheets will give a more precise answer.



Importance

Ground preparation, fertiliser, herbicide and pesticide inputs account for some of the highest costs in any cropping operation, and can increase significantly with increasing soil degradation. As degradation increases, the density and strength of the soil increases and, as a result, the soil becomes more resistant to tillage forces. Plough resistance increases so that larger tractors are required to avoid excessive wheel slip and the need to operate at lower ground speeds in a lower gear. The size, density and strength of soil clods also increase with increasing loss of soil structure, and careful timing and additional energy is needed to break them down to a seedbed. This energy is generally applied by using more intensive methods of cultivation and by making a greater number of passes. As a result, conventional tillage costs can increase by over 300 percent.

Continuous cropping using conventional cultivation techniques can also give rise to a significant loss of organic matter and, as a result, can substantially reduce soil fertility and the ability of the soil to supply nutrients. Higher amount of fertilizer are needed to compensate for the loss of these nutrients. The loss of organic carbon under continuous conventional cultivation could further incur a possible carbon tax in the future.

Reductions in crop yield are often not recognised as the result of the degradation of soil structure. Growers often assume that soil fertility is at fault and increase their production costs by applying extra amounts of fertilisers.

FIGURE 4 Assessment of production costs

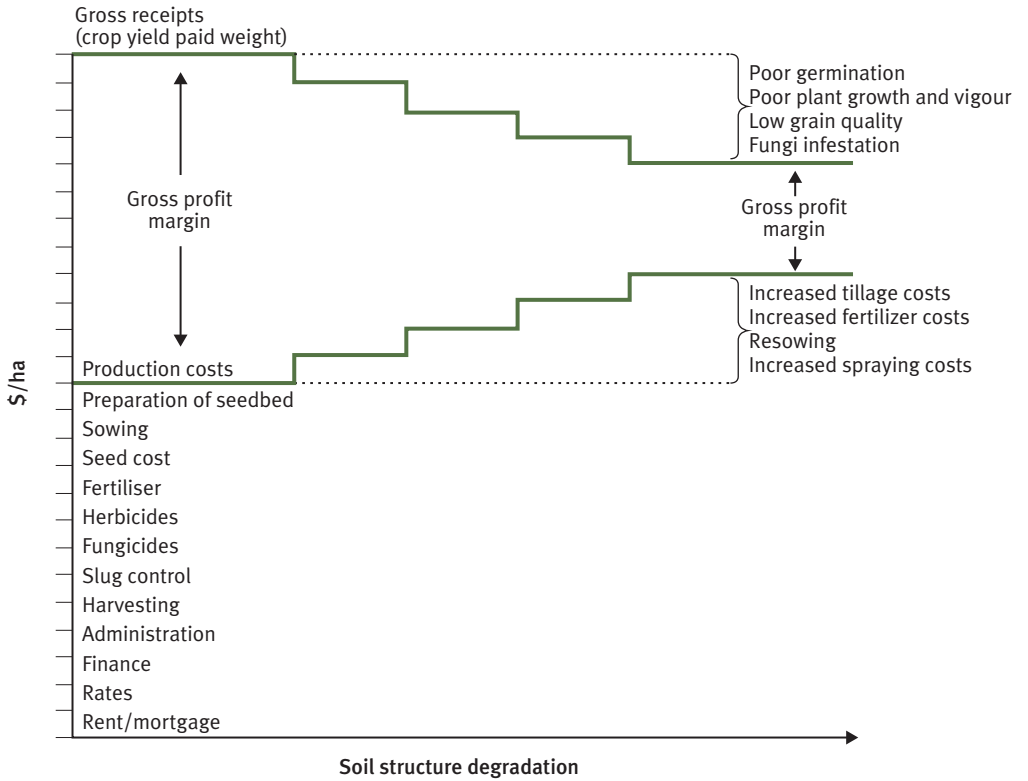


TABLE 10 Visual scores for production costs

Visual score (VS)	Production costs
2 [Good]	Production costs including ground preparation, fertiliser, herbicide & pesticide requirements have not increased
1 [Moderate]	Production costs including ground preparation, fertiliser, herbicide & pesticide requirements have increased moderately
0 [Poor]	Production costs including ground preparation, fertiliser, herbicide & pesticide requirements have increased greatly

Soil management of wheat crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, including no-tillage and minimum tillage that incorporate the establishment of temporary cover crops and crop residues on the surface (Plates 32–34), provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage also encourages soil life and biological activity (including earthworm numbers) and increases micro-organism biodiversity. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO_2) and enables the soil to operate as a sink for CO_2 . Soil organic matter levels build up as a result and create the potential to gain 'Carbon Credits'. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

On the other hand, conventional tillage can impact negatively on the environment, with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO_2), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. The fundamental difference between conventional tillage and conservation tillage is their relative environmental and economic sustainability. The long-term affects of conventional tillage are cumulatively negative whereas the long-term affects of conservation tillage are cumulatively positive.

PLATE 32 No-till drilling a wheat crop into an erosion-prone field protected by herbicided pasture [BAKER NO-TILLAGE LTD]



PLATE 33 Strip-tillage planting of an annual crop protected by good residue cover



PLATE 34 Harvesting a wheat crop followed immediately by no-till seeding the next crop into stubble [BAKER NO-TILLAGE LTD]



References

Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for wheat*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 1

Pastures



Pastures

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List of acronyms

AEC	Adenylate energy charge	MgO	Magnesium oxide
Al	Aluminium	Mn	Manganese
ASC	Anion storage capacity	Mn³⁺	Manganic
ATP	Adenosine triphosphate	Mn²⁺	Manganous
B	Boron	Mo	Molybdenum
C	Carbon	N	Nitrogen
Ca	Calcium	N₂	Nitrogen gas
Ca²⁺	Calcium cation	NO₃⁻	Nitrate
CEC	Cation exchange capacity	NO₃⁻-N	Nitrate-Nitrogen
CH₄	Methane	NO₂⁻	Nitrite
Cl	Chlorine	N₂O	Nitrous oxide
CO₂	Carbon dioxide	Na	Sodium
qCO₂	Metabolic quotient	Na⁺	Sodium cation
Co	Cobalt	NH₄⁺	Ammonium
CT	Condensed tannins	NH₃	Ammonia
Cu	Copper	O₂	Oxygen
DM	Dry matter	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂	Hydrogen gas	SO₄²⁻	Sulphate
H₂S	Hydrogen sulphide	SO₃²⁻	Sulphide
I	Iodine	Se	Selenium
K	Potassium	VS	Visual score
K⁺	Potassium cation	VSA	Visual Soil Assessment
KCl	Potassium chloride	WFP	Water-filled porosity
LHb	Leghaemoglobin	Zn	Zinc
Mg	Magnesium	ZnS	Zinc sulphide
Mg²⁺	Magnesium cation		
MgCl₂	Magnesium chloride		

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of pastoral land. A decline in soil quality has a marked impact on canopy cover, tiller density, pasture growth, pasture quality, food quality, animal health, production costs, nutrient loss into the groundwater and waterways, carbon sequestration and green-house gas emissions. It can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Soil physical properties control the movement of water and air into and through the soil, the ease with which roots penetrate the soil, the number, type and activity of soil organisms, and the availability and uptake of soil nutrients. Damage to the soil can change these properties and reduce plant growth, food quality and environmental outcomes, regardless of nutrient status. Safeguarding soil resources for future generations and minimizing the ecological footprint of pastoral agriculture is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil/pasture and food quality;
- ❖ the effect of land management decisions on soil quality, plant performance, and environmental outcomes.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance and quality of pastures and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for pasture grazing, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for pastoral agriculture. Scoring is out of 50: the higher the score, the better the condition of the soil and the performance of the plant. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

In addition, the VSA provides a quick, low cost method for estimating the potential for nutrient loss into the groundwater and waterways, C sequestration, and the emission of green house gases.

The VSA method

While the name Visual Soil Assessment implies a focus on the soil, the method is equally about assessing both the soil and the plant. Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a score card. Soil

quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the pasture. This knowledge will facilitate the satisfactory and rapid completion of the plant score card. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. they are capable of changing under different management regimes and land use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the 'soil' and 'plant' scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate, or poor condition.

Placing the soil and plant scores side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** (flat-faced) – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 x 350 x 250 mm) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260 x 260 x 20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750 x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;

PLATE 1 The VSA tool kit



- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A MAGNIFYING HAND LENS** – to assess the clover nodules;
- ❖ **A TAPE MEASURE** – to measure the sample depth, topsoil depth, and potential rooting depth;
- ❖ **A BRUX REFRACTOMETER AND GARLIC CRUSHER** – to measure the sugar content of pasture. Although the VSA method is designed to be instrument free, the refractometer is highly recommended;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the visual score (VS) for each indicator.

The procedure

When should it be carried out?

The test should be carried out when the soils are moist and suitable for grazing. If you are not sure, apply the ‘worm test’ (p. 70). For **silty soils**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to test. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to test.

Setting up

Time

Allow 40 minutes per site. For a representative assessment of soil quality, sample four sites over a 5 hectare area.

Reference sample

Take a small sample of soil (about 100 x 50 x 150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. Avoid areas that may have had heavier wheel and stock traffic than the rest of the field, e.g., around ‘camp’ sites, water troughs and gateways, etc. Also avoid atypical small areas within the field, such as small hollows or mounds, areas adjacent to groves or lines of trees, filled in pits, etc. VSA can also be used to assess the compactive and pugging effects of these high traffic areas on soil quality. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the score card. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicators score card.

Carrying out the test

Initial observation

Dig a small hole about 200 x 200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If, for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two 200 x 200 x 100 mm samples with a spade. If the 100–200 mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two 200 x 200 x 100 mm samples. Note that taking a 200-mm cube immediately below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and pasture/crop management.

The drop shatter test

Drop the test sample a maximum of three times onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, depends on the texture of the soil, and the degree to which the soil breaks up, as described on pp. 2 and 3.

Systematically work through the score card, assigning a visual score (VS) to each indicator by comparing it to the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS ranking in the right-hand column of the scorecard.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

“Despite mankind’s lofty aspirations and many notable achievements, our survival depends on a six-inch layer of topsoil and the fact that it rains”

anonymous

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality under pasture

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Topsoil depth:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____ **Date:** _____

Textual group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Moisture condition: Dry Slightly moist Moist Very moist Wet

Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Number and colour of soil mottles pg. 8		x 2	
Soil colour pg. 10		x 2	
Earthworms (Number =) (Av. size =) pg. 14		x 3	
Soil smell pg. 18		x 2	
Potential rooting depth (m) pg. 22		x 3	
Surface ponding pg. 26		x 3	
Surface relief pg. 30		x 1	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 20
Moderate	20–35
Good	> 35

Assessment

- ❶ Take a sample of soil half the size of your thumb from the topsoil to assess the *soil texture*. Take also a sample/s that is/are representative of the subsoil to assess the overall *textural group* of the soil profile.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball and then squeezing it between the thumb and forefinger. With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the *textural class* obtained by reference to the textural diagram (Figure 2a). The *textural group* is obtained by comparing the position of the textural class in Figure 2a with Figure 2b (e.g., silt loam = fine silty).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For instance, if the soil has a reasonably high content of organic matter, i.e. is humic with 17–29 percent organic matter, raise the textural score by one (e.g., from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size ≥ 0.06 mm; silt varies between 0.06 and 0.002 mm, while the particle size of clay is < 0.002 mm.

Texture influences soil behaviour in several ways, notably through its effect on water retention and availability, soil structure, aeration, drainage, soil trafficability and workability, soil life, and the supply and retention of nutrients. Knowledge of both the textural class and potential rooting depth (see p. 22) enables an approximate assessment of the total water holding capacity of the soil, one of the major drivers of pasture production.

FIGURE 2 Soil texture classes and groups

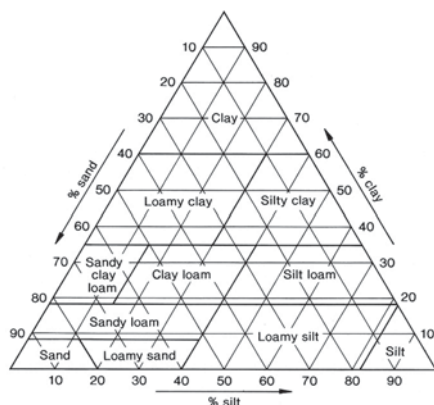


Figure 2a
Textural classes.

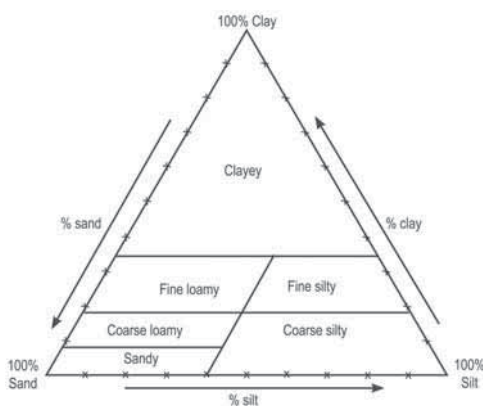


Figure 2b
Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
1 [Moderate]	Loamy silt	Smooth feel, non sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
0.5 [Moderately poor]	Silty clay & Clay	Very smooth, very sticky, very plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
0 [Poor]	Loamy sand	Gritty and rasping sound. Will almost mould into a ball but disintegrates when squeezed between thumb and forefinger
	Sand	Gritty and rasping sound. Cannot be moulded into a ball

Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade. When taking the sample, ensure the blade of the spade is inserted vertically to obtain the true volume of soil required for assessment.
- ❷ Drop the soil sample a maximum of three times from a height of one metre onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Don't drop any piece of soil more than three times. For soils with a sandy loam texture (p. 2), drop the cube of soil once only from a height of 0.5 metres. If the sandy loam is humic (17–29 percent organic matter), drop the soil twice from 1 metre. Transfer the soil onto the large plastic bag.
- ❸ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade once from a height of just 50 mm and then roll the spade over, spilling the soil onto the plastic bag.
- ❹ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures if present. If the clod cannot be easily parted, do not apply further pressure because the cracks and fissures are probably not continuous and therefore unable to readily conduct oxygen, air and water.
- ❺ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs and criteria given in Plate 2. The method is valid over a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.

Importance

SOIL STRUCTURE is important for pastures. It regulates soil aeration and gaseous exchange rates, soil infiltration and erosion, the movement and storage of water, soil temperature, root penetration and development, nutrient supply, and the resistance to structural degradation by compaction and deformation under wheel traffic and stock treading. Good soil structure improves the trafficability of the soil, increasing the window of opportunity for stock grazing and vehicle access without causing compaction. The loss of soil structure can alter seasonal growth patterns and change the botanical composition of pasture including an increase in the number of weeds. Structural degradation can reduce tiller density and canopy cover by 50 percent, pasture production by 30–50 percent in spring, and is often a catalyst for diseases. It also reduces the infiltration of water into and through the soil increasing the potential for erosion by sheet wash on sloping ground.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, sub-angular and sub-rounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or sub-angular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 Visual scoring (VS) of soil structure



GOOD CONDITION VS = 2
 Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally sub-rounded (nutty) and often quite porous.



MODERATE CONDITION VS = 1
 Soil contains significant proportions (50 percent) of both coarse clods and friable fine aggregates. The coarse clods are firm, sub-angular or angular in shape and have few or no pores.



POOR CONDITION VS = 0
 Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or sub-angular in shape and have very few or no pores.

 **Assessment**

- ❶ Remove a spade slice of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and break in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs and criteria given in Plate 3. Look for the spaces, gaps, holes, cracks, fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides additional information as to the porosity of the individual clods (the intra-aggregate porosity).

 **Importance**

SOIL POROSITY is important to assess along with soil structure. Soil porosity, and particularly macro porosity (or large pores), influence the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores or coarse micropores within the large clods, thus restricting their drainage and aeration.

Poor aeration leads to the build up of methane, sulphide gases and alcohol, and reduces the ability of plants to take up water and nutrients, particularly nitrogen, phosphorus, potassium, sulphur, zinc, copper and cobalt. Poorly aerated and compacted soils reduce plant-available nitrate-nitrogen (NO_3^- -N) and ammonium (NH_4^+) to nitrite (NO_2^-), nitrogen (N_2) gas and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available sulphate-sulphur (SO_4^{2-} -S) is also reduced to sulphite (SO_3^{2-}) and sulphides, rendering N and S unavailable to the plant. Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can also only utilize N if S is present in the oxygenated sulphate form. Moreover, the number, activity and biodiversity of micro-organisms and earthworms are greatest in well-aerated soils and are able to decompose and cycle organic matter and nutrients more efficiently than in poorly aerated soils.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilise the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, but greatly reduces fertiliser efficiency and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce less greenhouse gases. The greater the porosity the better the drainage and therefore the soil pores will be less likely to be water-filled to the critical levels required to generate the production of methane and nitrous oxide greenhouse gases (see pp. 92–93). Aim to keep the porosity score above 1.

PLATE 3 Visual scoring (VS) of soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present in parts of the soil on close examination. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.

Assessment

- Assess the number, size and colour of soil mottles by taking a sample of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and comparing it with the three photographs and criteria given in Plate 4. The percentage chart below will help you determine the percentage of the soil occupied by mottles.

Mottles are patches of different colour interspersed within the dominant (background) soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also early warnings of a decline in soil structure as a result of treading damage and compaction under wheel traffic. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces iron (Fe) and manganese (Mn) from their *brown/orange* oxidised ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey due to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey mottles predominate. The abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicate the soil is moderately well drained, and no mottles indicate good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S, Zn, Cu and Co (p. 6). Depending on soil type and soil condition, Olsen P levels of 22–35 mg/L are generally required for optimum pasture production. However, P levels need to be raised (sometimes to 40–50 mg/L) in compacted, poorly aerated soils to produce a positive dry matter production response. In addition, sulphur and nitrogen are reduced to plant-unavailable forms as described on the previous page. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, alcohol

(ethanol and ethylene), acetaldehyde and formaldehyde, which are toxic to plant roots. Root damage and reduced nutrient and water uptake give rise to poor pasture vigour. If your visual score for the number and colour of soil mottles is one or less, you need to aerate the soil.

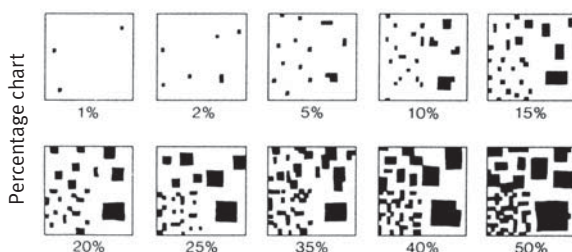


PLATE 4 Visual scoring (VS) of the number and colour of soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has many (10–20 percent) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has profuse (> 50 percent) medium and coarse orange and particularly grey mottles.

Assessment

- 1 Compare the moist colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area (Plate 5). If the soil is dry, pour water over the surface of the sample.
- 2 Using the three photographs and criteria given in Plate 6, compare the *relative change* in soil colour that has occurred. As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.

Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not so easily and accurately assessed; in general, the darker the colour, the greater the amount of organic matter and humus in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, collectively determining soil health. It promotes infiltration, the movement and retention of water, helps develop and stabilise soil structure, cushions the impact of wheel traffic and stock treading, reduces the potential for wind and water erosion, plays a key role in maintaining the cation exchange and buffering capacity of the soil, and indicates whether the soil is

PLATE 5 Soil colour under the fenceline



Soil colour under the fenceline on the left compared with that in the field on the right. The comparative difference in soil structure and porosity is also a useful observation to make.

PLATE 6 Visual scoring (VS) of soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is similar to, or darker than that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with under the fenceline.

functioning as a carbon 'sink' or as a source of green-house gases. Organic matter acts as a major reservoir of organic carbon in the soil, carbon that is sequestered by microorganisms and from CO₂ in the atmosphere by plants. Organic matter also provides an important food resource for soil organisms and is an important source and major reservoir of plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; nitrogen, phosphorus, potassium and sulphur requirements of pastures increase markedly, and other major and minor elements are more readily leached. The result is an increased dependency on fertiliser input to maintain nutrient status.

Dark-coloured soils due to high amounts of organic matter and humus provide a major source of nitrogen and phosphorus. A soil with 1 percent organic carbon in the top 0–100 mm contains about 1200 kg of organically bound N per ha. Over the course of a year, 1–5 percent of the organic N is mineralised by soil microorganisms to plant-available inorganic N in the form of ammonium (NH₄⁺) and nitrate-nitrogen (NO₃⁻-N). A soil with 1200 kg N/ha can therefore potentially provide around 60 kg of plant available N/ha/yr. If we assume soils have an average organic C content of 5 percent, the activity of soil microbes can potentially supply 300 kg N/ha/yr. Ensuring a good, healthy, biologically active soil with average soil C levels can therefore provide the N requirements of a high-producing dairy farm. This is borne out by the fact that dairy farms with good soil life are commonly producing in excess of 17 tonne dry matter/ha/yr with no mineral N applied. Many soils have well in excess of 5 percent organic C in the top 0–100 mm and therefore hold greater amounts of organically bound N that could potentially become plant available. The key is to ensure that management practices, including the type and amount of fertilisers used, encourage rather than suppress the biological life of the soil and therefore the amount of available N present.

Soil colour (compared with that under the fenceline) can be a useful indicator of whether soils on a farm or in a field are becoming darker due to gaining (sequestering) carbon. If the soil is paler, it could possibly be losing carbon, i.e. becoming C negative. If there is no colour difference, the soil carbon regime may be in a steady (C neutral) state, i.e. neither losing nor gaining carbon. Soil colour, along with soil texture, clay mineralogy, earthworm numbers, root length and density, potential rooting depth, pasture growth (dry matter production), pasture colour and growth compared with urine patches, and the amount and form of fertiliser and N applied (see following pages) can collectively provide a clear indication whether a particular management practice or land use is carbon positive, neutral or negative. A farm that has similar or darker coloured topsoils in the field relative to the fenceline, with fine silty or clayey textures, good earthworm numbers, root length and density, potential rooting depth, pasture growth (dry matter production), pasture colour and growth relative to urine patches, and is applying carbon-friendly forms of fertiliser and N will sequester significant amounts of carbon (see carbon sequestration, pp. 80–89). The farm will therefore be C positive and in a position to potentially gain 'carbon credits' rather than possibly pay a carbon tax.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is markedly influenced by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Very dark brown, brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidised form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that along with low pH, reduce the form of Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Ferrous and manganous oxides are more soluble than their oxidised forms and are therefore more readily taken up by the plant. High levels of Fe and Mn in the soil and pasture suppress the availability of cobalt (Co), which in turn reduces the appetite of ruminant stock – as a consequence, stock lose condition.

In addition to the production of toxic levels of Fe^{2+} and Mn^{2+} ions, poor aeration and waterlogging gives rise to a further series of chemical and biochemical reduction reactions that produce toxins such as hydrogen sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde that damage the root system. This reduces the ability of plants to take up water and nutrients (particularly N, P, K, S, Zn, Cu and Co), causing poor pasture growth and vigour. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, pastures typically have low energy levels and are not as palatable because they are unable to take up nutrients such as Na that are necessary to make sugars.

What is more, soil colour can indicate the potential of a soil to convert plant-available forms of nutrients into unavailable forms. Soils that are distinctly grey in colour due to being anaerobic and waterlogged reduce plant-available N in the form of nitrate (NO_3^-) and ammonium (NH_4^+) to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available S in the form of sulphate-sulphur (SO_4^{2-} -S) is reduced to unavailable sulphides. Sulphur and nitrogen can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Plants also need S in the sulphate form to utilise N.

Dark coloured soils further suggest that the microbial biomass is predominantly aerobic, enabling the efficient decomposition of organic matter to humus and the retention, immobilisation and release of soil nutrients.

Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 2, p. 5 & Plate 7). Note also the number of species present (Plates 8–10) and compare with the criteria given in Table 2. Earthworms vary in size and number depending on the species, maturity, and the season. For year-to-year comparisons, therefore, earthworm counts must be made at the same time of year (preferably late winter to early spring), and when soil moisture and temperature levels are good; avoid dry conditions. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. As a 200-mm cube sample is equivalent to 1/25 square metre, the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.

Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digesting, and casting, earthworms have a major effect on the chemical, physical, and biological properties of the soil: they shred and decompose plant residue converting it to humus and releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg, characteristics that are due in part to the higher enzyme activity in

the casts (see p. 20). They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter, and water content. In addition, dead earthworms can contribute significant amounts of N to the soil, being 60–70 percent protein (dry weight) with a N content of 12 percent. Forty-five earthworms per 200-mm cube of soil ($1\ 125/m^3$) are roughly equivalent to a biomass of 4 tonnes of earthworm/ha, and could release 43–50 kg N/ha upon their death. The presence of earthworms also increases the mobilization of nitrate-N by 10 times and that of ammonium-N by 80 times, compared with soils without earthworms.

PLATE 7 Sample for assessing earthworms



Sample for assessing earthworms. Photo shows earthworms present in a 200-mm cube sample of soil.

PLATE 8 *Lumbricus rubellus*

A very active surface litter and dung feeding earthworm; commonly red-brown or red-purple in colour with a paler underside; has a distinctly flattened tail; commonly 25–220 mm long.

PLATE 9 *Aporectodea caliginosa*

A medium-sized (40–90 mm) topsoil dwelling earthworm; commonly grey-pink on both the dorsal and ventral surfaces; does not have a flattened tail.

PLATE 10 *Aporectodea longa*

A long (90–180 mm) deep burrowing earthworm; commonly dark grey-brown with a black head; tail end is paler and slightly flattened. Underside is paler than the dorsal surface.

TABLE 2 Visual scores (VS) for earthworms

Visual score (VS)	Earthworm numbers (per 200 mm cube of soil)
2 [Good]	≥ 45 (with preferably 3 or more species)
1.5 [Moderately good]	35–44
1 [Moderate]	25–34 (with preferably 2 or more species)
0.5 [Moderately poor]	15–24
0 [Poor]	< 15 (with predominantly 1 species)

Earthworms also act as biological aerators and physical conditioners of the soil, improving soil porosity, aeration, soil structure, soil aggregate stability, water retention, water infiltration, and drainage, and reducing surface runoff and erosion. They promote pasture growth by secreting plant-growth hormones and increasing root density and root development through the rapid growth of roots down nutrient-enriched worm channels. They also contribute to nitrogen fixation by promoting nitrogen-fixing microorganisms, nitrogen-fixing nitrogenase enzymes and the availability of Mo. While earthworms can deposit around 25–30 tonnes of casts/ha/yr on the surface (Plate 11), 70 percent of their casts are deposited below the surface of the soil. Earthworms can therefore have a major effect on the overall properties and condition of the soil.

Earthworms also increase the population, activity, and diversity of soil microbes. The number of beneficial bacteria can increase three-fold from 3 million per gram in soils with no worms to 10 million per gram after colonization by worms. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus and the supply of nutrients. Earthworms therefore play an important role in pastoral agriculture and can increase pasture production by 10–30 percent.

Earthworms can increase the depth of topsoil and the carbon content of both topsoil and subsoil by their burrowing, digesting, reworking, and mixing of soil and plant residues (bioturbation), and by the deposition of worm casts. High numbers of earthworms ingest considerable amounts of soil and plant material, building up soil C levels by converting C to more stable organic compounds bonded to clay particles. Organic matter gradually works down to the subsoil and so increases the depth of topsoil. The burrowing, casting,

and incorporation of organic matter into the soil contributes to increasing topsoil depth by decreasing soil density and increasing the porosity, and therefore the volume of soil. Given that 30 percent of worm casts are deposited on the surface and 70 percent below ground, the potential for earthworms to increase soil carbon levels and topsoil depth is substantial. Deposition rates of soil at the surface due mainly to earthworm casts can vary from 2–20 mm/yr.

PLATE 11 Surface of field 'boiling' with worm casts



Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by pasture production and the stocking rate. Their numbers are also governed by soil moisture, temperature, texture, soil aeration, pugging, legume content, pH, soil nutrients (including Ca), and the type and amount of fertiliser and nitrogen used. The over-use of acidifying salt-based fertilisers and ammonia-based products can reduce earthworm numbers.

PLATE 12 Yellow-tail earthworm (*Octolasion cyaneum*)



Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep burrowing species that pull down and mix plant litter and organic matter at depth.

Earthworm species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 12) can indicate adverse soil conditions.

Assessment

- 1 Remove a spade slice of soil (approximately 100 mm wide × 100 mm long × 100 mm deep) and break in half. Place the exposed face of the soil close to your nose, take three deep sniffs, and compare with the criteria given in Table 3. Before sniffing the soil, place a tissue (or mask) over your nose to prevent the inhalation of any harmful microbes. The test is best carried out when the soil is moist, including during or immediately after the wet months of the year.

Importance

SOIL SMELL, while very dependent on the water content and aeration status of the soil, is also a good indicator of the amount and the activity of soil life and therefore soil health. Soil smell is determined principally by the gases given off by the aerobic or anaerobic respiration of soil microbes, and by the type and amount of organic matter and humus present in the soil. Aerobic respiration by soil fungi, bacteria, yeast, protozoa (i.e. single cell animals), nematodes, arthropods (mites, beetles, millipedes, etc.), and earthworms produce distinctive odours. The degree and nature of the odours are determined by the composition and activity of the soil biology which in turn is governed in part by the available food supply in the form of organic matter and humus. Soils rich in fungi, for example, produce aromatic compounds and organic acids that give an earthy, rich, sweet, fresh or sometimes musty smell. These are often the characteristic smells of forest soils, which are generally rich in fungi. The presence of similar fungal smells in a pastoral soil suggests it is not only well aerated but also has a good, active microbial biomass (Plate 14). This is because it must have large numbers of bacteria to maintain a fungal to bacteria ratio of 0.75:1 (or 1:1) that is necessary to preserve and promote pastoral plants. An imbalance of this ratio along with poor soil nutrition could explain why pastures may show poor persistence and a tendency to revert to other plant species such as woody weeds. Pastoral soils that are intensively grazed and fertilised tend to have a greater abundance of bacteria relative to fungi than soils that are less intensively grazed and fertilised. As a consequence, they are more

TABLE 3 How to assess soil smell

Visual score (VS)	Soil smell
2 [Good]	Soil has a distinct rich, earthy, sweet, wholesome or fresh smell.
1 [Moderate]	Soil has a slight earthy, sweet odour or a mineral smell.
0 [Poor]	Soil has a putrid, sour, chemical or unpleasant smell.

sensitive to stress such as droughts, are less efficient in terms of uptake, cycling and retention of nutrients including N, and are more susceptible to N leaching.

Biological regimes are sensitive to intensive land uses with the result that soils can have little or no soil smell. Anaerobic respiration of microorganisms (including anaerobic bacteria and yeast) in saturated, poorly aerated soils produce methane and nitrous oxide (greenhouse gases), alcohol (ethanol and ethylene), acetaldehyde formaldehyde, and putrid sulphide gases including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS), all of which inhibit root growth when accumulated in the soil (Plate 15). Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

While soils should have good microbial biomass with levels preferably in excess of 1800 mg/kg, and a good microbial quotient (i.e. the ratio of microbial biomass C to total organic C), to be beneficial, soil microbes also need to be active. The level of activity and therefore functionality of the microbial biomass is something that must always be kept in mind when assessing the status of the soil biological community. The activity and energy status of soil microbes can be assessed by measuring their respiration, the level of their respiration relative to their biomass (i.e. the respiration to biomass ratio or the metabolic quotient qCO_2), and their AEC, which should be ≥ 0.8 . Microbial viability is maintained at AEC values between 0.8 and 0.5 – the cells die at values below 0.5.

Soil microbes, including actinomycetes and mycorrhizal fungi, play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important stable organic compound that comprises up to 30 percent or more of the humus fraction in pastoral soils. Soil organisms also play a key role in the promotion and maintenance of soil fertility through nutrient and carbon cycling, and their role in the N and S cycle. Microbes immobilise and retain significant amounts of nutrients in the humus they produce and in their biomass, releasing them when they die. Moreover,

PLATE 13 Sample to assess soil smell



soil microbes, including mycorrhizal fungi, play a major role in the supply of plant-available nutrients, digesting soil and fertiliser, and unlocking nutrients such as phosphorus that are fixed by the soil. Mycorrhizal fungi and bacteria provide a fundamentally important ‘microbial bridge’ that allows the bidirectional flow of liquid C (sugars) from the plant to the soil, and nutrients and plant growth hormones from the soil to the plant. High organic matter and microbial activity further result in a high level of activity of soil enzymes such as urease, protease, phosphatase and sulfatase, which result in a high turnover of N, P and S through the soil organic pool.

In addition, soil microbes and particularly bacteria play a major role in the fixation and supply of nitrogen. *Rhizobium* bacteria in clover nodules fix N directly from the atmosphere. The ammonia produced by N-fixation is taken up by the plant to produce protein and organic N compounds that are then mineralised by a further range of bacteria and fungi, releasing N in the form of plant available ammonium (NH_4^+) when the plant dies. Under aerobic conditions, the ammonium is converted by nitrosomonas and nitrobacter bacteria to nitrate (NO_3^-), another plant available form of N (a process known as nitrification). Free-living aerobic *Azotobacter* bacteria and anaerobic (*Clostridium*) bacteria in the soil further promote the fixation and supply of plant-available N.

Nitrogen fixing bacteria, be they free-living in the rhizosphere, confined to nodules on plant roots, or existing as endophytes in leaves or stems, derive most of their energy from dissolved organic carbon (liquid sugar) produced by photosynthesis. N-fixation is therefore very dependent on the flow of liquid carbon from the leaf to the roots. If plants are mycorrhizal, i.e. have high populations of mycorrhizal fungi and bacteria attached to the roots that form a microbial bridge between the plant and the soil, they don’t require N in a mineralised form such as nitrate or ammonium. In order to transport mineralised N, mycorrhizal fungi have to convert it to glutamate, which represents an energy cost. For this reason, N is preferentially transported in an organic form, generally as amino acids such as glycine and glutamine.

PLATE 14 Soil with a moderately good smell



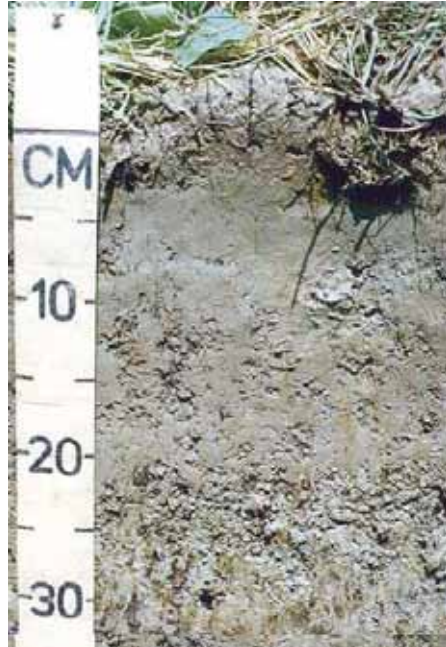
Soil has a moderately rich, earthy, sweet smell with a smell score of 1.5.

Moreover, bacterial- and fungal-feeding protozoa and nematodes release large amounts of N when feeding on their selected prey and are responsible for much of the plant-available N in the majority of soils. The predator-prey interaction of protozoa on bacteria releases 5 units of plant-available N in the form of ammonium for every six bacteria consumed. The feeding of nematodes on bacteria releases 19 units of N for every 20 bacteria consumed. Given that bacterial numbers should be greater than one million per gram for all agricultural soils, and nearer 100 million per gram for productive soils, the potential storage and release of N from bacteria is considerable. Between 40 and 80 percent of the N in plants can come from the predator-prey interaction of protozoa with bacteria.

In addition to adding organic matter to the soil, soil organisms play a key role in soil formation by developing and promoting the structure, aggregate stability, porosity, aeration, infiltration and water-holding capacity of the soil, and reduce waterlogging and runoff from the topsoil. Soil microbes also play an important role in purifying water and filter, buffer, degrade, immobilise, and detoxify organic and inorganic pollutants. Moreover, they suppress pests and diseases, producing compounds that inhibit the growth of, or are toxic to pathogens, reducing the invasion of the plant by a pathogen. *Beauveria* fungi, for example, destroy the adult clover root weevil, providing an effective biological control. Soil microbes also produce plant growth hormones and compounds that stimulate root growth and produce B group vitamins, including vitamin B12 which is important for rumen function.

The collective benefits of microbes can reduce fertiliser requirements and more than double the growth of ryegrass and clover. They can also significantly improve the sugar content, nutrient density, and health of the plant. Soil life can therefore be effectively described as the 'engine room' of the soil, with mycorrhizal fungi being the powerhouse. The trick to smart and sustainable farming is to ensure the engine remains well oiled.

PLATE 15 Soil with a poor smell



Soil has a putrid, unpleasant smell of hydrogen sulphide with a smell score of 0.

Assessment

- 1 Assess the potential rooting depth by digging a hole to identify the depth to a limiting (restricting) layer if present, and compare with the class limits given in Table 4. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks, and fissures down which roots can extend. Note also whether there is an overthickening of roots (a result of a high penetration resistance), and whether the roots are forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed due to prolonged waterlogging, and whether there is a hard pan present such as a strongly developed human-induced tillage or plough pan (p. 24), or a strongly developed natural pan such as an iron, silica or calcitic pan. An abrupt transition from a fine textured material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.

Importance

POTENTIAL ROOTING DEPTH is the depth of soil plant roots can potentially exploit before reaching a barrier to root growth, and indicates the ability of the soil to provide a suitable rooting medium for plants. The greater the rooting depth, the greater the available water-holding capacity of the soil, the greater the availability of soil nutrients, and the greater the resulting dry matter production. Fertilisers applied to pastures with deep rooting systems are more effectively utilised by the plant, resulting in less leaching of nutrients into the groundwater and waterways. During drought periods deep roots can access larger water reserves alleviating water stress and promoting the recovery and survival of the pasture. Conversely, soils with a restricted rooting depth due, for example, to a layer with a high penetration resistance (such as a compacted layer or a hardpan) limit uptake of water and nutrients, reduce fertiliser efficiency, increase leaching of nutrients, and limit pasture growth. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hard pans impede the movement of air, oxygen and water through the soil profile, the latter increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ❖ an abrupt textural change;
- ❖ low pH;
- ❖ aluminium (Al) toxicity;
- ❖ nutrient deficiencies;
- ❖ salinity;
- ❖ sodicity;
- ❖ a high or fluctuating water table;
- ❖ low oxygen levels.

Anaerobic (anoxic) conditions due to deoxygenation and prolonged water-logging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions.

Pastures with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth, thereby contributing to the sequestration of C in the soil. The physical action of the roots and soil fauna and the glues they produce, promotes soil structure, porosity, water storage, aeration and drainage at depth. The presence of nitrogen-fixing clover root nodules at depth also encourages the further development of the root system by supplying nitrogen. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Pastures are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up, so reducing losses by leaching into the environment.

PLATE 16 Potential rooting depth



Photo: Courtesy of Aaron Topp

Hole dug to assess the potential rooting depth.
Photo showing good potential rooting depth with abundant fine roots extending beyond the bottom of the photo at 810 mm depth.

TABLE 4 Visual scoring (VS) of potential rooting depth

VSA score (VS)	Potential rooting depth (mm)
2.0 [Good]	800
1.5 [Moderately good]	600–800
1.0 [Moderate]	400–600
0.5 [Moderately poor]	200–400
0 [Poor]	< 200

Identifying the presence of a hardpan

Assessment

- 1 Examine for the presence of a strongly developed hard pan by rapidly jabbing the side of the soil profile (dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically to the bottom of the hole (Plate 17). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (see photos below).
- 2 Having identified the possible presence of a hard pan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hard pan is. A strongly developed hard pan is very tight and extremely firm and has a high penetration resistance to the knife. Confirm also its presence or absence by removing a large, hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (by referring back to pp. 4, 6 and 8). In addition, look for the presence or absence of roots. Compare with the photos and criteria given in Plate 18. Only a strongly developed hardpan will restrict all root development and its presence will determine the potential rooting depth.

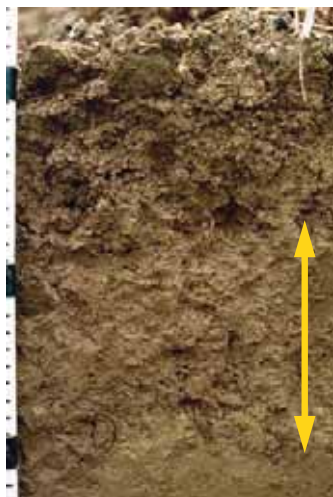
PLATE 17 Identifying the presence or absence of a hardpan with a knife



PLATE 18 Visual assessment of a hard pan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding based on your observation or general recollection of the time ponded water took to disappear after a wet period during the autumn, spring and summer, and compare with the three photographs and criteria given in Plate 19.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the infiltration rate into and through the soil, a high water table, and the time the soil remains saturated. Roots need oxygen for respiration, and prolonged waterlogging depletes oxygen in the soil, causing anaerobic (anoxic) conditions that induce root stress and restrict root respiration and growth. Roots are most vulnerable to surface ponding and saturated soil conditions in the spring when respiration and transpiration rates rise markedly, oxygen demands are high, and plant roots and shoots are actively growing. Such waterlogging causes the death of the fine roots responsible for nutrient and water uptake. Roots are also susceptible to ponding in the summer when transpiration rates are highest – reduced water uptake while the pasture is actively transpiring causes leaf desiccation and the wilting of plants.

Waterlogging causes pasture growth to decline due to poor shoot growth, fewer tillers, poor plant vigour, and chlorosis. In addition, pasture utilisation is reduced as a result of poor palatability, which is a function of:

- ❖ a change in pasture composition;
- ❖ deficiency in nutrients and sugars/carbohydrates;
- ❖ pasture becoming unpalatable and inaccessible by being soiled and trampled into the mud.

Prolonged waterlogging can change the composition of the pasture by stressing the less water-tolerant species and encouraging the development of undesirable water-tolerant species such as pennyroyal, duckweed, buttercup, etc. Prolonged waterlogging also increases root rot and soil-borne pathogens and limits the ability of roots to overcome the harmful effects of pathogens resident in the topsoil.

PLATE 19 Visual scoring (VS) of surface ponding



GOOD CONDITION VS = 2

No surface ponding of water evident after 1 day¹ following heavy rainfall on soils that were at or near saturation.



MODERATE CONDITION VS = 1

Moderate surface ponding occurs for 3–5 days¹ after heavy rainfall on soils that were at or near saturation.



POOR CONDITION VS = 0

Significant surface ponding occurs for longer than 7¹ days after heavy rainfall on soils that were at or close to saturation.

¹ Assuming little or no air is trapped in the soil at the time of ponding.

Waterlogging and deoxygenation result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are either toxic to roots or are in a form that is unable to be taken up by the plant, e.g.:

- ✦ iron is reduced to soluble ferrous (Fe^{2+}) ions and Mn to manganous (Mn^{2+}) ions;
- ✦ plant-available nitrate-nitrogen (NO_3^- -N) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas;
- ✦ plant-available sulphate-sulphur (SO_4^{2-} -S) is reduced to unavailable sulphite (SO_3^{2-}) and sulphides, including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS).

Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form.

In addition to N and S, waterlogging and poor aeration reduces the availability and uptake of P, K, Zn, Cu, and Co. This is partly because prolonged ponding of water kills off mycorrhizal fungi, soil organisms that facilitate the efficient uptake and utilisation of soil nutrients, and P in particular. While Olsen P levels of 22 mg/L are generally adequate for optimum pasture production on most soils in good condition, poorly aerated and waterlogged soils with relatively high Olsen P levels (40–50 mg/L) can show a positive pasture response to applied P. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, pastures typically have low energy levels and are not as palatable because they are unable to take up nutrients such as Na that are necessary to make sugars.

Anaerobic respiration of micro-organisms in waterlogged and poorly aerated soils produces methane (greenhouse gases), hydrogen gas, alcohol (ethanol and ethylene), acetaldehyde, and formaldehyde, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The by-products of anaerobic respiration and the lack of oxygen in poorly aerated and waterlogged soils also prevent the decay of organic material in the soil. As the soil becomes progressively degraded, the amount of CO_2 increases relative to O_2 and reaches a point where plant residues cannot decay; instead they begin to ferment, producing alcohol, formaldehydes and methane, which make proper decay and the turnover of organic matter impossible.

Prolonged surface ponding increases the susceptibility of soils to damage by wheel traffic and stock treading, reducing vehicle access, trafficability, and grazability by stock. Waterlogged topsoils on sloping ground are also prone to erosion by sheetwash and sloughing, the latter process caused by the physical shunting of soil downslope brought about through the treading effect of stock. Soils susceptible to surface ponding therefore need to be carefully managed to minimise the effects of such ponding on soil, pasture growth, utilisation and quality, and the environment.

The tolerance of the root system to surface ponding and waterlogging depends on a number of factors, including the pasture species and the time of year. Tolerance of waterlogging also depends on soil and air temperatures, soil type and condition, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and the oxygen consumption rate of plant roots.



Assessment

- 1 Observe the surface relief (smoothness) of the paddock at the end of the winter and compare it with the three photographs and criteria given in Plate 20.

Although soils are most susceptible to treading damage (pugging) during wet winter months, observations of surface relief at any time of the year will give useful information on damage caused by past grazing and its likely effects on soil quality.



Importance

SURFACE RELIEF shows the severity of pugging under stock treading, and can indicate structural damage below the surface. Wet soils can pug severely under intensive grazing by heavy weight animals when the load-bearing capacity of the soil is insufficient to support the weight of the animal. This damages the soil structure and reduces the pores in the soil, which are important for water, nutrient and air movement, and root penetration. Infiltration rates and the movement of water through the soil decreases, increasing runoff, soil erosion, and the risk of flash flooding. Very broken and deeply incised soil as a result of severe pugging can also damage the pasture root system and increase the area of bare ground. It can further induce surface ponding and anaerobic conditions, reducing pasture utilisation and impairing pasture growth as a result of poor shoot growth, fewer tillers and poor plant vigour (see p. 26). In addition, the decay and turnover of organic matter is impaired by the production of methane, alcohol and aldehydes as described on p. 19.

PLATE 20 **Visual scoring (VS) of surface relief**



GOOD CONDITION VS = 2
Surface is relatively smooth and unbroken.



MODERATE CONDITION VS = 1
Surface terrain is somewhat broken up and incised by occasional heavy treading events but it is not difficult to walk over.



POOR CONDITION VS = 0
Surface is very broken and deeply incised by severe repeated treading. The terrain is difficult to walk across and care must be taken to avoid twisting ankles.

FIGURE 3 Plant scorecard – visual indicators to assess plant performance in pasture

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Pasture quality (Brix=) pg. 34		x 3	
Clover nodules pg. 42		x 3	
Weeds pg. 46		x 2	
Pasture growth pg. 50		x 3	
Pasture colour and growth relative to urine patches pg. 52		x 3	
Pasture utilisation pg. 58		x 3	
Root length and root density pg. 60		x 3	
Area of bare ground pg. 62		x 2	
Drought stress pg. 64		x 2	
Production costs to maintain stock-carrying capacity pg. 66		x 1	
PLANT PERFORMANCE INDEX (sum of VS rankings)			

Plant Quality Assessment	Plant Quality Index
Poor	< 20
Moderate	20–35
Good	> 35

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:

Assessment

- 1 Assess the amount of green grass leaf, legume and dead matter (using the percentage chart on p. 36), and the botanical composition of the pasture during the time of year when pasture growth is strong due to favourable moisture and temperature conditions, and compare with the photographs and criteria given in Plate 21. Also measure the Brix (sugar) content of the pasture during the middle part of a sunny day using a simple refractometer. While not essential, measuring the Brix level is highly recommended.

In making the assessments, consider the original sowing mix, grazing management, competition and shading by other plants, fertiliser regime, and seasonal climatic conditions including air temperature and sunlight. Note there is a tendency to overestimate the amount of clover and underestimate the amount of dead matter.

Importance

PASTURE QUALITY varies according to the amount of green leaf and grass stem, legume content, dead matter, botanical composition, and sugar (energy) content of the pasture. While the stem is often considered to be lower quality than the leaf, it can have high concentrations of carbohydrates. Dead material has a very low nutritive value. Although pasture quality is governed by a number of factors, it can be a good indicator of the condition of the soil.

Pasture species is governed in part by the fertility of the soil and whether the plant is a high, moderate or low fertility species. High fertility species include perennial and Italian ryegrass, tall and meadow fescue, prairie grass, timothy, phalaris and white clover. Moderate fertility species include cocksfoot, crested dogstail, Yorkshire fog, sweet vernal, Kentucky bluegrass, creeping bent, and brome. Low fertility species include browntop, Chewing's fescue, paspalum, ratstail, danthonia, goosegrass, hairgrass, and needlegrass.

Pasture species also vary in their tolerance to poor soil aeration, pugging, soil and air temperatures, and moisture stress due to either waterlogging or a moisture deficit. Consequently, their nitrogen and sulphur uptake, dry matter production, and survivability also vary markedly. *Phalaris aquatica*, tall fescue, meadow fescue, meadow foxtail, Yorkshire fog, *Poa trivialis*, timothy, creeping bent, sweet grass, pennyroyal, waterpepper, buttercup, duckweed, and dock are tolerant of poor aeration and waterlogging due to pugging or poor drainage. Perennial ryegrass, white clover, cocksfoot, chewing fescue, browntop, *Poa annua*, and crested dogstail are moderately tolerant of poor aeration and waterlogging. Matua prairie grass, sweet vernal, *Poa pratensis*, ratstail, meadow rice grass, and yarrow are sensitive to poor aeration and waterlogging and will die out if conditions persist.

PLATE 21 Visual scoring (VS) of pasture quality

**GOOD CONDITION VS = 2**

Pasture has ≥ 95 percent green leaf herbage with ≥ 60 percent legume cover (≥ 30 percent DM), and < 5 percent dead matter. Brix sugar levels are ≥ 12 .

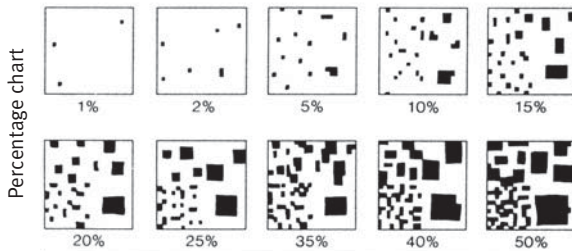
Pasture composition has a good mix of high-producing pasture species (e.g., ryegrass, white clover, cocksfoot, etc.) and species intolerant of poor aeration and waterlogging (see below). Pasture composition reflects the original mix. Forage herbs including chicory, plantain and yarrow also contribute to pasture quality.

**MODERATE CONDITION VS = 1**

Pasture has 75–80 percent green leaf herbage with 20–40 percent legume cover (10–20 percent DM), and 20–25 percent dead matter. Brix sugar levels are 6–9. Pasture composition has a mix of high and low fertility species. Pastures also show a range of tolerances to waterlogging and stock treading (see below). Pasture mix differs somewhat from that originally sown.

**POOR CONDITION VS = 0**

Pasture has < 50 percent green leaf herbage with little or no legume, and ≥ 50 percent dead matter. Brix sugar levels are ≤ 3 . Pastures are dominated by low-producing, low-fertility species and species that are more tolerant of poor aeration and waterlogging due to pugging; species such as ryegrass that are more tolerant of stock treading; and species such as white clover that quickly colonise bare ground created by severe treading (see below). Pasture composition has little relationship to the original seed mix.



Pasture composition will also change according to the degree of treading damage. Ryegrass and *Poa pratensis* resist treading damage better than many other species, and often become more common in pugged pastures. *Poa trivialis*, brown top, white clover, and timothy are moderately tolerant of treading.

Cocksfoot, red clover, Yorkshire fog, and many low fertility pasture species such as sweet vernal and chewing fescue are sensitive to intensive treading and disappear under prolonged pugging. Treading damage and the exposing of bare ground will also allow the invasion by opportunist species such as white clover and *Poa annua*, broadleaf dock and other weeds, and less desirable pasture species. White clover, being stoloniferous, can rapidly colonise bare ground and become dominant in severely pugged pasture.

The importance of pasture quality

While the quantity (intake) of pasture is important in terms of stocking rate and animal performance, maximising pasture quality provides dramatic increases in overall farm profitability and environmental performance. The quality of the pasture has a major effect on conception and survival rates, live-weight gain, animal health, wool and milk production, and food quality. Quality pasture maximises the feed conversion factor into milk solids and meat thereby maximizing the dollar return per kg of dry matter consumed.

White clover contains more crude protein (or total N) and readily fermentable carbohydrates, but lower concentrations of water soluble carbohydrates (sugars), lipids, lignin, cellulose and fibre than perennial ryegrass. With the exception of Italian, tetraploid and hybrid diploid (high sugar) ryegrasses, which have higher soluble carbohydrate levels compared with many perennial ryegrasses, grasses often have similar nutrient levels under similar soil fertility, regardless of species. Legumes and herbs, on the other hand, have a higher nutritive value and feed quality than grasses, especially in summer when temperatures are higher. Legumes such as clover contain more Ca, P, Mg, Zn, Cu, B and Co, but lower concentrations of Na and Se than perennial ryegrass. Yarrow has significantly higher concentrations of P, K, Fe, Mn, Cu, B, Co and I than mixed ryegrass/white clover, and explains why lambs kill-out heavier when grazing paddocks containing yarrow. Chicory is higher in K, Na, Zn and Mo than ryegrass, and plantain is higher in Ca, Na, Fe, B, Co, Se, I and tannins than mixed ryegrass/white clover.

Condensed tannins (CT) in temperate pastures protect plant protein from digestion in the rumen, which results in a greater supply of protein to the small intestine, thus improving protein adsorption and animal performance in terms of live-weight gain, wool production, and reproductive efficiency. CTs also help protect ruminants against bloat, reduce the

level of scouring and dags when grazing protein-rich pastures, reduce methane emissions by 15 percent by decreasing methanogenesis, and have a direct negative effect on internal parasites. Pastures containing birdsfoot trefoil (*Lotus corniculatus*), plantain and dock contain the most desirable forms of CTs, while the CTs in sainfoin, lotus major and sulla seem only to mitigate the impact of parasites. CT levels in pastures are generally low, and raising their concentration would improve pasture quality.

Pastures with a high energy level, nutrient density, and nutritive value have a higher palatability and digestibility and contain more useful energy per unit of dry matter. They also maintain good microbial growth rates and an active bacterial population in the rumen. Animals therefore have a higher feed-conversion efficiency and eat less to attain the number of kilojoules required for body maintenance, growth and lactation. Pasture quality also influences feed intake because while the animal wants to eat more herbage of low nutritive value to correct mineral imbalances, it moves more slowly through the animal's digestive track, physically restricting intake.

Pastures rich in crude protein and nitrate-N and with a low sugar content are difficult for the micro-organisms in an animal's rumen to break down by fermentation because of the lack of energy (sugars) in the pasture. Crude protein/nitrate-rich pastures also produce large amounts of nitrite (NO_2^-) that accumulates in the rumen during the reduction of nitrate (NO_3^-) to ammonia (NH_3). Nitrite reduces the total microbial population and, in particular, three of the four bacteria commonly found in the rumen. As a consequence, digestibility is reduced and livestock are only able to convert about 20 percent of the protein in the herbage into milk, meat and fibre – a low feed-conversion efficiency. Furthermore, because of the low sugar levels and high nitrate concentration, rumen microbes do not have the energy or capacity required to utilize the excess N in the feed and, as a consequence, convert 80 percent of it into ammonia. Some of the ammonia is used by the rumen bacteria for their own growth while most is absorbed into the blood stream. High concentration of ammonia in the blood (a toxic substance) overloads the liver as it attempts to convert it to urea, which is subsequently excreted in urine, milk and breath – this comes at a high energy cost to the animal. The bile ducts can also become blocked, forcing yellow bile out between the forelegs of the animal. The high concentration of N in the urine markedly increases the amount of N leached into the groundwater and waterways (pp. 75 & 76) and the amount of nitrous oxide (N_2O) emitted into the atmosphere (pp. 94–97). Poor rumen function also produces higher amounts of carbon dioxide (CO_2) and methane (CH_4). Moreover, pasture with poor digestibility spends more time in the rumen, thereby producing more fermentation gases, including CH_4 and CO_2 , which further increase the emissions of green house gases into the atmosphere.

Additionally, high crude protein/nitrate-rich pastures cause a number of animal health issues. While rumen bacteria attempt to convert non-protein N into usable protein, the bacteria burn much energy doing so, and as a result the animal draws from its body

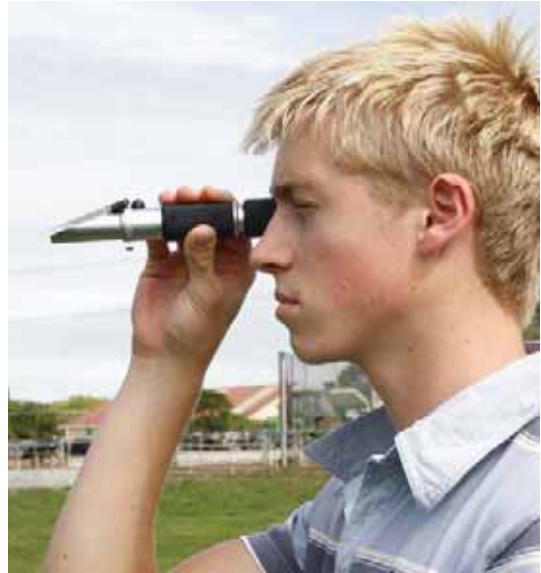
reserves of carbohydrates and stored fats (ketosis), eventually losing body condition and becoming run down and stressed. High concentrations of nitrite produced by the reduction of nitrate-rich pasture to ammonia in the rumen also give rise to nitrite poisoning (toxicosis). Nitrite is absorbed into the blood stream and combines with haemoglobin to form methaemoglobin. As methaemoglobin is unable to carry and transport oxygen it causes death through anoxia. It also suppresses oxygen transfer to the foetus, causing oxygen starvation and the abortion of the foetus. Lack of sufficient oxygen due to nitrate/nitrite toxemia is a common cause of infertility and high empty rates. High nitrate levels also suppress the production of Vitamin E, a key vitamin in protecting oxygen supply to the foetus.

High crude protein/nitrate-rich pastures and the resulting high nitrate/nitrite/ammonia levels in the rumen and subsequently the blood, also raise the blood pH to levels above the 7.3 required for a healthy animal. The overly alkaline gut and elevated blood pH (alkalosis) causes a range of metabolic disorders, including increased susceptibility to pulmonary emphysema, mastitis, laminitis, scouring, severe dags, and, if the pH rises above 7.4, death. Moreover, high pH affects the tenderness, flavour, colour and shelf life of meat.

Pastures can contain cyanogenic glycosides (hydrocyanocides) in new and rapidly growing shoots, and particularly during the spring flush. Growth rates are exacerbated by the addition of soluble, salt-based nitrogenous fertilisers during this period, producing crude protein/nitrate-rich pasture and subsequent alkalosis. Hydrocyanocides break down to hydrocyanic acid (HCN or hydrogen cyanide) under overly alkaline conditions in the rumen, causing cyanide poisoning and death.

High nitrate levels also suppress the production of Vitamin D₃, an important component of the melanin pigment under the skin that protects the animal from the sun's ultra-violet rays. This makes the animal more susceptible to sunburn (spring eczema). In addition to

PLATE 22 Assessing the sugar content



Assessing the sugar content (Brix) of pasture sap with a hand-held refractometer.

creating nitrate/crude protein-rich pastures, the excessive use of N causes luxury uptake of K, which suppresses the absorption of Ca, Mg (and Na) in the animal, causing milk fever (hypocalcaemia) and grass tetany (hypomagnesaemia). While attempts to manage the effects of high K levels often include the use of magchloride ($MgCl_2$) and causmag (MgO), such products would not be necessary if the appropriate fertilisers were used and the uptake of Ca and Mg not suppressed. The use of some forms of chlorides (such as KCl) and caustics should be avoided where possible.

High levels of N in the soil and pasture can promote the pathogenesis of viruses, bacteria and fungal disease (see p. 54), and insect pests. The application of optimum levels of Ca can help counterbalance the effect of N, particularly when added in conjunction with Na, B, carbohydrates, humates, and organic acids.

One of the keys to successful pastoral farming is to grow pasture with a high sugar (energy) content (with Brix levels of 12 or more) and a high nutrient density. This is achieved by ensuring a good mix of pasture species, including a good herb and clover content, and by promoting the photosynthetic pathway through ensuring the presence of key sugar-making elements and the subsequent conversion of the sugars into fats, carbohydrates, starch and mature protein. In addition to N, P, K, and S, this requires Ca, Mg, Na, Fe, Mn, Cu, Zn, Mo, Co, B, Cl, B vitamins, vitamin C, adenosine triphosphate (ATP), and good soil life. An example of pastures developing a higher nutrient density and nutritional value after just one year in biologically grown pasture versus conventionally grown pasture is given in Table 5 and Figure 4. Correcting nutritional imbalances by raising the nutrient density and sugar level will also help to curtail or eliminate insect pests. Moreover, the presence of adequate levels of sugars, carbohydrates and starch in the pasture are vital because they are acidifiers, countering the alkaline effect of nitrates and other nutrients, and so help maintain the pH of the rumen at optimum levels. Soluble carbohydrate concentrations are influenced by sunlight and Brix (sugar) levels are therefore best measured mid-afternoon on sunny days (Plate 22). Overcast conditions will reduce soluble carbohydrate concentrations.

In addition to raising pasture sugars levels, rumen function (and feed-conversion efficiency) is improved by ensuring yttrium and cobalt levels are adequate in the pasture. To enable the bacteria in the rumen to produce the vitamin B_{12} necessary to promote efficient digestion, Co levels in the herbage should be of the order of 0.1–0.15 mg/kg. The animal is better able to store trace elements in its organs and glands and utilise them over a longer term if the nutrients are adsorbed through the digestive system, rather than being administered as generic forms in drenches, bullets or injections.

The age of the pasture since grazing (i.e. the length of the regrowth period) also has a significant bearing on the chemical composition and nutritive value of the pasture. Pasture quality in the spring, summer, and autumn is greatest 25–40 days after grazing. Before that, the fibre, dry matter, and mineral (ash) content is lower and pastures are

rich in nitrate-N and crude protein through insufficient time for the soluble carbohydrates (sugars), organic acids and mature protein to build up. After a period of approximately 4–6 weeks, the quality of the pasture starts to decline with cell age, increased lignification and fibre content, and because nutrients begin to translocate down from the leaf to the root system. Rapidly growing pasture requires approximately 5–6 week to mature, while slow growing grass needs only 3–4 weeks.

White clover (*Trifolium repens* L.) is important for pastoral agriculture, not only because of its ability to fix nitrogen, but also because of its high nutritive and feed value (high protein and high mineral content), its seasonal complementarity with the growth pattern of grasses (perennial ryegrass), and its ability to improve animal feed intake and utilisation rates. While the quality of ryegrass is high in the spring, clover and herbs (such as chicory) are able to maintain their high nutritive value in the summer. White clover and herbs enhance the palatability of the pasture and because of their high digestibility and metabolisable energy, are utilised more efficiently than grasses, thus increasing the energy level, body condition, live-weight gain and reproductive function of the animal. The high digestibility of clover and herbs also gives rise to increased milk production with high protein, lactose and fat yield and a more efficient use of feed nitrogen, reducing the concentration of N in the blood and excreta. Furthermore, the more efficient digestion of clover and herbs enables the animal to better utilise the energy content of the pasture, converting it to meat, milk and fibre instead of methane and carbon dioxide. Animals grazing a ryegrass sward produce twice the amount of CH₄ (24 g/kg dry matter intake) compared with animals grazing white clover (12.9 g/kg dry matter intake). Methane emissions can be reduced by at least 10 percent when grass forage is replaced by a mixed ryegrass/legume sward. In addition, the meat tends to have a higher Omega 3 content, a better flavour, and the animal has a higher kill-out weight due to a higher muscle:fat ratio.

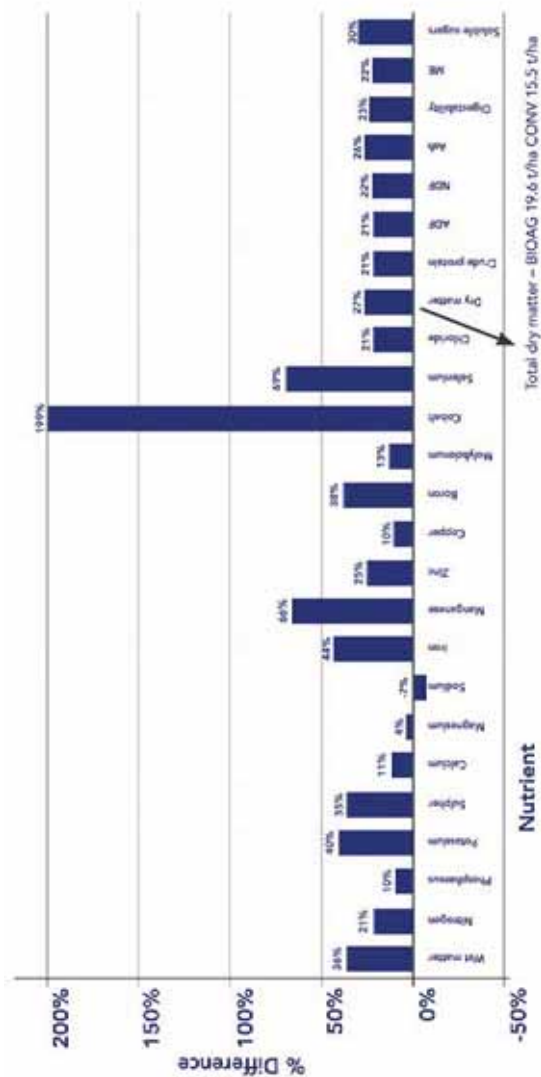
Clover drives the growth rates in lambs and, because of its high feed quality, stock generally gain more live-weight on white clover (growing 90 percent faster) than on perennial ryegrass. Diet selection studies show sheep prefer around 70 percent (dry matter) of their intake to come from white clover and 30 percent from grass. While cows milk better on clover pastures, the clover content of dairy pastures, often around 15–20 percent, is lower than the 50–70 percent needed for maximum milk solid production. A clover content in dairy pastures of at least 30–50 percent DM is also required for maximum pasture growth. Clearly, a greater proportion of white clover in mixed pastures would be beneficial to animal production. This can be achieved by promoting the condition of the soil, a higher level of N fixation through strong clover nodulation and the enhancement of free-living N-fixing bacteria, good grazing management practices, and meeting the nutritional requirements of clover including the appropriate use of specific forms of fertilisers other than nitrogen. The frequent and heavy use of fertiliser-N suppresses N-fixation, clover content, and clover growth, and limits clover recovery once N rates are reduced (see pp. 44–45). Because of this, 30 percent of clover DM in the pasture sward is not achievable and the pasture will therefore not meet the criteria required to be in good condition as defined in Plate 21.

TABLE 5 Nutrient densities¹ of biologically grown pasture versus conventionally grown pasture

Treatment	N	P	K	S	Ca	Mg	Na	Cl	Fe	Mn	Zn	Cu	B	Mo	Co	Se
Biologically grown pasture	3.24	0.39	3.20	0.40	0.62	0.23	0.17	1.04	159	89	178	6.8	5.8	1.43	0.19	0.19
Conventionally grown pasture	3.40	0.42	2.98	0.32	0.59	0.25	0.22	0.93	120	59	150	6.8	5.4	1.66	0.07	0.07

¹ Mean of 5 cuts taken in the autumn and spring. Data from the first year of field trials on a Waikato dairy farm; courtesy of Abron Living Soil Solutions.

FIGURE 4 Nutrient level improvements in pasture



Nutrient level improvements of biologically grown pasture versus conventionally grown pasture on a Waikato dairy farm. Values represent the mean of nine analyses of samples taken over an 11 month period and adjusted for differences in total dry matter production; courtesy of Abron Living Solutions.

Assessment

- ❶ The N-fixing ability of a pasture can be assessed by the density, size, colour and depth of clover nodules.
- ❷ Remove three to four clover plants with a spade, pushing the spade down to a depth of 250 mm. Gently shake the soil free exposing the root system and clover nodules (Plate 23).
- ❸ Assess the number of nodules, their size, the depth at which they occur, and the colour of the leghaemoglobin within the nodule (Plate 24), and colour, compare with the criteria given in Table 6. Clover nodules are best assessed in the spring when leaf growth and N demand is greatest, but can be checked at any time of the year provided the plant isn't under stress through defoliation, drought, or soil and air temperatures being too high or low.
- ❹ Nodules on clover have a short life-cycle of 3–4 weeks. Healthy nodules start as white, then become pink on the surface as red leghaemoglobin develops inside the nodule, at which point it become active, fixing N_2 . The redder the colour, the more active it is. The nodules then decline as the leghaemoglobin decays to a yellow bile pigment (Plate 24) and eventually becomes elongated and white or grey again, appearing like a deflated balloon. Depending on their stage of maturity, nodules will also display a range of sizes varying from very small up to 3–5 mm. Nodules on mature healthy roots will therefore have a range of colours, shapes and sizes. To assess the degree of redness of the leghaemoglobin, select 3 or 4 of the pinkest nodules and split them in half between your fingernails and observe the colour with a magnifying hand lens. Discard any nodules showing yellow bile pigment because they are becoming inactive and nearing the end of their cycle.

Importance

CLOVER NODULES are produced in response to invasion through the root hairs by *Rhizobium*, a bacterium which infects and stimulates the proliferation of root cells to form nodules. Once the nodule is formed, the bacterium multiplies and changes form into a bacteroid that contains a nitrogenase enzyme capable of reducing atmospheric nitrogen gas to ammonia ($N_2 + 8H^+ \rightarrow 2NH_3 + H_2$). The nitrogenase enzymes break the triple bond holding the two N atoms of the N_2 molecule, and adds hydrogen to form ammonia. The reaction requires hydrogen and a considerable amount of energy in the form of adenosine triphosphate (ATP) and carbohydrates from photosynthesis. The enzyme has two components, a molybdenum-iron protein and an iron protein. Molybdenum and iron must therefore be present in adequate amounts to enable the production of the nitrogenase enzyme and therefore the fixation of N_2 . While *Rhizobium* is an aerobe, nitrogenase enzymes cannot function in the presence of oxygen and so oxygen levels are kept low by a diffusion barrier on the outer wall of the nodule, by high bacterial respiration rates within the nodule, and by the presence of leghaemoglobin. The critical function of leghaemoglobin is to absorb O_2 and transport it within the anaerobic zone to the bacterial cells to support their respiration. Leghaemoglobin can only be produced if levels of Fe, Mn, Zn, Co, Se and in particular Cu (the blood elements) are adequate. A pink/red colour

PLATE 23 **Clover nodules**



Clover roots showing strings and clusters of distinct healthy pale pink nodules. Photo taken in the spring: Courtesy of John Brock.

PLATE 24 **Inside a clover nodule**



Clover nodule split open showing brownish red leghaemoglobin (LHb). Note the decay of the LHb to the yellow bile pigment above the red area. Photo: Courtesy of Michael Templer.

inside the nodule indicates the nodule is actively fixing N; the redder the colour, the more active it is. The ability of the *Rhizobium* bacteria to fix N also depends on whether the strains of rhizobia present in the soil have an effective nitrogenase system, and if not, then clover seed needs to be inoculated with effective strains.

The ammonia produced by N-fixation is rapidly converted to ammonium (NH_4^+) and taken up by the plant to produce protein and organic N compounds. The N fixed by clover nodules is only released to other pasture plants such as grasses by a combination of two processes. First, when the clover plant dies and decomposes, the organically bound N compounds are mineralised by a wide range of bacteria and fungi in the soil to release N in the form of plant available ammonium (NH_4^+). Under aerobic conditions, the majority of ammonium is converted to nitrate (NO_3^-), another plant available form of N by nitrosomonas and nitrobacter bacteria (a process known as nitrification). Second, most of the N ingested by grazing animals is returned to the soil as urine, which then hydrolyses to urea. Urea is converted to ammonia by the urease enzyme followed by its hydrolysis to ammonium and then nitrification to nitrate-N. A possible third but minor mechanism could involve the direct excretion of small amounts of N through root leakage from intact growing legumes.

Depending on its relative dominance in a sward, white clover is able to fix up to 300 kg N/ha/year in high-producing sheep farms, and up to 380 kg N/ha/year in dairy farms. Higher levels of N fixation could possibly be achieved if optimal conditions for N fixation were provided. The actual amount of N fixed is very dependent on a number of factors including the performance and condition of the clover nodules. Factors that limit white clover growth often result in much lower N fixation rates of 80–150 kg N/ha/year. Such factors include moisture stress, high temperatures, cultivar choice, competition from grasses and incompatible companion species, pasture establishment, shading, grazing management, endophytic toxins from ryegrass, pest and diseases, soil acidity ($\text{pH} < 5.8$), low soil carbon, low soil fertility (other than N) including low Ca levels, and poor soil aeration. Poorly aerated and compacted soils have less air and consequently less N available for biological fixation. In addition to the elemental requirements for the production of nitrogenase and leghaemoglobin, white clover plants require adequate levels of N, P, K, S, Ca, and B for root development and growth. Aerobic N-fixing micro-organisms also require adequate levels of Ca and Co, and good soil aeration to function at optimum levels.

N-fixation by clover nodules is further governed by the amount of mineral-N in the soil. Clover prefers to take up mineral-N than fix N from the atmosphere because it is a more energy-efficient process and therefore has less energy cost to the plant. Clover will only resort to N-fixation when a deficiency in N occurs within the plant. Thus the frequent and heavy use of water-soluble N in the form of urea, anhydrous ammonia or nitrate will suppress N-fixation, clover content, and clover growth, and limit clover recovery once N rates are reduced.

TABLE 6 Visual scoring (VS) clover nodules

Visual score (VS)	Clover nodules
2 [Good]	Clover roots have strings and clusters of lots of nodules (4–8 per 20 mm) and occur to a depth of 150–200 mm; many are large (> 2 mm). At least 50 percent of the nodules have a distinct pale pink hue on the surface and a bright red or brownish red leghaemoglobin content that bleeds when split open and squeezed.
1 [Moderate]	Clover roots have a moderate number of nodules (1 per 20 mm) to a depth of 75–150 mm. The largest nodules are of medium size (1–2 mm) and have a faint pale pink hue on the surface and a pink to pale reddish brown leghaemoglobin content when split open.
0 [Poor]	Clover roots have few or no nodules and only occur in the upper 75 mm of the soil. Nodules are small (< 1 mm) and are white on the surface with little or no signs of leghaemoglobin when split open.

Nitrogen can also be fixed by free-living N-fixing aerobic *Azotobacter* bacteria and by anaerobic *Clostridium* bacteria. The fixed-N (up to 10–15 kg N/ha/yr) is made available to the plant when the bacteria die and decompose. *Azotobacter* bacteria need good aeration, high levels of available C, and non-acidic soils to function in large numbers. Under favourable, non-acidic, well-aerated soil conditions with optimum levels of trace and major elements including Ca and C, as well as a good earthworm population, free-living N-fixing bacteria could potentially produce substantially more than 10–15 kg N/ha/yr.

Nitrogen fixing bacteria, be they free-living in the rhizosphere, confined to nodules on plant roots, or existing as endophytes in leaves or stems, derive most of their energy from dissolved organic carbon (liquid sugar) fixed during photosynthesis. N-fixation is therefore very dependent on the flow of liquid carbon from the leaf to the roots.

The rate of N-fixation depends on the demand for N, which is governed by the clover growth rate. Because N-fixation is influenced by the amount of mineral-N in the soil, clover growth is not necessarily a direct indicator of N-fixation. In spring, grasses are more active and use most of the soil N, and while clover growth may not be high, N-fixation will be. In summer when clover is more active, grasses are less active and soil N can accumulate and clover N-fixation may be lower.



Assessment

- 1 Assess the number of weeds (using the percentage chart on p. 48) and variety of undesirable weeds in the pasture, and at what level their presence detracts from the value of the pasture. Undesirable weeds include ragwort, barley grass, bristle grass, water pepper, willow weed, wild carrot, mayweed, hedge mustard, buttercup, duckweed, and thistles.

In making your assessment, consider how often a given level of weed infestation occurs in the paddock from season to season, and at what level it is perceived to be a problem. Consider also your grazing management and the need for weed control measures, including the use of herbicides, biological control agents, mowing, steaming, cultivation, pastoral renewal, and other measures taken to deal to weeds before they go to seed. Make your assessment according to the photos and criteria given in Plate 25 on the basis of what the field would look like without any weed control measures except for grazing management.



Importance

WHILE SOME WEEDS are beneficial and contain a number of essential nutrients for stock, others have little nutritional value, are difficult to digest, can be poisonous, and generally reduce the overall value of the feed. Weeds compete with desired pasture species for water, nutrients and growing space, displacing more beneficial, high-producing pasture species, thereby encouraging the use of clover-damaging herbicides. They allow poor pasture quality to develop, reducing pasture utilisation and plant and animal production.

While weeds can occur for a number of reasons, they can be useful indicators of the condition of the soil, including the level of compaction, soil aeration and waterlogging, nutrient fertility, pH, the amount and type of organic matter, and the microbial biomass. It is commonly believed that healthy soils support weeds and desirable pasture species equally well. In the same way that insect infestation indicates unhealthy plants with a nutritional imbalance, a weed infestation indicates something is not right with the soil, which is suppressing the growth of high producing pasture species and providing an environment favouring weeds. Soil structural degradation resulting from stock treading (pugging), wheel traffic, over-cultivation, or soil dispersion due to a low Ca:Mg ratio or high Na levels, reduces soil aeration, soil drainage, available water-holding capacity, nutrient uptake, and the rooting potential of the crop, allowing weeds to establish and compete with the crop. Lighter soils with a coarser textural class can have more weeds than heavier soils with a finer textural class, while acidic soils can have a greater variety of weeds than non-acid soils.

PLATE 25 **Visual scoring (VS) of weeds**



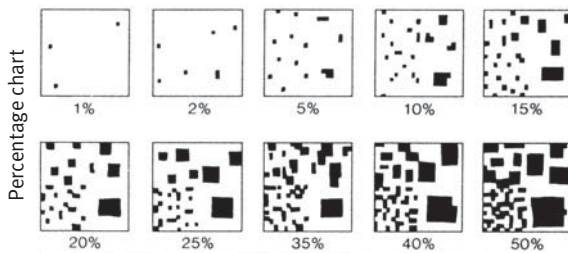
GOOD CONDITION VS = 2
Pasture has few or no weeds.



MODERATE CONDITION VS = 1
Weeds are very common covering 5–10 percent of the ground surface.



POOR CONDITION VS = 0
Weeds are abundant covering ≥ 20 percent of the ground surface. They indicate either significant compaction, poor aeration, waterlogging, low functional organic carbon and Ca, or poor mineral and microbial composition.



Weeds will also develop and thrive in soils that have a poor mineral and microbial balance. Weeds will grow and proliferate where there is a Ca and P deficiency and an excess of K and Zn. They will develop where there is an imbalance of Fe to Mn, a lack of biologically available Ca, a lack of biologically active carbon

including humus and humic acids, and where there are high nitrate levels, and a lack of bacteria or fungi. Pastoral soils need to maintain a fungal to bacteria ratio of 0.75:1 (or 1:1), which is necessary to preserve and promote pastoral plants. An imbalance of this ratio along with poor soil nutrition could explain why pastures may show poor persistence and a tendency to revert to other plant species such as woody weeds.

Thistles, including the nodding, wing, Scotch and Californian thistles, are some of the most annoying and destructive weeds: the smothering and competitive effects of rosettes reduce pasture production, and the prickly leaves discourage even grazing and good pasture utilisation. Thistles can indicate the soil is deficient in Ca and bacteria and high in K and S. An infestation of thistles would suggest soil conditions and fertility are insufficiently adequate to maintain a complete, vigorous pasture cover and the high growth rates required to reduce seed germination and kill young seedlings and developing rosettes.

Broad-leaved weeds such as dock can develop on soils that are moderately acidic with moderately high fungal levels. They like a soil environment that is low in Ca and P and high in N and K, where available K greatly exceeds the available P. High nitrate levels also help to promote seed germination. Dock can further indicate a decline in the C:N ratio. If the available K continues to increase relative to P, a point may be reached where herbicides cannot control the broadleaf weed. While they are poor competitors and germination is inhibited under a dense leaf canopy, dock can establish and take hold in open or disturbed patches of pasture due to overgrazing, compaction, pugging, and the uneven application of slurry or manure. Some would argue that docks in grassland are not weeds because they contribute trace elements and herbage to a grazing animal's diet and hence do not need to be controlled. Broad-leaved dock is relatively high in P and K in the leaves, and is particularly high in Mg. Cattle fed on herbage containing docks help to prevent bloat because tannins in the dock leaves help to protect plant proteins from digestion and degradation and precipitate out soluble proteins in the rumen, thus preventing the formation of a degraded protein-based foam.

Barley grass is found on rough bare ground in summer-dry, seasonally stressed areas, on soils deficient in Na, and on the margins of cultivated fields. Barley grass does not compete well against a vigorous perennial ryegrass/white clover sward on fertile, moist

soils. **Ragwort** is not common in seasonally stressed, summer-dry pastures and is more usually associated with wetter areas, and on soils low in Ca, P, Co and bacteria, and high in K (particularly when using muriate of potash). The ragwort seed is well adapted to areas of local disturbance, as may be found in well-trafficked, compacted areas. Ragwort does not compete well against strong competition from vigorous, rapidly growing perennial ryegrass/white clover pastures on good quality, highly fertile soils. Ragwort is toxic to stock and can induce photosensitization, jaundice, weight loss, and impairment of liver function. **Dandelions** indicate a Ca, P, vitamin A and in some cases an Fe deficiency in the soil. Their occurrence is exacerbated by Mg, Zn and the excessive use of K (muriate of potash), which further suppresses Ca levels. **Buttercup** grows especially well on wet, poorly drained, poorly aerated soil, and soils that are low in Ca, P, humus and bacteria and high in K (particularly if using muriate of potash). It is tolerant of compaction and grazing, and fresh plants can be bitter and toxic to grazing animals.

The condition and properties of the soil have a major bearing on whether the pasture is able to grow in a sufficiently vigorous way to out-compete, and prevent or restrict the establishment and growth of weeds. Competitive suppression by vigorous pasture growth plays a major role in preventing weed establishment. Weed suppression can also occur after a pasture is sown by the production of auxins (or plant growth hormones) when the seed germinates. Auxins limit or stop the germination of other seeds from either pasture or weeds. While this suppression lasts for only 1–2 days in poor quality soils, it can last for 6–8 weeks in biologically active, well-aerated soils, thus providing an effective, natural weed control. The application of liquid calcium incorporating a form of organic carbon such as molasses or humic/fulvic acids (to act as a food supply for soil microbes), along with the addition of an organic form of phosphorus and selected trace elements such as B, Co and Se, can help alter the soil environment in such a way that weeds are suppressed. As the soil chemistry adjusts and nitrogen is converted to an organic form (freely available to mycorrhizal fungi but not to annual weeds), the incidence of weeds, pests and diseases that are stimulated by low levels of microbial diversity and high rates of non bio-friendly, water soluble potassic and nitrogenous fertilizers, will decline.

Changing the soil environment can successfully deal with any weed problem and can provide a more effective solution than the application of straight herbicides, which gives a short-term and often limited response. However, where weeds are an initial problem, the incorporation of herbicides into a solution containing ammonium humate or fulvic/humic acids with a pH modifier, can provide good weed control. Such a mixture enables the amount of herbicide used to be reduced by 25–35 percent, and also helps buffer the effect of the herbicide on soil life. The regular use of herbicides and pesticides have an adverse effect on soil microbes (including mycorrhizal fungi), which are responsible for maintaining the nutrient balance and availability of nutrients in the soil. The quick-kill approach using chemical herbicides only addresses the symptoms and does nothing to rectify the underlying cause.

Assessment

- Assess pasture growth since the last grazing by pasture probe, rising plate, herbage cut measurements, or alternatively by visual estimation (Plate 26), and compare with the criteria given in Table 7. If this information is not available, use visual approximations of dry matter (DM) production levels. For a reliable comparison, make assessments at the same time of year, preferably in mid spring. Consider also the total dry matter production per annum.

Importance

HIGH PASTURE PRODUCTION AND GROWTH RATES depend on good soil structure and aeration, good soil fertility, earthworm and microbial activity, available water, seasonal weather conditions, and the maintenance of good residual levels ($\geq 1\ 800$ kg DM/ha) after grazing. Just as pasture quality has a marked effect on live-weight gain, milk and fibre production, livestock health, and reproductive performance, so does pasture quantity. Intake is influenced in part by the amount of pasture offered to the animal. The more offered, the more can potentially be eaten, up to a maximum where increased DM production has no more influence on intake and live-weight gain. For stock to be in good condition at calving and lambing, an adequate pasture cover of 2 000 kg DM/ha is needed, and pastures need to be capable of rapid regrowth.

Treading damage on compacted moist soils can reduce pasture production by up to 27 percent; on pugged (deformed) wet soils, however, the reduction can be as much as 45 percent. As a consequence, farmers are forced to budget for extra feed (up to 30 percent more) in the winter. Moderately pugged ground with a moderate VSA soil structure score (of 1) can give rise to a loss of 200 kg DM/ha/month or 13 kg milk solids/ha/month. Assuming a payout of \$5.50/kg MS, this would equate to a loss of approximately \$715/ha/yr or \$107,250 in income from a 150-ha dairy farm.

TABLE 7 Visual scoring (VS) pasture growth

Visual score (VS)	Pasture growth	Dry matter production (tonnes/ha/yr)	
		Lowland farms	Upland farms (300 m [1 000 ft] above sea level)
2 [Good]	Good pasture growth	17	13
1 [Moderate]	Moderate pasture growth	13–15	9–11
0 [Poor]	Poor pasture growth	< 11	< 7

PLATE 26 Assessing dry matter production



Assessing dry matter production and pasture growth rates with a rising plate meter.

Treading damage and the loss of dry matter production can be reduced significantly by grazing paddocks when the soil is sufficiently dry to minimise compaction and pugging. To assess whether soil conditions are suitable for grazing, apply the ‘worm test’ (Plate 47, p. 70). Take a piece of soil (half the volume of your index finger) and press firmly with your fingers to form a pencil. For silty soils, if you can roll a worm 10 mm wide by 50 mm long (7 mm wide by 50 mm long for clayey soils) between the palms of your hand without it cracking, the soil is too wet to graze. If the worm cracks when it is 10 mm wide for silty soils (7 mm for clayey soils), the soil is ready to graze. Compacted, pugged pastures and the subsequent reduction in dry matter production can also be ameliorated by artificial soil aeration. To assess whether soil conditions are suitable for aerating, apply the ‘worm test’ (Plate 47, p. 70). Aerating the soil can increase DM production by 33 percent after 6 months and by 52 percent after 8 months. Pasture composition and nutritional value are also significantly improved.



Assessment

- 1 Compare the colour and growth of the pasture between urine patches with the colour and growth of the urine patches, and compare with the three photographs and criteria given in Plate 27. The best time to carry out the assessment is just before the next grazing in the autumn, late winter and late spring, avoiding very cold and wet weather. In making the assessment, consideration must be given to the time of year, the pasture species, stage of growth, soil moisture and temperature conditions, and also the presence of pests and diseases (e.g., nematodes). If the pasture receives more than 30 kg/ha/yr of artificially applied nitrogen, consider what the pasture looks like just before the application of N.



Importance

THE COLOUR AND GROWTH OF THE PASTURE RELATIVE TO THE URINE PATCHES and blemishes on the leaf can provide a good indication of the nutrient status and condition of the soil. Pasture colour depends on a number of factors, including a deficiency or excess of N, P, S, Ca, Mg, Fe, Mn, Cu, B, Co, and Mo. Chlorosis (or yellowing of pasture) due to the loss or inadequate formation of chlorophyll, commonly occurs as a result of low N, S, Mg, Fe, Mn, Cu and Zn levels in the soil, low soil and air temperatures, prolonged cloudy days, and poor soil aeration resulting from compaction and waterlogging.

The difference in pasture growth in and between urine patches can distinguish between pastures that are and are not reliant on fertiliser-N to generate growth. The frequent and excessive application of N (especially during dry conditions) together with certain types of fertilisers, herbicides and pesticides can adversely affect the biological regime and nitrogen cycle of the soil, and can also suppress other elements critical for plant growth. As a result, pastures can become dependent on a 'fix' of nitrogen or fertiliser to stimulate growth. Yellow, stunted grass between darker green urine patches (pastoral chickenpox), can be a further sign that the nitrogen cycle has broken down and the utilisation and supply of N and other nutrients by micro-organisms has been adversely affected. In other words, the engine room of the soil, as discussed on p. 21, has become 'rusty' and no longer has the 'horse power' to produce the dry matter required. The addition of N in such cases will only give a short-term pasture response, and an ongoing dependency on N can result – no applied nitrogen, no grass.

Yellow, stunted grass between urine patches can also occur as a result of a N and S deficiency caused by a reduction of plant-available forms of N and S to plant-unavailable forms in poorly aerated, waterlogged soils (pp. 6, 13 & 28). S and N can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form. Plants can also only utilise N if S is present in oxygenated sulphate form.

PLATE 27 **Visual scoring (VS) pasture colour and growth relative to urine patches****GOOD CONDITION VS = 2**

Pasture colour is uniformly deep green with little difference in growth between urine patches. The odd colour blemish on leaves may be apparent within a broad area.

**MODERATE CONDITION VS = 1**

Moderate difference in pasture colour and growth between urine patches. Pasture is yellowish green or medium green between urine patches. Few colour blemishes on leaves may occur.

**POOR CONDITION VS = 0**

Significant difference in pasture colour and growth between urine patches. Pasture is quite yellow between urine patches. Colour blemishes on leaves may commonly occur.

In addition to a yellowing of the pasture, discolorations or blemishes on the leaf can indicate mineral deficiencies (Plates 28–35). Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of S, Zn and Cu while high S levels can suppress the uptake of P and Mg. Excess N can strip Ca from the soil, block Mn, Zn, B and Cu uptake, and cause the plant to luxury feed on K, which in turn can also tie up Mn and B, and suppress the utilisation of Ca and Mg by the animal.

Moreover, N-rich pastures growing on urine patches are often avoided by cattle; they will only eat it when the feed supply is short, or when its sugar level rises. When nitrates exceed 0.23 percent of the DM, nitrate poisoning (toxicosis) is likely to occur as nitrate is reduced to nitrite (NO_2^-) in the rumen. N-rich growth patches also bring increased risk of mycotoxins and toxic substances produced by fungi, which results in milk production losses, reduced feed intake, feed refusal, unthriftiness, rough hair-coat, ketosis, retained placenta, metritis, fatty livers, reproductive problems and poor body condition.

PLATE 28 Phosphorus deficiency in clover



Photo: T. Wallace (1961)

Phosphorus deficiency in clover: Dull bluish green or yellowish green leaves with small bronze spots over the surface.

PLATE 29 Phosphorus deficiency in grass



Phosphorus deficiency in grass: Leaves show a distinct purple colouring.

PLATE 30 **Magnesium deficiency in clover**

Photo: T. Wallace (1961)



Magnesium deficiency: Interveinal chlorosis and of the leaf margins

PLATE 31 **Calcium deficiency in clover**

Photo: H.B. Sprague (1964)



Calcium deficiency: Leafstalks collapse and wilt; leaves are chlorotic with scorched margins.

PLATE 32 Potassium deficiency in clover



Potassium deficiency: White spots on margins of leaves.

PLATE 33 Sulphur deficiency in clover



Sulphur deficiency: Pink clover leaves.

PLATE 34 **Boron deficiency in clover**

Photo: T. Wallace (1961)



Boron deficiency: Reddish margins of clover leaves; thickened & stiff stems.

PLATE 35 **Copper deficiency in grass**

Photo: W. Bergmann (1993)



Copper deficiency: Chlorosis of the margins and tips of grasses.

Assessment

- 1 Assess pasture utilisation by estimating the proportion of pasture that has been well grazed or poorly grazed, and the proportion not smeared or trampled into the mud by grazing animals, and compare with Plates 36–38 and the criteria in Table 8. In making the assessment, consider the time of year, the pasture species, stage of growth, soil moisture and temperature conditions, radiation levels from the sun, grazing management practices, stocking rate, and the type and amount of fertilisers applied.

Assessments should be made at or as near the end of the grazing period.

Importance

PASTURE UTILISATION provides a good indication of the quality and palatability of the pasture and can be a useful guide to the nutrient status and condition of the soil. Pastures have a high palatability if they are rich in sugars and carbohydrates relative to protein, with a high nutritional value, containing many of the essential elements required and sought after by the animal. As a result, stock graze the whole field with a utilisation of around 80 percent. Conversely, pastures that are protein rich and deficient in sugars and essential elements have poor palatability. Stock graze selectively and roam a lot, and pasture utilisation can be reduced to 40 percent. The nutritional value of the pasture and the degree of utilisation also depend on soil aeration and the vigour and distribution of the root system. Pastures with an extensive root system in well-aerated soils are able to utilise a greater reservoir of water and nutrients. Poorly aerated soils have limited root systems and suppress the availability of elements in a form required by the plant (see pp. 8, 13 & 28). Palatability can further be affected by the pasture being contaminated with fungal toxins.

Utilisation of pasture can also be influenced by treading damage (pugging) when wet. As a result, pastures can experience prolonged surface ponding and are easily trampled into the mud. This makes the pasture both inaccessible and unpalatable to stock. Trampling and surface ponding can reduce pasture utilisation by 20–40 percent.

TABLE 8 **Visual scoring (VS) of pasture utilisation**

Visual score (VS)	Pasture utilisation
2 [Good]	Good pasture utilisation with high palatability and only a little of the pasture being trampled into the mud.
1 [Moderate]	Moderate utilisation of pasture due to moderate palatability or a significant amount of pasture being covered by, and trampled into the mud.
0 [Poor]	Poor utilization of pasture due to poor palatability or a large proportion of pasture being covered by, and trampled into the mud.

PLATE 36 Good utilisation of pasture



Even grazing and good utilisation of pasture due to high palatability.

PLATE 37 Poor utilisation of pasture with low palatability



Poor utilisation of pasture with low palatability. Stock selectively graze and roam a lot.

PLATE 38 Poor utilisation of pasture



Poor utilisation due to severe trampling into the mud.



Assessment

- 1 Remove a piece of soil 200 mm square by approximately 300 mm deep with a spade from the side of the hole where the 200-mm cube was removed for the drop shatter test. With the help of a knife, carefully loosen the soil between the roots and then expose the root system by gently shaking the soil free by tapping the soil sample against the edge of the hole. Compare both the length and the density of the roots with the three photographs and criteria given in Plate 39.

The root length and root density is best assessed in late autumn–early winter when maximum root development occurs, but can also be assessed in late winter–mid-spring when soil moisture and soil temperatures are usually not limiting pasture growth.



Importance

ROOT LENGTH AND ROOT DENSITY provide good indications of the condition of the plant root system. Pastures with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared with pastures with a shallow, thin root system. Dry matter production and tillering is therefore likely to be greater, root pulling less of a possibility, and pastures will have a lower susceptibility to drought stress and recover quicker when the rains come. Pastures with a dense, deep, vigorous root system also raise soil organic matter levels and soil life at depth, thereby sequestering (adding) significant amounts of carbon. The physical action of the roots and soil fauna, and the glues they produce, promote the development of soil structure, soil aeration and drainage. Worm-populated soils also have many tunnels that are coated with mucus and rich in nitrates. Plant roots take advantage of the tunnels as easy-growth channels, extending quickly by taking nutrition from the nitrogen-rich mucus and water as they go. The presence of clover root nodules at depth supplying nitrogen as a result of N fixation further encourages the development of the root system.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Pastures are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up, reducing losses by leaching into the groundwater and waterways.

Root length, root density, plant growth and vigour can be restricted by the mechanical impedance of roots and the lack of soil pores due to soil compaction, a hardpan or rock. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, major and trace element deficiencies, the application of excess nitrogen causing lazy plants, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and poor soil aeration. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, all by-products of chemical and biochemical reduction reactions (see pp. 13 & 28).

PLATE 39 Visual scoring (VS) of root length and root density



GOOD CONDITION VS = 2
Good root length & root density with an evenly distributed root system.



MODERATE CONDITION VS = 1
Moderate root length & density with the root system being somewhat patchy.



POOR CONDITION VS = 0
Poor root length & density with the root system being restricted to limited areas.



Assessment

- 1 Assess the area of bare ground in winter or early spring. Compare the surface of the ground with the three photographs and criteria given in Plate 40. If there is canopy closure due to good growth, part the pasture with your hands and score at ground level. An assessment of an area of bare ground after a long dry period will show how much pasture has died from lack of moisture.



Importance

IN ADDITION TO STOCK CAMPING, DISEASE, INSECT PESTS AND DROUGHT EFFECTS, BARE GROUND is formed by the physical churning up of the soil from treading and pugging. This churning causes leaf and stem crushing, reduced tiller density, the uprooting or burial of plants, and root damage, all of which reduce tiller numbers and pasture density, vigour and growth. Weeds and less desirable pasture species can invade the resulting gaps, further reducing pasture production. Like surface relief, the area of bare ground can be a good indicator of below-ground damage.

Bare ground on fields with a slope can increase their susceptibility to water erosion. Good pasture cover on the other hand, and its below-ground root system, returns organic matter to the soil and promotes soil life including earthworm numbers and activity. The physical action of the roots and soil fauna, and the glues they produce promote the development of soil structure, soil aeration and drainage. As a result, infiltration rates and the movement of water through the soil increases, decreasing runoff, soil erosion, and the risk of flash flooding. Pasture cover on sloping ground also reduces soil erosion by intercepting high impact raindrops, and minimising rain-splash and saltation. Moreover, it acts as a sponge, retaining rainwater longer so that it infiltrates into the soil. The root system of good pasture cover further reduces soil erosion by stabilising the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved, with lower sediment loading and lower nutrient and coliform content. The ground surface needs to have at least 70 percent cover to give good protection; ≤ 30 percent cover provides poor protection.

Good ground cover (with a high leaf-area index) intercepts and absorbs a large amount of carbon dioxide (CO_2) as it escapes from the soil. This increases pasture production as a result of the greater photosynthetic uptake of CO_2 and decreases the amount of CO_2 emitted into the atmosphere, decreasing the level of green house gas emissions.

PLATE 40 Visual scoring (VS) of area of bare ground

75% cover



GOOD CONDITION VS = 2

Pasture covers all or most of the surface area. Surface cover is ≥ 80 percent.

50% cover



MODERATE CONDITION VS = 1

Pasture shows significant areas of bare ground and sporadic growth with the ingress of weeds and white clover caused by treading damage. Surface cover is ≥ 40 percent and < 60 percent.

20% cover



POOR CONDITION VS = 0

Large areas of bare ground (≤ 20 percent cover) occur because of treading damage and the reduction in density and vigour of the pasture. White clover and less desirable pasture species and weeds may have invaded degraded and bare areas

Surface cover photos: courtesy of A. Leys

Assessment

- 1 Assess, from visual evidence and local knowledge, the degree to which pastures are drought stressed during prolonged dry periods by comparing the greenness of the pasture with the three photographs and criteria in Plate 41. Assess also the level of dry matter production, whether drought tolerant species have become dominant in the pasture sward, and how quickly the pasture declines going into a drought and how quickly it recovers following the first rains, according to the criteria given in Plate 41.

Importance

THE DEGREE OF DROUGHT STRESS in dry periods depends on climatic conditions, grazing management, the drought tolerance of the pasture, and the condition of the soil, including the amount of water able to infiltrate into the soil and the water-holding capacity (AWC) of the soil. The latter is governed by soil depth, the length and density of the root system, soil texture, the number and size of soil pores, and amount of soil carbon. One part of soil humus (a relatively stable form of soil carbon) can retain a minimum of four parts of soil water. Pastoral soils with a good structure and soil life, including earthworm populations, have a large number of macropores and coarse and medium-sized micropores, and, subsequently, have a higher water-holding capacity than degraded soils with few pores. Soils with good structure also have high infiltration rates with little or no run-off and are able to capture most of the rainfall. Loamy and silty soils, and in particular soils with silt loam textures and good organic matter levels (of 15–30 percent), are able to store and retain a lot more plant-available water than very fine (clayey) and coarse (sandy) textured soils, particularly if the soil organic matter content is low.

Calcium (in a form such as lime) promotes the biological life, structure and porosity of the soil and therefore the AWC. Lime also converts to water by the following reaction, which increases the soil's resistance to drought: $\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{CO}_2 + \text{H}_2\text{O}$. Optimum levels of Zn and K promote the uptake of water and therefore water-use efficiency by facilitating the movement of water into plant cells. High K levels will suppress the wetting of soils and reduce Ca levels. Although Mg has an affinity for water, increasing plant-available water, too much Mg (and Na) disperses soil clay particles, causing the collapse of the soil structure and pores and consequently the reduction of their water-holding capacity. Ensure the soil has good amounts of Ca relative to Mg, with a Ca/Mg ratio of 7:1 for clayey soils, 5:1 for silty soils and 3:1 for sandy soils.

Mycorrhizal fungi can supply moisture to plants by exploring micropores not accessible to plant roots. They can also improve water flow by their hyphae bridging macropores. This wicking effect along the hyphae can be very significant in dry soils. Mycorrhizal fungi can also increase drought resistance by stimulating an increase in the number and depth of plant roots.

Pastures on good quality soils are slow to decline going into a drought and quick to recover following the first rains. Conversely, pastures on poor quality soils are quick to decline going into a drought and slow to recover following the first rains. This is particularly so for white clover.

PLATE 41 Visual scoring (VS) of drought stress of pastures during prolonged dry periods

**GOOD CONDITION VS = 2**

Pastures are slow to decline going into a drought and remain relatively green, with dry matter production able to hold on, albeit at low levels, further into dry summers. Recover is quick following the first rains. Pasture composition is dominated by ryegrass and white clover during dry periods.

**MODERATE CONDITION VS = 1**

Non-drought tolerant pastures 'brown off' significantly during dry summer months, although thin green patches are still present close to the ground. Dry matter production is very low and pastures become dominated during drought by the more drought-resistant cocksfoot, tall fescue, phalaris, birdsfoot, Lotus trefoil, meadow rice-grass, rats tail and small annual clovers. Deep rooted flat weeds and hawkbit may also be common. Pastures are moderately quick to decline going into a drought and recovery is somewhat delayed following the first rains.

**POOR CONDITION VS = 0**

With the possible exception of drought tolerant grass species and deep rooting herbs such as chicory, pastures brown off completely and pasture growth stops during dry periods. Pastures are quick to decline going into a drought and die off during times of prolonged drought. With the exception of subterranean clover and drought-tolerant species such as phalaris, pastures are slow to recover following the first rains.



Assessment

- 1 Assess the stock-carrying capacity of the paddock in relation to production costs and whether overall production costs have increased in order to maintain stock-carrying capacity.

In making your assessment, consider all production costs including, for example, the use of nitrogen, lime, additional fertilisers, feed supplements, soil aeration of the topsoil (Plates 42–45), subsoiling (deep ripping), artificial drainage, resowing, under-sowing, over-sowing, weed control, drenching, animal health issues, and veterinary costs, etc. Compare with the criteria given in Table 9.



Importance

PRODUCTION COSTS TO MAINTAIN STOCK-CARRYING CAPACITY can provide a good indication of the performance of the soil and pasture. While fertiliser should be seen as an investment rather than a cost, it is one of the major costs associated with farming. The amount, type and therefore cost of applied fertiliser can be significantly influenced by the condition of the soil and the performance of the pasture. The condition of the soil can have a major effect on fertiliser use efficiency, including the N and P conversion factor, i.e. the N and P captured in production going from the farm. For example, poorly aerated and waterlogged soils reduce plant available nitrate-nitrogen (NO_3^- -N) to nitrite (NO_2^-) and N_2 gas, and sulphate-sulphur (SO_4^{2-} -S) to sulphite (SO_3^{2-}) and sulphides, rendering the N and S unavailable to the plant. The N cycle also cannot work if the S cycle is not working, i.e. plants need sulphur in sulphate form to utilize N. It is partly for this reason that farmers commonly apply more N and S than would otherwise be the case in an attempt to overcome the losses incurred by the chemical reduction effect of soils in poor condition.

Poorly aerated and waterlogged soils also decrease the uptake of phosphorus by pastures. Degraded soils with relatively high Olsen P levels (40–50 mg/L) can show a positive pasture production response to applied P. Moreover, plant uptake of Cu and Co is suppressed when the soil is waterlogged and anaerobic. Again, to boost production, farmers will often apply more phosphorus and trace elements than normally would be required in order to mitigate any nutrient deficiencies.

Do you use fertiliser to grow the plant, or do you use fertiliser to feed the soil to grow the plant?

PLATE 42 Farm with low production costs



Farm with on-going low production costs to maintain its current stock-carrying capacity of 3.4 cows per ha.

PLATE 43 Maintenance application of fertiliser

Photo: Courtesy of Robert Tucker



TABLE 9 How to score production costs to maintain stock-carrying capacity

Visual score (VS)	Production costs
2 [Good]	Production costs have not increased. Only maintenance fertiliser applications required to maintain stock-carrying capacity.
1 [Moderate]	Some additional costs required to maintain stocking rates including some additional fertiliser.
0 [Poor]	Significant additional costs required to maintain stocking rates including significant additional fertiliser.

PLATE 44 Use of feed supplements



Feed supplements such as maize silage, wholecrop cereal silage, palm kernel, etc., are often used not only to overcome feed shortages but also to provide an adequate diet of low crude protein and high soluble carbohydrates and starch that are deficient in poor quality pastures.

PLATE 45 Artificial aeration

Photo: Courtesy of James Engineering



Ameliorating poorly aerated, compacted soil by artificial aeration.

In addition to soil fertility issues, soils in poor physical condition can have a significant effect on pasture production. Pasture production can recover almost completely within approximately 6 months if the soils are only moderately compacted by stock treading and wheel traffic. Severe compaction and pugging, and the subsequent increase in root penetration resistance and loss of soil structure, porosity, aeration, root length density,

and water-holding capacity can reduce dry matter production by up to 40–45 percent. The soil can also take years to recover. If feed utilisation ratios are around 0.7, this decline in pasture uptake would reduce potential stock numbers by 10–20 percent. To offset this trend, additional fertiliser is often applied to maintain dry matter production and stock numbers.

The application of fertiliser can be reduced or kept to maintenance levels if the soil is maintained in good condition. Such conditions includes having good soil aeration with good structure, porosity, root length and root density, good levels of soil carbon, and good soil life in terms of the amount, activity and diversity of soil microbes and earthworms. Keeping your soils in good condition can have a significant effect on keeping production costs to a minimum.

Compacted, poorly aerated soils can be ameliorated by artificial aeration. Aerating the soil can increase dry matter production by 33 percent after 6 months and by 52 percent after 8 months. To minimise the effects of root-pruning and maximise root development, compacted soils should be artificially aerated in the autumn just prior to, or during the root development cycle of the pasture, and when transpiration and respiration demands on the plant are lower than in the spring and summer. Soils should also be aerated when they are moist and sufficiently crumbly to give maximum fracturing (Plate 46) and a smooth surface finish behind the aerator (Plate 45). This can be achieved by using the ‘worm test’ (Plate 47). Spending money on diesel instead of fertiliser to aerate compacted soils will often give better pasture production and pasture quality.

PLATE 46 Aerating in the autumn at the optimum water content for maximum results

Photo: Courtesy of James Engineering



Artificial aeration of compacted topsoils must be timed correctly in the autumn to cause maximum fracturing and minimum disturbance of the surface.

PLATE 47 The 'worm test'



For **silty soil**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to aerate. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to aerate.

The amount of feed supplements grown and brought onto the farm not only affects production costs but also provides an indication of the ability of a farm to grow grass and quality pasture. Feed supplements such as maize silage, wholecrop cereal silage, palm kernel, etc., are used not only to overcome feed shortages but also to provide the necessary diet of low crude protein and high soluble carbohydrates and starch. These dietary components are deficient in poor quality pastures but are a feature of high quality pasture. The amount of supplements used could therefore be appreciably reduced by simply improving pasture quality – thereby significantly reducing costs.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 2

Pastures

Visual indicators
of environmental performance
under pastoral grazing

A GUIDE



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A GUIDE

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List of acronyms

AEC	Adenylate energy charge	MgO	Magnesium oxide
Al	Aluminium	Mn	Manganese
ASC	Anion storage capacity	Mn³⁺	Manganic
ATP	Adenosine triphosphate	Mn²⁺	Manganous
B	Boron	Mo	Molybdenum
C	Carbon	N	Nitrogen
Ca	Calcium	N₂	Nitrogen gas
Ca²⁺	Calcium cation	NO₃⁻	Nitrate
CEC	Cation exchange capacity	NO₃⁻-N	Nitrate-Nitrogen
CH₄	Methane	NO₂⁻	Nitrite
Cl	Chlorine	N₂O	Nitrous oxide
CO₂	Carbon dioxide	Na	Sodium
qCO₂	Metabolic quotient	Na⁺	Sodium cation
Co	Cobalt	NH₄⁺	Ammonium
CT	Condensed tannins	NH₃	Ammonia
Cu	Copper	O₂	Oxygen
DM	Dry matter	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂	Hydrogen gas	SO₄²⁻	Sulphate
H₂S	Hydrogen sulphide	SO₃²⁻	Sulphide
I	Iodine	Se	Selenium
K	Potassium	VS	Visual score
K⁺	Potassium cation	VSA	Visual Soil Assessment
KCl	Potassium chloride	WFP	Water-filled porosity
LHb	Leghaemoglobin	Zn	Zinc
Mg	Magnesium	ZnS	Zinc sulphide
Mg²⁺	Magnesium cation		
MgCl₂	Magnesium chloride		

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER PASTORAL GRAZING

A GUIDE



1. Nutrient loss into the groundwater and waterways



2. Carbon sequestration



3. Greenhouse gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways



Assessment

- ① To assess the susceptibility of soils under pasture to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 79), the visual scores (VS) for the Textural group, Soil structure and the Potential rooting depth from the Soil Scorecard, and the visual scores (VS) for Root length and root density, Pasture quality, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Also add a ranking score for stocking rate and the amount and form of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.



Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals¹, have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is >7:1, P is limiting growth. If the N:P <7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

¹ Non-crystalline iron and aluminium hydrous oxides and non-crystalline aluminosilicate clays such as ferrihydrite and allophone.

PLATE 48 Nutrient loss into waterways



- a) Paddock with a moderate potential for nutrient loss into the groundwater and lake. While the soil has a sandy textural group and good soil structure with a rapid permeability, it has a good potential rooting depth, moderately good root length and root density, moderately high carbon levels and CEC in the topsoil, and receives moderate amounts of low water-soluble fertiliser. The paddock has a moderate pasture quality with a moderately low stocking rate.
- b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly estimated from seven of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^- -N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain

more clay and generally more humus as well. Hence their CECs are higher and more able to adsorb and retain positively charged nutrients such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+ , etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic silty clay*, *peaty silt loam*) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P in solution can also leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root length and root density** (p. 60) – Pastures with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with pastures with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root length and root density and the potential rooting depth.

Pasture quality (p. 34) can provide a good indication of the potential for nutrient loss into the groundwater and waterways. Pastures rich in crude protein and nitrate-N with low sugar content are difficult for the micro-organisms in the rumen of the animal to break down by fermentation because of the lack of energy (sugars) in the pasture. As a consequence, livestock are only able to convert about 20 percent of the protein in the herbage into milk, meat and fibre. Furthermore, because of the low sugar levels, the rumen microbes do not have the energy required to utilize the excess N in the feed, converting 80 percent of it into ammonia as a consequence. As a result, the concentration of N in urine patches is markedly increased to 1 000–1 600 kg N/ha, increasing the amount of N lost by surface runoff and leaching into the groundwater and waterways. Leaching from urine patches accounts for about 55 percent of the total N leached from pastures. The amount of N lost can be significantly reduced by simply reducing the concentration of N in the urine by ensuring stock graze sugar-rich, nutrient-dense high quality pasture containing mature proteins, soluble non-structural carbohydrates, cobalt and condensed tannins.

Pasture colour and growth relative to urine patches (p. 52) can also provide a good indication of the potential for nutrient loss versus the retention and utilisation of nutrients in the soil (Plate 49). The greater the colour/growth contrast, the greater the loss potential. Poor growth and yellow pasture relative to urine patches often indicate the nitrogen and/or sulphur cycle has broken down. This is because the amount of humus and the number and activity of soil organisms responsible for nutrient retention, turnover and supply, have been degraded by, for example, the frequent and excessive application of artificial N and certain types of fertilisers, herbicides and pesticides. Without the humus and microbial population, subsequent applications of nutrients, particularly in the form of highly soluble fertilisers and N, will be more readily leached through the soil profile. The presence of

PLATE 49 High potential for nutrient loss



Paddock with a high potential for nutrient loss into the groundwater and waterways due partly to poor pasture quality and associated high concentration of N in the urine as indicated by the tall, dark green grass (nitrogen hills) in the urine patches compared with between urine patches.

tall, dark green grass in the urine patches compared with yellow, poor pasture growth areas between urine patches also indicates a high concentration of N in the urine and its subsequent potential for loss by leaching. In addition, organic acids released from animal manure, and the high pH of liquid manure and sewage sludge, enhance the mobilisation of phosphorus, increasing the amount of P that is leached.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light, well-structured soils, particularly when applied in large amounts. The over-use of highly soluble granulated N products also readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^- . Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching in urine patches. Nitrate and H^+ ions are produced in the urine patch following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes.

The frequent addition of soluble nitrogenous products to boost dry matter production also increases the concentration of N in the herbage and subsequently, the concentration of N in the urine. Moreover, the extra amount of nitrate-rich pasture grown by applying N is consumed by the animal, producing a greater amount of urine. As a consequence, the production of additional amounts of N-rich urine increases the amount of N leached into the groundwater and waterways. In contrast, the application of ‘smart’ fertiliser products that help generate sugar-rich, nutrient-dense, high-quality pastures with a high metabolisable energy and digestibility, result in the animal producing lower concentrations of N in the urine. The energy demand of the animal eating higher quality pasture is also met by it consuming less, thereby producing less urine. In addition, the concentration of N in the urine is reduced by ensuring the animal intake of Co in the herbage is adequate to enable the bacteria in the rumen to produce vitamin B_{12} necessary to promote efficient digestion through good rumen function. To this end, Co levels in the pasture should be of the order of 0.1–0.15 mg/kg. The production of less urine with a lower concentration of N significantly reduces the input of N into the groundwater and waterways. Additionally, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of soluble, salt-based forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate

can strongly inhibit soil life. Soil microbes and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant. Nutrient loss can therefore be reduced by applying fertilisers in a way that promotes soil life.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to pastures to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain carbohydrates and organic C (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and pasture growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^- -N) from urine patches and soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+ -N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. It can further produce phytotoxic effects and yield reductions in white clover and clover N_2 fixation. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Stocking rate (see scorecard – p. 79) can significantly influence nutrient loss into the groundwater and waterways. Animal urine contains a lot of nitrogen and is the principal source of leached N in managed grazing systems (Plate 56, p. 98). The amount of urine produced is roughly proportional to the animal liveweight. A 500-kg dairy cow produces 13–27 litres of urine/day, approximately seven times the amount of a 70-kg ewe, which produces 1.8–3.6 litres of urine/day (Table 10). While urine patches can contain 1 000–

TABLE 10 Average liveweight and the amount of urine produced for different stock classes

Stock class	Average live weight (kg)	Stock unit equivalent ¹	Volume of urine per day (litres)	Volume of urine per year (litres)
Friesian cow	500–550	6.3	13–27	4 740–9 850
Jersey cow	400–450	5.3		
Beef cow	500–600	6.3		
Heffer	250–350	3.4		
Deer	120	2.1		
Goat	60			
Ewe	60–75	1.2	1.8–3.6	650–1 310
Hogget	50	1		
Lamb	35–40	0.7		

¹ Cornforth and Sinclair (1984).

1 600 kg N/ha, N leaching losses from dairy/beef and sheep farms commonly range from 15 to 115 and 10 to 66 kg N ha/yr respectively. The actual amount of N in urine strongly depends on the amount and form of soluble, salt-based nitrogenous fertiliser applied, the amount, quality and type of feed consumed, and the efficiency of rumen function. A high stocking rate on crude protein/nitrate-rich pasture receiving high amounts of soluble salt-based fertiliser N will significantly increase the amount of leached N compared with low stocking rates. All things being equal, 4 cows/ha will add roughly twice as much urinary N as 2 cows/ha.

Animal liveweight per hectare instead of stock units is used to define stocking rates because of the difficulty of accurately reporting stock units for different classes of livestock, and at different times of the year in terms of their size, feed (energy) requirements, animal performance and farming systems. The average liveweight per animal for different stock classes is given in Table 10 and can be quickly used to calculate stocking rate (and feed-use efficiency), regardless of the class of livestock.

Any one of the above indicators provides an estimate of the susceptibility of a soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 28 , certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 28 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching and surface runoff into the environment. Pastures are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth. Farmer involvement is the key to reducing nutrient loss into the groundwater and waterways. The Nutrient Loss Scorecard provides farmers with a simple, quick tool to help them mitigate nutrients emissions into the environment.

FIGURE 5 Scorecard – visual indicators to assess the potential for nutrient loss

Landowner: _____ Land use: _____ Site: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey

Visual indicators of nutrient loss	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	pg. 2	x 3	
Soil structure (Scoring protocol is given below ²)	pg. 4	x 2	
Potential rooting depth (mm)	pg. 22	x 3	
Root length & root density	pg. 60	x 3	
Pasture quality	pg. 34	x 3	
Pasture colour & growth relative to urine patches	pg. 52	x 2	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 3	
Stocking rate (Scoring protocol is given below ⁴)	pg. 77	x 2	
NUTRIENT LOSS INDEX (sum of VS rankings)			

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 15
Moderate potential for nutrient loss	15–28
Low potential for nutrient loss	> 28

1 Textural group (Figure 2b, p. 3):

VS = 2 for Clayey; VS = 1.5 for Fine silty; VS = 1.0 for Fine loamy; VS = 0.5 for Coarse silty; VS = 0 for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 respectively to the VS score. Note VS scores cannot exceed a value of 2.

2 Soil structure – Is the land most susceptible to a) leaching, or b) runoff?

a) Land susceptible to leaching – Flat land with little or no runoff (overland flow)

VS = 2 for Poor soil structure; VS = 1.5 for Moderately poor soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately good soil structure; VS = 0 for Good soil structure.

b) Land susceptible to runoff – Gently undulating to rolling and hilly land

VS = 2 for Good soil structure; VS = 1.5 for Moderately good soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately poor soil structure; VS = 0 for Poor soil structure.

3 Amount and form of fertiliser and N applied

VS = 2 if using liquid foliar sprays, conditioner, or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 30 kg N/ha/yr are applied; VS = 1.0 if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 60–90 kg N/ha/yr using highly soluble, salt-based and nitrogenous fertilisers; VS = 0 if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 120 kg N/ha/yr are applied.

4 Stocking rate – kg liveweight (Lwt) per ha

VS = 2 if the Lwt is ≤ 1 000 kg (≤ 2 cows*)/ha; VS = 1.5 if the Lwt is 1 250 kg (2.5 cows)/ha; VS = 1 if the Lwt is 1 500 kg (3 cows)/ha; VS = 0.5 if the Lwt is 1 750 kg (3.5 cows)/ha; VS = 0 if the Lwt is ≥ 2 000 kg (≥ 4 cows)/ha. [* assuming a cow of 500 kg liveweight]

2. Visual indicators to assess the potential for carbon sequestration



Assessment

- Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 7, p. 89) the visual scores (VS) for the Textural group, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root length and root density, Pasture growth, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Add also a ranking score for the clay mineralogy and the amount and form of fertiliser and nitrogen applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.



Importance

THE AMOUNT OF C in a soil = C inputs – C losses. Carbon inputs and losses are in equilibrium with soil temperature, moisture, mineralogy, drainage status, decomposition rates, leaching, volatilisation, farming systems, and soil and pasture management. With the exception of the last three, most of these governing factors remain fairly constant, providing a potential steady state in the carbon-carrying capacity of the soil. The equilibrium can, however, swing towards increasing soil C by increasing the input of relatively stable forms of carbon through adopting appropriate farm management practices. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition (by oxidation and mineralisation), leaching and volatilization. A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than C losses. Farmers can reduce their ecological and carbon footprint and 'grow' their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture's contribution to CO₂ emissions, providing a cost-effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, three indicators of plant performance, and from the amount and form of fertiliser and nitrogen applied, as described below.

PLATE 50 Carbon positive soil

A carbon positive soil with good soil colour compared with the fenceline, good potential rooting depth, pasture growth, pasture colour and growth compared with urine patches, moderately good earthworm numbers, root length and root density, and carbon-friendly forms of nitrogen applied annually in low amounts.

PLATE 51 Carbon neutral soil

A carbon neutral soil with moderate soil colour compared with the fenceline, moderate earthworm numbers, potential rooting depth, pasture growth, pasture colour and growth compared with urine patches, moderately poor root length and root density, and moderate amounts of granular nitrogenous products applied annually.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of soil C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are $<2\ \mu\text{m}$ and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

Clay mineralogy (see scorecard, p. 89) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Mollic Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and aluminosilicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under pasture contain about 235 t C/ha in the top 1 m, of which 163 t C/ha (69 percent) occur in the upper 300 mm, and 72 t C/ha (31 percent) between 300 and 1000 mm. Compare this with non-allophanic soils below.

Soils with a high proportion of amorphous (poorly crystalline) aluminosilicate clay minerals have a high anion storage capacity (ASC) while soils dominated by crystalline aluminosilicate clays have a low ASC. The ASC can therefore provide a useful indication of the proportion and general type of clay minerals present and can be used to broadly describe the clay mineralogy of the soil. The ASC is also commonly reported on most soil tests, and so farmers will have the information required to score this indicator, as defined in the scoring protocol on p. 89.

Soil colour compared with that under the fenceline (p. 10) can provide a rough indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present (Fig. 6, p. 88). With the exception of poorly aerated and saturated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C.

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. Earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil carbon. Soils are also less well aerated and have fewer microbes at depth and so organic carbon is more protected and able to build up because it is less likely to be oxidised and mineralised.

Potential rooting depth (p. 22) and the **Root length and root density** (p. 60) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 160 tonnes C/ha, of which 117 t C/ha (73 percent) occur in the upper 300 mm, and 43 t C/ha (27 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good rooting depth contain about 173 t C/ha in the top 1 m, of which 103 t C/ha (60 percent) occur in the upper 300 mm, and 70 t C/ha (40 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme.

Pasture growth (p. 50) provides a further indication that soil C is increasing, decreasing or at steady state. The greater the dry matter production, the greater the root and shoot mass, and therefore the greater the C input from the root system and the decomposition of the additional surface litter and animal dung. A farm growing 18 tonnes of dry matter (DM)/ha/yr with a shoot:root ratio of 1:1 adds similar amounts of plant material to the soil, of which 41 percent or 7.4 t/ha/yr is carbon. Approximately 6.2 t C/ha/yr is added to the soil from the roots and 1.2 t C/ha/yr from plant litter, assuming 84 percent pasture utilisation. A further 4.3 t C/ha/yr is added from animal excreta, making a total input of 11.7 t C/ha/yr. Of this, approximately 0.43 t C/ha/yr is incorporated as soil C. A farm growing just 15 t DM/ha/yr adds a total input of 9.8 t C/ha/yr, of which approximately 0.36 t C/ha/yr is incorporated as soil C, 16 percent less than the higher producing farm. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the pasture is not overstocked, has good residual levels, root-length density, and potential rooting depth, and the soil is allophanic with good soil life and doesn't receive high applications of salt-based nitrogenous products. In addition, the

microbial decomposition of roots, plant litter, and dung produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture, and soil and air temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing pasture growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Pasture colour and growth relative to urine patches (p. 52) can provide an additional indication of the potential of the soil to sequester or lose C. First, poor growth and yellow pasture relative to urine patches indicate the N and S cycle has broken down because the amount of humus and the number and activity of soil organisms responsible for nutrient retention, turnover and supply have been degraded. The input of soil C declines as a consequence causing a net loss of C. Second, the strong growth of grass in the urine patches also indicates the dissolution and loss of a significant amount of C by the high concentration of N in the urine patch (see below).

Amount and form of fertiliser and nitrogen applied to pastoral soils (see scorecard, p. 89) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, vermicasts, worm leachates, animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' conditioner fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and pasture management practices, good pasture production, pasture quality and soil C levels can be sustained and increased over the long term.

The plant converts CO_2 in the atmosphere into dissolved organic carbon (DOC, i.e. liquid sugar) by photosynthesis in the leaves of the plant. The dissolved liquid carbon is subsequently transported in the sap through the roots to the soil across a microbial 'bridge' formed by the mycorrhizal fungi. This provides a constant flow of C to the soil and at the same time feeds the microbes (mycorrhizal fungi and bacteria) attached to the roots and in the soil. The microbes in turn provide macro-nutrients (such as P, organic N and

Ca), trace elements (Zn, B, and Cu), and plant growth hormones to the plant in exchange for the sugar, a process known as ‘bidirectional flow’. The supply of nutrients stimulates plant growth, which in turn increases the photosynthetic supply of liquid C to the soil and soil microbes, increasing the population of soil microbes. Mycorrhizal roots can transfer as much as 15 times more carbon to the soil than can non-mycorrhizal roots. The DOC not used directly by the soil microbes is converted through the process of microbial humification to humus, which is a relatively stable form of carbon. Up to 80 percent of DOC can be humified if there is sufficient microbial diversity and the right fungal metabolites (including amino acids) and enzymes are present. Soil microbes, including actinomycetes and mycorrhizal fungi, also play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important stable organic compound that can comprise 30 percent or more of the humus fraction in pastoral soils.

Mycorrhizal fungi and bacteria, include those forming the microbial bridge between the soil and the plant roots are strongly inhibited by excessive soil disturbance and high levels of water-soluble, salt-based forms of N and P. Cultivation and the application of high levels of mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP), superphosphate, urea, and anhydrous ammonia suppress and disrupt the mycorrhizal colonization of plant roots and thus the microbial bridge, reducing the photosynthetic rate by up to 35 percent and, as a result, significantly reducing C flow to the soil and its humification to humus. Conversely, appropriately managed farmland promotes carbon sequestration by allowing the liquid carbon pathway to function.

Moreover, while nitrogen promotes pasture growth, and therefore the input of C into the soil, certain forms of N are more effective at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic C and carbohydrates such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N.

The application of frequent and high rates of soluble granular forms of N and high analysis nitrogenous fertilisers to boost dry matter production:

- i) promotes the vegetative growth of the shoots relative to the roots and creates lazy plants, encouraging a shallow root system. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil because shoots contribute 6 times less C than roots do;
- ii) produces ‘watery’ pasture with a lower dry matter content and a lower concentration of C in the shoots and roots, adding less C to the soil on decomposition;
- iii) leads to the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 20:1 or less;

- iv) causes the N enrichment of urine and the subsequent mineralisation of soil C by stimulating the activity of the microbial biomass through the priming action of dissolved carbon in the urine. As a result, bacteria mineralise 2–3 times the amount of humus they would ordinarily mineralise. High concentrations of N in urine patches may also cause the dissolution (emulsification) of soil humus and its subsequent loss as dissolved organic C in the leachate;
- v) reduces the earthworm and microbial biomass, further reducing C levels in the soil.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to pastures to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (such as ammonium humate, humic/fulvic acids), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent). The utilisation of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root length density, and pasture growth.

The form in which essential elements are applied can also have a significant effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and, as such, increases pasture production and C flow to the soil, partly by providing a soil environment conducive to mycorrhizal activity and the formation of a microbial bridge between the roots and soil. Potassium chloride (muriate of potash), on the other hand, can be harmful to the roots and soil life, and can have adverse effects on animal health.

Moreover, the addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore 'grow' the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 30), certain management practices and specific types of fertiliser and N (if required) need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 30) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits as well.

Off-setting GHG emissions

The sequestration over a 12 month period of 6.3 and 7.1 tonnes C/ha in the top 1 m of soil (an increase of 3.6 and 5.5 percent respectively from the previous year) on two dairy farms that recently converted from soluble, salt-based high-analysis N:P:K fertilisers to bio-

friendly fertilisers, equates to the sequestration of 23 and 26 tonnes CO₂ equivalents/ha respectively. GHG emissions from dairy farms are typically of the order of 7–9 tonnes CO₂ equivalents/ha/yr, two-thirds less than the 23–26 tonnes CO₂ equivalents/ha sequestered as soil C. The soil clearly has a huge capacity to act as a carbon sink under appropriately managed farmland, off-setting GHG emissions. Soil carbon sequestration by adopting carbon farming strategies, such as developing the root system, increasing earthworm numbers, and applying bio-friendly forms of fertilizer, is consequently a cost-effective strategy to mitigate GHG emissions.

Carbon sequestration of atmospheric CO₂ in the soil, ultimately as stable humus, may well provide a more lasting solution than temporarily sequestering CO₂ in the standing biomass through re- and afforestation. Carbon sequestration will also contribute to higher soil fertility, greater biodiversity, aeration, infiltration and water-holding capacity, less droughtiness and dependence on supplements in protracted dry periods, and sustainable food productivity and quality.

PLATE 52 A carbon negative field



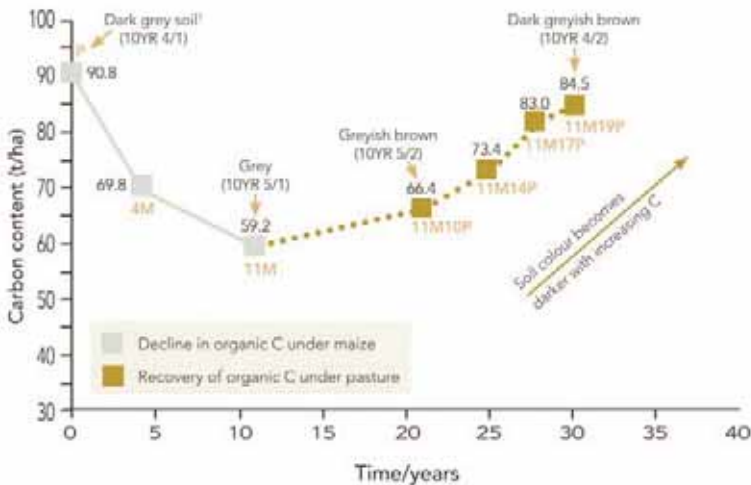
Total organic C declined in the upper 200 mm of soil from 90.8 tonnes/ha under pasture to 59.2 tonnes/ha after 11 years of maize under poor management practices (Figure 6). Photo taken in 1984 after harvesting for the 11th consecutive year of maize (for grain).

PLATE 53 Carbon sequestration under pasture



Carbon sequestration under pasture following 11 yrs of continuous maize cropping. Total organic C recovered from 59.2 tonnes/ha under 11 yrs of maize to 84.5 tonnes/ha in the upper 200 mm of soil after 19 yrs of ryegrass/clover pasture, an average recovery rate of just 1.3 tonnes C/ha/yr (Fig. 6). The rate of C sequestration could have been much greater had pastoral management practices focused better on promoting soil life, the potential rooting depth, root length and root density, pasture production and pasture quality, and applied the appropriate amount and form of fertiliser and N.

FIGURE 6 Rate of recovery of total C under pasture following intensive cropping



† Soil colour according to the Munsell notation.

Total C in the topsoil (0–200 mm) and associated soil colour after 10, 14, 17 and 19 years of pasture following 11 yrs of maize under conventional cultivation.

FIGURE 7 Scorecard – visual indicators to assess the potential for carbon sequestration

Land owner:	Land use:	Site:	GPS:	
Soil type:	Drainage class:	Topsoil depth:	Date:	
Textural group <input type="checkbox"/> Sandy <input type="checkbox"/> Coarse loamy <input type="checkbox"/> Fine loamy <input type="checkbox"/> Coarse silty <input type="checkbox"/> Fine silty <input type="checkbox"/> Clayey <input type="checkbox"/> Peaty (upper 1 m):				
Visual indicators of soil carbon		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹) pg. 2			x 2	
Clay mineralogy (Scoring protocol is given below ²) pg. 82			x 2	
Soil colour pg. 10			x 1	
Earthworms (Number =) (Av. size =) pg. 14			x 3	
Potential rooting depth (mm) pg. 22			x 3	
Root length and root density pg. 60			x 3	
Pasture growth pg. 50			x 3	
Pasture colour and growth relative to urine patches pg. 52			x 2	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)			x 3	
SOIL CARBON INDEX (sum of VS rankings)				
Soil Carbon Assessment		Soil Carbon Index		
Soil is potentially carbon negative		< 16		
Soil is potentially carbon neutral		16–30		
Soil is potentially carbon positive		> 30		

- 1 Textural group (Fig. 2b, p. 3):** VS = 2 for Clayey; VS = 1.5 for Fine loamy and Fine silty; VS = 1.0 for Coarse silty and Peaty (virgin land); VS = 0.5 for Coarse loamy; VS = 0 for Sandy and Peaty (developed land). Strictly speaking, peaty soils cannot be defined as a textural group; however, they are closely aligned to, and have a huge effect on, soil texture.
- 2 Clay mineralogy:** VS = 2 if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; VS = 1 if the soil has moderate levels of Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an ASC of 60–75 percent; VS = 0 if the soil has little or no Fe & Al hydroxides and amorphous aluminio-silica minerals; ASC is < 45 percent.
- 3 Amount and form of fertiliser and N applied:** VS = 2 if ‘smart’ conditioner fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 30 kg N/ha/yr is applied as urea or in other forms of highly soluble, salt-based nitrogenous fertilisers; VS = 1 if moderate amounts of highly soluble, non-biologically friendly salt-based phosphatic & potassic fertilisers are used, and 60–90 kg N/ha/yr is applied as urea or in other highly soluble, salt-based nitrogenous fertilisers; VS = 0 if high amounts of highly soluble, salt-based phosphatic & potassic fertilisers are used, and > 120 kg N/ha/yr is applied as urea or in other highly soluble, salt-based nitrogenous fertilisers.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions



Assessment

- 1 Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 9, p. 99) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual scores for Pasture quality, Pasture growth, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Also add a ranking score for stocking rate and the amount and form of nitrogen applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.



Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C ; without them the earth's average temperature would be around -18°C . However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Solar radiation



Agriculture can provide a significant source of methane and nitrous oxide and is responsible for 15 percent of greenhouse gas emissions worldwide. In an agriculture-based country like New Zealand, farming practices can produce half the country's GHG emissions, of which 33 percent is breathed out as CH_4 from the digestive system of the animal and from dung emissions, and 17 percent is emitted as N_2O from animal urine, dung and nitrogenous fertilisers. These high emission levels are more to do with farm-management practices than the farming of ruminant animals. Climate-friendly and smart agricultural management can significantly reduce emissions.

GHG emissions result from a number of sources, including the soil, stock, and applied fertiliser N. The level of emissions varies according to a number of factors, including the condition of the soil, the quality of the pasture, and the application of nitrogenous fertilisers, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this

PLATE 54 Field with a low potential for greenhouse gas emission

Field with a low potential to emit GHGs due to good pasture quality and the soil being a well-drained, coarse silty soil with good porosity. The stocking rate is moderately low, urine patches are not readily apparent and little water-soluble, salt-based nitrogenous fertilizer is applied. In addition, good pasture growth and cover removes a large amount of CO_2 from the atmosphere by photosynthesis and intercepts/absorbs a large amount of CO_2 escaping from the soil.

PLATE 55 Field with a high potential for greenhouse gas emission

Field with a high potential to emit GHGs due to poor pasture quality and the soil being an imperfectly drained, fine silty soil with poor porosity. The stocking rate is high, urine patches are strongly expressed, and high application rates of water-soluble, salt-based nitrogenous fertilizer are applied. In addition, poor pasture growth and cover removes only a small amount of CO_2 from the atmosphere by photosynthesis and intercepts/absorbs a small amount of CO_2 escaping from the soil.

by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO_2 to soil C, and by promoting the soil as a CH_4 sink. Apart from improving soil quality, the C credits gained can off-set farmer's GHG emissions.

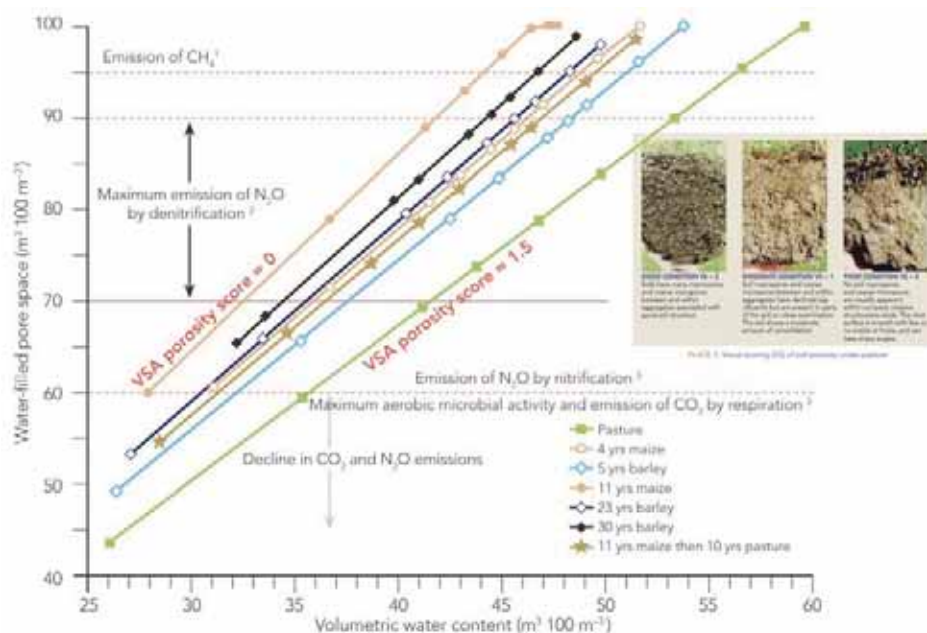
While CO_2 is a major GHG, it is reabsorbed as photosynthate by plants and can therefore be greenhouse neutral. Most atmospheric methane is also removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radical in the atmosphere. In addition, methane is inactivated by oxidation in aerated, biologically active soils (methanotrophy), and represents a globally significant sink. Nitrous oxide emissions, however, are more of an issue because their Global Warming Potential (i.e. a heat-absorbing ability) is 310 times that of CO_2 and, unlike CO_2 and CH_4 , they do not have a natural means of regulating their levels in the atmosphere. While 70 percent of the total global N_2O is produced during denitrification, denitrifying bacteria and denitrification enzymes would have to achieve complete denitrification to emit N_2 instead of N_2O as an end product. Emphasis must therefore be placed on reducing the application of nitrogenous fertilisers and the emission of N from stock, and on promoting the many alternative pathways to supply N through biological processes (pp. 12, 14 & 20–21) and from legumes such as clovers (p. 44–45).

The potential of a site to emit GHGs can be roughly estimated from four indicators of soil quality, three indicators of plant performance, and from the amount and form of nitrogen applied, as described below.

Textural groups (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major ‘driver’ of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs. Finer textured (heavier) soils also tend to be more poorly drained and therefore more likely to emit GHGs, as discussed below. Soils with a peaty ‘textural’ group are high amitters of CO_2 and CH_4 .

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O , and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 8); emissions of N_2O are lowest when the WFPS is <50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils. Soil compaction can cause a seven-fold increase in N_2O emissions.

FIGURE 8 Effect of water-filled pore space and water content on greenhouse gas emissions



¹ After MacDonald *et al.* (1996); ² After Dobbie *et al.* (1999); ³ After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 8) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O . In contrast, a severely compacted soil after 11 years of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 8) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2 . While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is hence an effective means of reducing GHG emissions. The relationship between the WFPS

and the visual assessment of the porosity of the soil, as shown in Fig. 8, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Emissions of N_2O can be 20 percent lower in a well-drained sandy loam soil than in a poorly drained silt loam soil. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink.

Pasture quality (p. 34) can provide an additional indication of the potential for GHG emissions. Poor quality pastures with high nitrate-N and crude protein levels, poor pasture composition, and low sugar (energy) levels are difficult for the microorganisms in the rumen of the animal to break down by fermentation. As a result these pastures have a low feed-conversion efficiency, producing high amounts of CO_2 and CH_4 , which the animal emits through belching and flatulence. High N and low sugar levels in the pasture also markedly increase the concentration of N excreted in the urine and dung because the rumen microbes have insufficient energy to utilize the excess N in the feed, converting 80 percent of it into ammonia instead of into milk, meat and fibre. As a consequence, the high concentration of N in the urine, often equivalent to 1 000–1 600 kg N/ha, markedly increases the amount of N_2O emitted into the atmosphere. High nitrate, crude-protein pastures also cause an overly alkaline gut that results in scouring and the production of 'liquid' dung with high concentrations of N and CH_4 that are subsequently emitted into the atmosphere. In contrast, nutrient-dense, sugar-rich, high-quality pastures containing mature proteins, high levels of soluble non-structural carbohydrates, condensed tannins and cobalt, have a high metabolisable energy and digestibility. As a consequence, they have a high feed-conversion efficiency that produces significantly less CO_2 and CH_4 in the rumen and digestive tract. They also produce less N in the urine and less N and CH_4 in the dung, and therefore emit less GHGs. Condensed tannins can reduce CH_4 emissions by 15 percent, by decreasing methanogenesis. Moreover, high quality pastures shift the production of acetates (CH_3COOH) in the rumen to propionates (volatile fatty acids – $\text{CH}_3\text{CH}_2\text{COOH}$), leading to a reduction in hydrogen and consequently in the production of CH_4 . Plants such as coriander and turmeric could reduce the amount of methane produced by bacteria in an animals stomach by up to 40 percent.

The concentration of N in the urine and GHG emissions is also reduced by ensuring the animal intake of Co in the herbage is adequate to enable the bacteria in the rumen to produce the vitamin B_{12} necessary to promote efficient digestion through good rumen function. To this end, Co levels in the herbage should be of the order of 0.1–0.15 mg/kg. Moreover, good

rumen function and therefore greater feed-conversion efficiency (to build protein) and lower GHG emissions are improved by ensuring yttrium levels are adequate in the rumen.

Pasture quality also influences the volume of feed intake and thus the amount of GHGs emitted. Good quality pastures with high energy levels, nutrient density and nutritive value have a higher palatability and digestibility and contain more useful energy per unit of dry matter than poor quality pastures. Animals therefore need to eat less to attain the number of kilojoules required for body maintenance, growth, and lactation. As a result, the amount of forage digested is less, which reduces the level of GHGs emitted. The animal produces less dung and urine and consequently there are less CH₄ emissions from the dung and N₂O from the urine. Highly digestible forage also spends less time in the rumen thereby producing fewer fermentation gases, including CH₄ and CO₂. Animals grazing a ryegrass sward produce twice the amount of CH₄ (24 g/kg dry matter intake) compared with animals grazing white clover (12.9 g/kg dry matter intake). Methane emissions can be reduced by at least 10 percent when grass forage is replaced by a mixed ryegrass/legume sward.

While forage-fed ruminants can emit significant amounts of GHGs and as a result are often used as global warming scapegoats, in reality much can be done to significantly reduce their emissions. This can be achieved by improving the quality of advice given to farmers, including addressing the factors discussed above.

Pasture growth (p. 50) can provide an indication of the potential to reduce GHG emissions. The greater the pasture growth, the greater the amount of CO₂ removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO₂ emitted by microbial respiration and the conversion of pasture into GHGs by grazing animals. As CO₂ escapes from the soil, most, if not all, is absorbed by the stomata on the leaves, which have an insatiable appetite for CO₂. The greater the pasture cover (leaf area index), the greater the amount of CO₂ removed. Furthermore, if we assume that one kilogram of carbon in the dry matter grown removes 3.67 kg CO₂ from the atmosphere, a farm growing 18 tonnes of dry matter/ha/year (or 7.4 t C/ha/yr) will remove approximately 27 tonnes of atmospheric CO₂/ha/yr. A farm growing just 15 tonnes of dry matter/ha/yr (or 6.2 t C/ha/yr) will remove approximately 23 tonnes of atmospheric CO₂/ha/yr, 15 percent less than the higher producing farm. While CO₂ is the least potent of the GHGs with a Global Warming Potential (i.e. a heat-absorbing ability) that is 21 and 310 times less than CH₄ and N₂O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO₂ into sugars and oxygen, and subsequently into soil carbon, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Pasture colour and growth relative to urine patches (p. 52) can provide a further indication of the potential for GHG emissions. First, poor growth and yellow pasture between urine patches and strong pasture growth in the urine patches indicate poor quality pasture with low sugar levels and the subsequent emission of CH₄ and excretion of N-rich urine. The N gives rise to increased emissions of N₂O by the denitrification of nitrate and nitrification of ammonium present in high concentrations in the urine patches. Second, poor growth

and yellow pasture between urine patches indicates the nitrogen and/or sulphur cycle has broken down, suggesting a decline in the uptake of N by the plant and its subsequent release to the environment.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 99) can provide another indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and in particular by denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 8). In addition to N added in the form of animal excreta, particularly as urine, the nitrification of urea and ammonium-based fertilisers, and the denitrification of high concentrations of nitrates in the soil resulting from the excessive application of other salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Increasing the application rate of urea from 80 to 190 kg N/ha, for example, can increase N_2O emissions from 1.2 to 3.6 t/ha (on a CO_2 -equivalent basis).

The excessive use of nitrogenous products can also reduce the capacity of soils to take up and oxidise atmospheric CH_4 , thereby reducing the ability of the soil to act as a methane sink. Aerobic soils can be net sinks for CH_4 due to the presence of methanotrophic bacteria that take up methane as their sole source of energy. Methanotrophs are however chemically sensitive, and their biomass and activity is reduced by nitrogenous and other soluble, salt-based inorganic fertilisers, the N inhibitor Dicyandiamide (DCD), herbicides, insecticides, acidification and excessive soil disturbance. Farming in ways that enhance rather than inhibit soil biological activity would improve the capacity of agricultural soil to act as a methane sink, helping to mitigate CH_4 emissions.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to pastures to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides microsites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root length and root density, and pasture growth, improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70 percent, they can increase NH_3 emissions and potential NH_4^+ -N leaching losses. The jury is also still out as to their long-term impact on soil biology,

in terms of microbial biomass, diversity and activity. The N inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. It can further produce phytotoxic effects and yield reductions in white clover. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures giving limited grass growth despite the application of N. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available to reduce N loss.

Stocking rate (see scorecard – p. 99) can significantly influence GHG emissions. Nitrogen deposited in the form of animal urine and dung is a principal source of N_2O production in managed grazing systems (Plate 56). More than half New Zealand's N_2O emissions originate directly from excretal N in grazed pastoral soils, while another 30 percent of emissions are from indirect emissions from leached and volatilized excretal-N. Nitrous oxide emissions from soils are caused principally by microbial nitrification and especially denitrification, processes controlled partly by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil. Animal urine contains a lot of nitrogen, with urine patches containing an equivalent of up to 1 000–1 600 kg N/ha. The amount of urine produced is roughly proportional to the animal liveweight. A 500-kg dairy cow produces 13–27 litres of urine/day, approximately seven times the amount of a 70-kg ewe, which produces 1.8–3.6 litres of urine/day (Table 10, p. 78). The actual amount of N in urine depends strongly on the amount and form of soluble, salt-based nitrogenous fertiliser applied, the amount, quality and type of feed consumed, and the efficiency of rumen function. A high stocking rate on crude protein/nitrate-rich pasture receiving high amounts of soluble salt-based fertiliser N will significantly increase N_2O emissions compared with low stocking rates.

About 96 percent of anthropogenic CH_4 (i.e. caused by humans) is emitted from ruminant animals by methanogenic fermentation in the gut. Methane is also produced by anaerobic fermentation of animal manure. Like N_2O , the greater the stocking rate on poor quality, crude protein/nitrate-rich pasture, the greater the emissions of CH_4 . Most of the methane, however, is removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radicals in the atmosphere, and by methanotrophic oxidation in aerated, biologically active soils, producing a globally significant sink.

Animal liveweight per hectare instead of stock units is used to define stocking rates because of the difficulty of accurately reporting stock units for different classes of livestock, and at different times of the year in terms of their size, feed (energy) requirements, animal performance and farming systems. The average liveweight per animal for different stock classes is given in Table 10 (p. 78) and can be quickly used to calculate stocking rate (and feed-use efficiency), regardless of the class of livestock.

PLATE 56 High stocking rate with >2 000 kg liveweight/ha



Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by Emission Trading Schemes. If the GHG Emission Index is ≤ 26 , certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of >26 provides significant environmental benefits because less GHGs would be emitted into the atmosphere. Farmer involvement is the key to reducing agricultural emissions of GHGs. The GHG Emissions Scorecard provides farmers with a simple, quick tool to help them mitigate the production of GHGs.

Off-setting GHG emissions. The sequestration over a 12 month period of 6.3 and 7.1 tonnes C/ha in the top 1 m of soil (an increase of 3.6 and 5.5 percent respectively from the previous year) on two dairy farms that recently converted from soluble, salt-based high-analysis N:P:K fertilisers to bio-friendly fertilisers, equates to the sequestration of 23 and 26 tonnes CO₂ equivalents/ha respectively. GHG emissions from dairy farms are typically of the order of 7–9 tonnes CO₂ equivalents/ha/yr, two-thirds less than the 23–26 tonnes CO₂ equivalents/ha sequestered as soil C. The soil clearly has a huge capacity to act as a C sink, mopping up most of the excess carbon being emitted into the atmosphere. Soil C sequestration can therefore more than off-set GHG emissions under appropriately managed farmland. Soil carbon sequestration by adopting carbon farming strategies, such as developing the root system, increasing earthworm numbers, and applying bio-friendly forms of fertilizer, is consequently a cost-effective strategy to mitigate GHG emissions.

Enhanced feed nutrition and sequestration of atmospheric CO₂ in the soil, ultimately as stable humus, may well provide a more lasting solution than temporarily sequestering CO₂ in the standing biomass through re- and afforestation. Improved feed nutrition and microbially active soils will also help reverse the processes of land degradation and thus contribute to higher soil fertility, greater biodiversity, aeration, infiltration and water-holding capacity, less droughtiness and dependence on supplements in protracted dry periods, and sustainable food productivity and quality.

FIGURE 9 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner: _____ **Land use:** _____ **Site:** _____
Soil type: _____ **Drainage class:** _____ **Date:** _____
Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Peaty

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	. 2	x 2	
Soil porosity	. 6	x 3	
Number and colour of soil mottles	.	x 3	
Soil colour	. 10	x 1	
Pasture quality	. 34	x 2	
Pasture growth	. 50	x 2	
Pasture colour and growth relative to urine patches	. 52	x 2	
Amount and form of N applied (Scoring protocol is given below ²)	. 6	x 2	
Stocking rate (Scoring protocol is given below ³)	. 9	x 2	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 14
Moderate potential GHG emissions	14–26
Low potential for GHG emissions	> 26

1 Textural group (Figure 2b, p. 3):

VS = 2 for Sandy and Coarse loamy; VS = 1.5 for Coarse silty; VS = 1.0 for Fine loamy; VS = 0.5 for Fine silty; VS = 0 for Clayey and Peaty. Strictly speaking, peaty soils cannot be defined as a textural group; however, they are closely aligned to, and have a huge effect on, soil texture.

2 Amount and form of N applied:

VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 30 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 60–90 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 120 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 Stocking rate – kg liveweight (Lwt) per ha

VS = 2 if the Lwt is ≤ 1000 kg (≤ 2 cows*)/ha; VS = 1.5 if the Lwt is 1250 kg (2.5 cows)/ha; VS = 1 if the Lwt is 1500 kg (3 cows)/ha; VS = 0.5 if the Lwt is 1750 kg (3.5 cows)/ha; VS = 0 if the Lwt is ≥ 2000 kg (≥ 4 cows)/ha. [* assuming a cow of 500 kg liveweight]

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Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for Pasture*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 1

Maize



Maize

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List of acronyms

AEC	Adenylate energy charge	Mn²⁺	Manganous ions
Al	Aluminium	Mo	Molybdenum
ASC	Anion storage capacity	N	Nitrogen
ATP	Adenosine triphosphate	N₂	Nitrogen gas
B	Boron	NO₃⁻	Nitrate
C	Carbon	NO₃⁻-N	Nitrate-nitrogen
Ca	Calcium	NO₂⁻	Nitrite
Ca²⁺	Calcium cation	N₂O	Nitrous oxide
CEC	Cation exchange capacity	Na	Sodium
CH₄	Methane	Na⁺	Sodium cation
CO₂	Carbon dioxide	NH₃	Ammonia
qCO₂	Metabolic quotient	NH₄⁺	Ammonium
Co	Cobalt	O₂	Oxygen
Cu	Copper	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂S	Hydrogen sulphide	SO₄²⁻	Sulphate
K	Potassium	SO₃²⁻	Sulphide
K⁺	Potassium cation	VS	Visual score
Mg	Magnesium	VSA	Visual Soil Assessment
Mg²⁺	Magnesium cation	WFPS	Water-filled pore space
Mn	Manganese	Zn	Zinc
Mn³⁺	Manganic ions	ZnS	Zinc sulphide

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of maize cropping. A decline in soil quality has a marked impact on yield and quality of maize for grain and silage, production costs, the risk of soil erosion, nutrient loss into the groundwater and waterways, carbon sequestration and green-house gas emissions. It can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Soil physical properties control the movement of water and air into and through the soil, the ease with which roots penetrate the soil, the number, type and activity of soil organisms, and the availability and uptake of soil nutrients. Damage to the soil can change these properties and reduce plant growth, food quality and environmental outcomes, regardless of nutrient status. Safeguarding soil resources for future generations and minimizing the ecological footprint of maize cropping is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil, crops and food quality;
- ❖ the effect of land management decisions on soil quality, plant performance and environmental outcomes.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance of maize cropping and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for growing crops, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for maize. Scoring is out of 54: the higher the score, the better the condition of the soil and the performance of the plant. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

In addition, the VSA provides a quick, low cost method for estimating the potential for nutrient loss into the groundwater and waterways, C sequestration, and the emission of greenhouse gases.

The VSA method

While the name Visual Soil Assessment implies a focus on the soil, the method is equally about assessing both the soil and the plant. Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a score card. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require

knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant score card. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. they are capable of changing under different management regimes and land use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the 'soil' and 'plant' scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate, or poor condition.

Placing the soil and plant scores side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ✦ **A SPADE** (flat-faced) – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ✦ **A PLASTIC BASIN** (about 450 x 350 x 250 mm) – to contain the soil during the drop shatter test;
- ✦ **A HARD SQUARE BOARD** (about 260 x 260 x 20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ✦ **A HEAVY-DUTY PLASTIC BAG** (about 750 x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;

PLATE 1 The VSA tool kit



- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the sampling depth, topsoil depth, potential rooting depth, crop height, and the length of ears;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the visual score (VS) for each indicator.

The procedure

When should it be carried out?

The test should be carried out when the soils are moist and suitable for grazing. If you are not sure, apply the ‘worm test’ (p. 63). For **silty soils**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to test. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to test.

Setting up

Time

Allow 40 minutes per site. For a representative assessment of soil quality, sample four sites over a 5 hectare area.

Reference sample

Take a small sample of soil (about 100 x 50 x 150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in maize fields is site specific. Avoid areas that have had heavier traffic than the rest of the field and sample between wheel traffic lanes. VSA can also be used however, to assess the effects of high traffic on soil quality by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicators score card.

Carrying out the test

Initial observation

Dig a small hole about 200 x 200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200 mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If, for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two 200 x 200 x 100 mm samples with a spade. If the 100–200 mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two 200 x 200 x 100 mm samples. Note that taking a 200 mm cube immediately below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and crop management.

The drop shatter test

Drop the test sample a maximum of three times onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, depends on the texture of the soil, and the degree to which the soil breaks up, as described on pp. 2–4.

Systematically work through the score card, assigning a visual score (VS) to each indicator by comparing it to the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS ranking in the right-hand column of the scorecard.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

“Despite mankind’s lofty aspirations and many notable achievements, our survival depends on a six-inch layer of topsoil and the fact that it rains”

anonymous

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in maize

Landowner:

Land use:

Site location:

GPS ref:

Sample depth:

Topsoil depth:

Soil type:

Soil classification:

Drainage class:

Date:

Textual group: (upper 1 m) Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Moisture condition: Dry Slightly moist Moist Very moist Wet

Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Number and colour of soil mottles pg. 8		x 2	
Soil colour pg. 10		x 2	
Earthworms (Number =) (Av. size =) pg. 14		x 3	
Soil smell pg. 18		x 2	
Potential rooting depth (m) pg. 22		x 3	
Surface ponding pg. 26		x 3	
Surface cover and surface crusting pg. 30		x 2	
Soil erosion (wind/water) pg. 32		x 1	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 20
Moderate	20–37
Good	> 37



Assessment

- ❶ Take a sample of soil half the size of your thumb from the topsoil to assess the *soil texture*. Take also a sample/s that is/are representative of the subsoil to assess the overall *textural group* of the soil profile.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball and then squeezing it between the thumb and forefinger. With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the *textural class* obtained by reference to the textural diagram (Figure 2a). The *textural group* is obtained by comparing the position of the textural class in Figure 2a with Figure 2b (e.g., silt loam = fine silty).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For instance, if the soil has a reasonably high content of organic matter, i.e. is humic with 17–29 percent organic matter, raise the textural score by one (e.g., from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.



Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt, and clay. Sand is that fraction that has a particle size ≥ 0.06 mm; silt varies between 0.06 and 0.002 mm, while the particle size of clay is < 0.002 mm.

Texture influences soil behaviour in several ways, notably through its effect on water retention and availability, soil structure, aeration, drainage, soil workability and trafficability, soil life, and the supply and retention of nutrients. A knowledge of both the textural class and potential rooting depth (p. 22) enables an approximate assessment of the total water holding capacity of the soil, one of the major drivers of crop yield.

FIGURE 2 Soil texture classes and groups

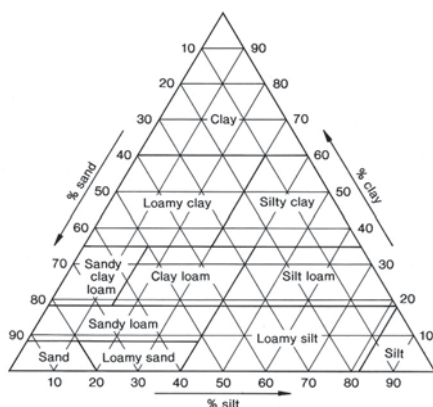


Figure 2a
Textural classes.

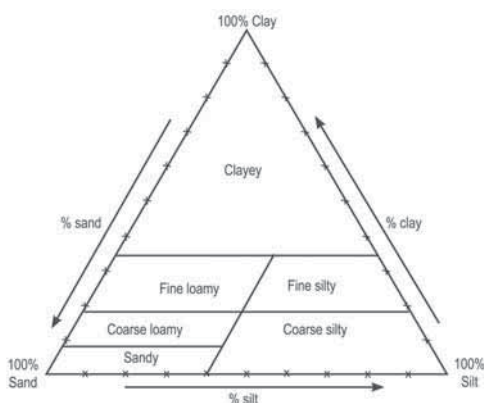


Figure 2b
Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
1 [Moderate]	Loamy silt	Smooth feel, non sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
0.5 [Moderately poor]	Silty clay & Clay	Very smooth, very sticky, very plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
0 [Poor]	Loamy sand	Gritty and rasping sound. Will almost mould into a ball but disintegrates when squeezed between thumb and forefinger.
	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
 - ❷ Drop the soil sample a maximum of three times from a height of one metre onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Don't drop any piece of soil more than three times. For soils with a sandy loam texture (p. 3), drop the cube of soil once only from a height of 0.5 metres. If the sandy loam is humic (17–29 percent organic matter), drop the soil twice from 1 metre. Transfer the soil onto the large plastic bag.
 - ❸ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade once from a height of just 50 mm and then roll the spade over spilling the soil onto the plastic bag.
 - ❹ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures if present. If the clod cannot be easily parted, do not apply further pressure because the cracks and fissures are probably not continuous and therefore unable to readily conduct oxygen, air and water.
 - ❺ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs and criteria given in Plate 2.
- The method is valid over a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for grain maize crops. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum till, controlled traffic or conventional cultivation under optimum soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, sub-angular and sub-rounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or sub-angular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 Visual scoring (VS) of soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally sub-rounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50 percent) of both coarse clods and friable fine aggregates. The coarse clods are firm, sub-angular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or sub-angular in shape and have very few or no pores.

Assessment

- ❶ Remove a spade slice of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and break in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs and criteria in Plate 3. Look for the spaces, gaps, holes, cracks, fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).

Importance

SOIL POROSITY is important to assess along with soil structure. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores or coarse micropores within the large clods, thus restricting their drainage and aeration.

Poor aeration leads to the build up of methane, sulphide gases and alcohol, and reduces the ability of plants to take up water and nutrients, particularly nitrogen, phosphorus, potassium, sulphur, zinc, copper and cobalt. Poorly aerated and compacted soils reduce plant-available N in the form of nitrate-nitrogen (NO_3^- -N) and ammonium (NH_4^+) to nitrite (NO_2^-), nitrogen (N_2) gas and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available sulphate-sulphur (SO_4^{2-} -S) is also reduced to sulphite (SO_3^{2-}) and sulphides, rendering N and S unavailable to the plant. Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilise the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, but greatly reduces fertiliser efficiency and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce less greenhouse gases. The greater the porosity the better the drainage and therefore the soil pores will be less likely to be water-filled to the critical levels required to accelerate the production of greenhouse gases (see p. 82–83). Aim to keep the porosity score above 1.

PLATE 3 Visual scoring (VS) of soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present in parts of the soil on close examination. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few cracks or holes, and can have sharp angles.

Assessment

- Assess the number, size and colour of soil mottles by taking a sample of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and comparing it with the three photographs and criteria in Plate 4. The percentage chart below will help you determine the percentage of the soil occupied by mottles.

Mottles are patches of different colour interspersed within the dominant (background) soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also early warnings of a decline in soil structure as a result of compaction under wheel traffic and over-cultivation. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces iron (Fe) and manganese (Mn) from their *brown/orange* oxidised ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey due to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey mottles predominate. The abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicate the soil is moderately well drained, and no mottles indicate good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S, Zn, Cu and Co (p. 6). While Olsen P levels of 22 mg/L are generally adequate for optimum crop production on most soils in good condition, degraded, poorly aerated soils with relatively high Olsen P levels (40–50 mg/L) can show a positive crop response to applied P. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, which are toxic to plant roots. In addition, decay and die-back of roots can occur as a result of fungal diseases such as *Rhizoctonia*, *Pythium* and *Fusarium* root rot,

foot rot, and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for the number and colour of soil mottles is one or less, you need to aerate the soil.

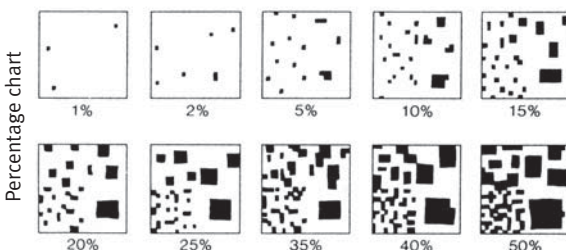


PLATE 4 Visual scoring (VS) of the number and colour of soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has many (10–20 percent) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has profuse (> 50 percent) medium and coarse orange and particularly grey mottles.

Assessment

- 1 Compare the moist colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area (Plate 5). If the soil is dry, pour water over the surface of the sample.
- 2 Using the three photographs and criteria given in Plate 6, compare the *relative change* in soil colour that has occurred. As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.

Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not so easily and accurately assessed; in general, the darker the colour, the greater the amount of organic matter and humus in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, collectively determining soil health. It promotes infiltration, the movement and retention of water, helps develop and stabilise soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and indicates whether

PLATE 5 Soil colour under the fenceline



Soil colour under the fenceline on the left compared with that in the field on the right. The comparative difference in soil structure and porosity is also a useful observation to make.

PLATE 6 Visual scoring (VS) of soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is similar to, or darker than that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with under the fenceline.

the soil is functioning as a carbon 'sink' or as a source of greenhouse gases. Organic matter acts as a major reservoir of organic carbon in the soil, carbon that is sequestered by microorganisms and from CO₂ in the atmosphere by plants. Organic matter also provides an important food resource for soil organisms and is an important source and major reservoir of plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; nitrogen, phosphorus, potassium and sulphur requirements of crops increase markedly, and other major and minor elements are more readily leached. The result is an increased dependency on fertiliser input to maintain nutrient status.

Soil colour (compared with that under the fenceline) can be a useful indicator of whether soils on a farm or in a field are becoming darker due to gaining (sequestering) carbon. If the soil is paler, it could possibly be losing carbon, i.e. becoming C negative. If there is no colour difference, the soil carbon regime may be in a steady (C neutral) state, i.e. neither losing nor gaining carbon. Soil colour, along with soil texture, clay mineralogy, earthworm numbers, root development, potential rooting depth, the amount and form of fertiliser applied, and the method of cultivation can collectively provide a good indication as to whether a particular management practice or landuse is carbon positive, neutral or negative. A farm that has similar or darker coloured topsoils in the field relative to the fenceline, with fine silty or clayey textures, good earthworm numbers, root development, potential rooting depth, crop yields, and is applying no-till technology and carbon-friendly forms of fertiliser and nitrogen will sequester significant amounts of carbon (see carbon sequestration, pp. 72–79). Farms will therefore be C positive and in a position to potentially gain 'Carbon Credits' rather than possibly pay a carbon tax.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is markedly influenced by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidised form of ferric (Fe³⁺) and manganic (Mn³⁺) oxides. Grey or grey-blue colours can indicate the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe²⁺) and manganous (Mn²⁺) oxides. Ferrous and manganous oxides are more soluble than their oxidised forms and are therefore more readily taken up by the plant. High levels of soluble Fe and Mn in the soil can however suppress the availability and uptake of other elements.

In addition to the production of toxic levels of Fe²⁺ and Mn²⁺ ions, poor aeration and waterlogging, gives rise to a further series of chemical and biochemical reduction reactions that produce toxins such as hydrogen sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde that damage the root system. This, and the effect of waterlogging, reduces the ability of plants to take up water and nutrients (particularly

N, P, K, S, Zn, Cu and Co), causing poor crop growth and vigour. Decay and die-back of roots can also occur as a result of pests and diseases including *Rhizoctonia*, *Pythium* and *Fusarium* root rot in soils prone to waterlogging. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, crops typically struggle to take up nutrients such as Na that are necessary to make carbohydrates, and K required for complete kernel filling.

What is more, soil colour can indicate the potential of a soil to convert plant-available forms of nutrients into unavailable forms. Soils that are distinctly grey in colour due to being anaerobic and waterlogged reduce plant-available N in the form of nitrate (NO_3^-) and ammonium (NH_4^+) to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available S in the form of sulphate-sulphur (SO_4^{2-} -S) is reduced to plant unavailable sulphite (SO_3^{2-}) and sulphides. Sulphur and nitrogen can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Plants also need S in the sulphate form to utilise N.

Dark coloured soils further suggest that the microbial biomass is predominantly aerobic enabling the efficient decomposition of organic matter to humus and the retention, immobilisation and release of soil nutrients.

Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 2, p. 5 & Plate 7). Note also the number of species present (Plates 8–10) and compare with the criteria given in Table 2. Earthworms vary in size and number depending on the species, maturity, and the season. For year-to-year comparisons, therefore, earthworm counts must be made at the same time of year (preferably late winter to early spring), and when soil moisture and temperature levels are good; avoid dry conditions. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. As a 200-mm cube sample is equivalent to 1/25 square metre, the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.

Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digesting, and casting, earthworms have a major effect on the chemical, physical, and biological properties of the soil; they shred and decompose plant residue converting it to organic matter and releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo,

and have a higher pH, organic matter, and water content. In addition, dead earthworms can contribute significant amounts of N to the soil, being 60–70 percent protein (dry weight) with a N content of 12 percent. Thirty-five earthworms per 200-mm cube of soil (875/m²) are roughly equivalent to a biomass of 3 tonnes of earthworm/ha, and could release 32–38 kg N/ha upon their death. Earthworms also act as biological aerators and physical conditioners of the soil, improving soil porosity, aeration, soil structure, soil aggregate stability, water retention, water infiltration, and drainage, and reducing surface runoff and erosion.

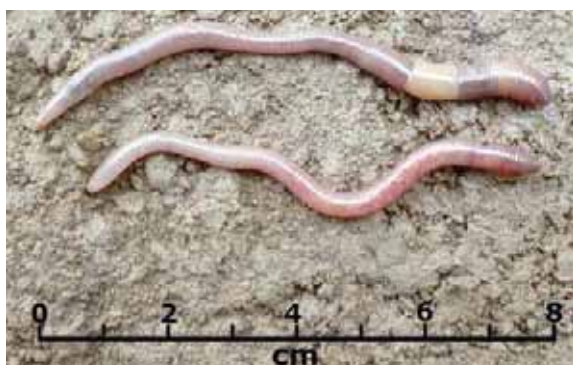
PLATE 7 Sample for assessing earthworms



Photo shows earthworms present in a 200-mm cube sample of soil.

PLATE 8 *Lumbricus rubellus*

A very active surface litter and dung feeding earthworm; commonly red-brown or red-purple in colour with a paler underside; has a distinctly flattened tail; commonly 25–220 mm long.

PLATE 9 *Aporectodea caliginosa*

A medium-sized (40–90 mm) topsoil dwelling earthworm; commonly grey-pink on both the dorsal and ventral surfaces; does not have a flattened tail.

PLATE 10 *Aporectodea longa*

A long (90–180 mm) deep burrowing earthworm; commonly dark grey-brown with a black head; tail end is paler and slightly flattened. Underside is paler than the dorsal surface.

TABLE 2 Visual scores (VS) for earthworms

Visual score (VS)	Earthworm numbers (per 200 mm cube of soil)
2 [Good]	35 (with preferably 3 or more species)
1.5 [Moderately good]	29–35
1 [Moderate]	22–28 (with preferably 2 or more species)
0.5 [Moderately poor]	15–21
0 [Poor]	< 15 (with predominantly 1 species)

They promote plant growth by secreting plant-growth hormones and increasing root development and root density through the rapid growth of roots down nutrient enriched worm channels. While earthworms can deposit around 25–30 tonnes of casts/ha/yr on the surface (Plate 11), 70 percent of their casts are deposited below the surface of the soil. Earthworms therefore play an important role in arable cropping and can increase growth rates, crop yields and protein levels significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in the supply of nutrients, digesting soil and fertiliser and unlocking nutrients such as P that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant growth hormones and compounds that stimulate root growth, and promote the structure, aeration, infiltration, and water-holding capacity of the soil. Microorganisms further encourage a lower incidence of pests and diseases, and promote a more rapid breakdown of organic herbicides. The collective benefits of microbes can increase crop production markedly while at the same time reducing fertiliser requirements.

Earthworms can increase the depth of topsoil and the carbon content of both topsoil and subsoil by their burrowing, digesting, reworking, and mixing of soil and plant residues (bioturbation), and by the deposition of worm casts. High numbers of earthworms ingest considerable amounts of soil and plant material, building up soil C levels by converting C to more stable organic compounds bonded to clay particles. Organic matter gradually works down to the subsoil and so increases the depth of topsoil. The burrowing, casting, and

incorporation of organic matter into the soil contributes to increasing topsoil depth by decreasing soil density and increasing the porosity, and therefore the volume of soil. Given that 30 percent of worm casts are deposited on the surface and 70 percent below ground, the potential for earthworms to increase soil carbon levels and topsoil depth is substantial.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the crops grown, the amount and quality of surface residues, the use of cover crops and the method of tillage. Earthworm populations can be up to three times higher under no-tillage than conventional cultivation. Earthworm numbers are also governed by soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertiliser and nitrogen used. The over-use of acidifying salt-based fertilisers, anhydrous ammonia, and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown and decompose plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest, and mix the top 200–300 mm of soil; and (iii) deep burrowing species that pull down and mix plant litter and organic matter at depth. Earthworm species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 12) can indicate adverse soil conditions.

PLATE 11 Earthworm casts under crop residue



PLATE 12 Yellow-tail earthworm (*Octolasion cyaneum*)



Assessment

- 1 Remove a spade slice of soil (approximately 100 mm wide × 100 mm long × 100 mm deep) and break in half. Place the exposed face of the soil close to your nose, take three deep sniffs, and compare with the criteria given in Table 3. Soil smell can be assessed on the same sample used to assess soil porosity. The test is best carried out when the soil is moist, including during or immediately after the wet months of the year.

Importance

SOIL SMELL, while very dependent on the water content and aeration status of the soil, is also a good indicator of the amount and the activity of soil life and therefore soil health. Soil smell is determined principally by the gases given off by the aerobic or anaerobic respiration of soil microbes, and by the type and amount of organic matter and humus present in the soil. Aerobic respiration by soil fungi, bacteria, yeast, protozoa (i.e. single cell animals), nematodes, arthropods (mites, beetles, millipedes, etc.), and earthworms produce distinctive odours. The degree and nature of the odours are determined by the composition and activity of the soil biology which in turn is governed in part by the available food supply in the form of organic matter and humus. Soils rich in fungi, for example, produce aromatic compounds and organic acids that give an earthy, rich, sweet, fresh or sometimes musty smell (Plate 14). These are often the characteristic smells of forest soils, which are generally rich in fungi. The presence of similar fungal smells in a cropping soil suggests it is not only well aerated but also has a good, active microbial biomass with a fungal to bacteria ratio of 3:1. Such a ratio is necessary to preserve and promote a good biological environment for crops. Intensively cropped and fertilised soils have a greater abundance of bacteria relative to fungi than soils that are less intensively cropped and fertilised. As a consequence, they are more sensitive to plant stress, are less efficient in terms of uptake, cycling and retention of nutrients including N, and are more susceptible to N leaching. An imbalance of the ratio of fungi to bacteria, along with poor soil nutrition could explain why crops may show consistently poor growth and vigour.

TABLE 3 **How to assess soil smell**

Visual score (VS)	Soil smell
2 [Good]	Soil has a distinct rich, earthy, sweet, wholesome or fresh smell.
1 [Moderate]	Soil has a slight earthy, sweet odour or a “mineral” smell.
0 [Poor]	Soil has a putrid, sour, chemical or unpleasant smell.

Biological regimes are very sensitive to intensive conventional cultivation practices with the result that well aerated soils can have very little or no soil smell. Anaerobic respiration of micro-organisms (including anaerobic bacteria and yeast) in saturated, poorly aerated soils produce methane and nitrous oxide (greenhouse gases), alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, and putrid sulphide gases including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS), all of which inhibit root growth when accumulated in the soil (Plate 15). Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root /shoot growth.

PLATE 13 Sample to assess soil smell



While soils should have good microbial biomass with levels preferably in excess of 1 600 mg/kg, to be beneficial, soil microbes also need to be active. The level of activity and therefore functionality of the microbial biomass is something that must always be kept in mind when assessing the status of the soil biological community. The activity and energy status of soil microbes can be assessed by measuring the level of their respiration relative to their biomass (i.e. the respiration to biomass ratio or the metabolic quotient qCO_2), and their AEC, which should be 0.8. Microbial viability is maintained at AEC values between 0.8 and 0.5 – the cells die at values below 0.5.

Soil microbes, including actinomycetes and mycorrhizal fungi, play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important organic compound that comprises up to 30 percent of the humus fraction in soils. Soil organisms also play a key role in the promotion and maintenance of soil fertility through nutrient and carbon cycling, and their role in the N and S cycle. Microbes immobilise and retain significant amounts of nutrients in the humus they produce and in their biomass, releasing them when they die. Moreover, soil microbes, including mycorrhizal fungi, play a major role in the supply of plant-available nutrients, digesting soil and fertiliser, and unlocking nutrients such as phosphorus that are fixed by the soil.

Where legumes are cropped, soil microbes and particularly bacteria also play a major role in the fixation and supply of nitrogen. *Rhizobium* bacteria in clover nodules fix N directly from the atmosphere. The ammonia produced by N-fixation is taken up by the plant to produce protein and organic N compounds that are then mineralised by a further range of bacteria and fungi, releasing N in the form of plant available ammonium (NH_4^+) when the plant dies. Under aerobic conditions, the ammonium is converted by nitrosomonas and nitrobacter bacteria to nitrate (NO_3^-), another plant available form of N (a process known as nitrification). Free-living aerobic *Azotobacter* bacteria and anaerobic (*Clostridium*) bacteria in the soil further promote the fixation and supply of plant available N.

In addition, bacterial- and fungal-feeding protozoa and nematodes release large amounts of N when feeding on their selected prey and are responsible for a large amount of plant-available N. The predator-prey interaction of protozoa on bacteria releases 5 units of plant-available N in the form of ammonium for every six bacteria consumed. The feeding of nematodes on bacteria releases 19 units of N for every 20 bacteria consumed. Given that bacterial numbers should be greater than one million per gram for all agricultural soils, and nearer 100 million per gram for productive soils, the potential storage and release of N from bacteria is considerable. Between 40 and 80 percent of the N in plants can come from the predator-prey interaction of protozoa with bacteria.

In addition to adding organic matter to the soil, soil organisms play a key role in soil formation by developing and promoting the structure, aggregate stability, porosity, aeration, infiltration and water-holding capacity of the soil, and reduce waterlogging and runoff from the topsoil. Soil microbes also play an important role in purifying water and filter, buffer, degrade, immobilise, and detoxify organic and inorganic pollutants. Moreover,

PLATE 14 Sample of a moderately good soil smell



Soil has a moderately rich, earthy, sweet smell with a smell score of 1.5.

PLATE 15 Sample of a poor soil smell



Soil has a putrid, unpleasant smell of hydrogen sulphide with a smell score of 0.

they suppress pests and diseases, producing compounds that inhibit the growth of, or are toxic to pathogens, reducing the invasion of the plant by a pathogen. Soil microbes further produce plant growth hormones and compounds that stimulate root growth and produce B group vitamins including vitamin B₁₂.

The collective benefits of microbes reduce fertiliser requirements and can give significant increases in crop yield. They can also significantly improve the nutrient density and health of the plant. Soil life can therefore be effectively described as the 'engine room' of the farm. The trick to smart and sustainable cropping is to ensure the engine remains well-oiled.



Assessment

- 1 Assess the potential rooting depth by digging a hole to identify the depth to a limiting (restricting) layer if present (Plate 16), and compare with the class limits in the Table 4. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks, and fissures down which roots can extend. Note also whether there is an overthickening of roots (a result of a high penetration resistance), and whether the roots are forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed due to prolonged waterlogging, and whether there is a hard pan present such as a strongly developed human-induced tillage or plough pan (pp. 24–25), or a strongly developed natural pan such as an iron, silica or calcitic pan. An abrupt transition from a fine textured material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.



Importance

POTENTIAL ROOTING DEPTH is the depth of soil plant roots can potentially exploit before reaching a barrier to root growth, and indicates the ability of the soil to provide a suitable rooting medium for plants. The greater the rooting depth, the greater is the available water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated crops. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the crop. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertiliser efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hard pans impede the movement of air, oxygen and water through the soil profile, the latter increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions.

Crops with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce, promotes soil structure, porosity, water storage, soil aeration, and drainage at depth. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be taken up, so reducing losses by leaching into the environment.

PLATE 16 Potential rooting depth



Hole dug to assess the potential rooting depth. The potential rooting depth extends to the base of the arrow at 350 mm below which the soil is extremely firm and very tight with no roots or old root channels, no worm channels, and no cracks and fissures down which roots can extend. Note the root mat at the bottom of the arrow. Compare the potential rooting depth of this soil with that in Plate 53, p.91

TABLE 4 Visual scoring (VS) of potential rooting depth

VSA score (VS)	Potential rooting depth (mm)
2.0 [Good]	800
1.5 [Moderately good]	600–800
1.0 [Moderate]	400–600
0.5 [Moderately poor]	200–400
0 [Poor]	< 200

Identifying the presence of a hardpan

Assessment

- 1 Examine for the presence of a hard pan such as a strongly developed tillage or plough pan by rapidly jabbing the side of the soil profile (dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically to the bottom of the hole (Plate 17). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (see photos below).
- 2 Having identified the possible presence of a tillage or plough pan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the pan is. A strongly developed pan is very tight and extremely firm and has a high penetration resistance to the knife. Confirm also its presence or absence by removing a large, hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (by referring back to pp. 4, 6 and 8). In addition, look for the presence or absence of roots. Compare with the photos and criteria given in Plate 18. Only a strongly developed hardpan will restrict all root development and its presence will determine the potential rooting depth.

PLATE 17 Identifying the presence or absence of a hardpan with a knife



PLATE 18 Visual assessment of a hard pan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).

Assessment

- 1 Assess the degree of surface ponding based on your observation or general recollection of the time ponded water takes to disappear after a wet period, particularly during early growth, and compare with the photographs and criteria given in Plate 19.

Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the infiltration rate into and through the soil, a high water table, and the time the soil remains saturated. Roots need oxygen for respiration, and prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress and restrict root respiration and growth. Roots are most vulnerable to surface ponding and saturated soil conditions in the spring when respiration and transpiration rates rise markedly, oxygen demands are high, and plant roots and shoots are actively growing. Such waterlogging causes the death of the fine roots responsible for nutrient and water uptake. Roots are also susceptible to ponding in the summer when transpiration rates are highest – reduced water uptake while the crop is actively transpiring causes leaf desiccation and the wilting of plants.

Prolonged waterlogging increases the likelihood of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Plant stress induced by poor aeration and prolonged soil saturation can render crops less resistant to attack from such insect pests as aphids, armyworm, cutworm, and wireworm. Crops decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, become discoloured, and die.

Waterlogging and deoxygenation also result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are either toxic to roots or are in a form that is unable to be taken up by the plant, e.g.:

- ✦ iron is reduced to soluble ferrous (Fe^{2+}) ions and Mn to manganous (Mn^{2+}) ions;
- ✦ plant-available nitrate-nitrogen (NO_3^- -N) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas;
- ✦ plant-available sulphate-sulphur (SO_4^{2-} -S) is reduced to unavailable sulphite (SO_3^{2-}) and sulphides, including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS).

Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form.

PLATE 19 Visual scoring (VS) of surface ponding

**GOOD CONDITION VS = 2**

No surface ponding of water evident after 1 day following heavy rainfall on soils that were at or near saturation¹.

**MODERATE CONDITION VS = 1**

Moderate surface ponding occurs for 2 days after heavy rainfall on soils that were at or near saturation.

**POOR CONDITION VS = 0**

Significant surface ponding occurs for 4 or more days after heavy rainfall on soils that were at or near saturation.

¹ Assuming little or no air is trapped in the soil at the time of ponding.

PLATE 20 Sample of prolonged waterlogging



Prolonged waterlogging can severely damage a crop in the early stages of growth.

In addition to N and S, waterlogging and poor aeration reduces the availability and uptake of P, K, Zn, Cu, and Co. This is partly because prolonged ponding of water kills off mycorrhizal fungi, soil organisms that facilitate the efficient uptake and utilisation of soil nutrients. While Olsen P levels of 22 mg/L are generally adequate for optimum crop production on most soils in good condition, degraded, poorly aerated soils with relatively high Olsen P levels (40–50 mg/L) can show a positive crop response to applied P. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots.

Anaerobic respiration of micro-organisms in waterlogged and poorly aerated soils produces methane (greenhouse gases), hydrogen gas, alcohol (ethanol and ethylene), acetaldehyde, and formaldehyde, all of which inhibit root growth when accumulated in the soil. As a result, crops often show poor vigour and ill-thrift. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The by-products of anaerobic respiration and the lack of oxygen in poorly aerated and waterlogged soils also prevent the decay of organic material in the soil. As the soil becomes progressively degraded, the amount of CO₂ increases relative to O₂ and reaches a point where plant residues and kernels cannot decay; instead they begin to ferment, producing alcohol, formaldehydes and methane, which make proper decay and the turnover of organic matter impossible.

Prolonged surface ponding makes the soil more susceptible to damage under wheel traffic, which reduces trafficability and vehicle access. Waterlogging can expose soils to severe wheel rutting and soil structural damage during pre-plant and side-dressing of fertiliser. It can also cause structural damage at sowing and harvesting, and result in significant delays to the timing of these activities. In addition, surface ponding reduces the workability of the soil, decreasing the number of spring-field work-days when the soil is suitable for cultivation. As a consequence, waterlogging can delay ground preparation. Sowing can be further delayed because the seedbed is below the crop-specific critical temperature. Increases in the temperature of saturated soils can be delayed as long as water is evaporating.

Waterlogged topsoils on sloping ground are also prone to erosion by sheetwash and rilling. Soils susceptible to surface ponding therefore need to be carefully managed to minimise the effects of such ponding on soil, crop yield and quality, and the environment.

The tolerance of the root system to surface ponding and waterlogging depends on a number of factors, including the time of year and the cultivar. Tolerance of waterlogging also depends on soil and air temperatures, soil type and condition, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate.

Assessment

- 1 Observe the degree of surface cover and surface crusting and compare with the photographs and criteria given in Plate 21. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.

Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. It also reduces aeration, causing anaerobic conditions by creating a barrier to gas exchange. Crusting cuts off oxygen to soil organisms and prevents the release of CO₂ from the soil to the plant canopy, thus reducing the uptake of photosynthetic CO₂ by the stomata on the crop leaf. The reduced availability of both water and CO₂ significantly limits crop yield. Crusting also prolongs water retention near the surface, which can hamper access by machinery for months. In addition, crusting can inhibit or deform cotyledon emergence. Crusting is most pronounced in fine-textured, poorly structured soils with low organic matter, low aggregate stability, high levels of Na and/or Mg and a dispersive clay mineralogy.

SURFACE COVER after harvesting and before canopy closure of the next crop helps prevent crusting by minimising the dispersion of the soil surface by rain or irrigation. It also helps reduce crusting by intercepting the large rain droplets before they strike and compact the soil surface. In addition, vegetative cover and its root system, together with surface residue, return organic matter to the soil and promote soil life. Earthworm and microbial biomass are strongly correlated to the amount of surface residue present: the greater the surface residue, the greater the biomass of earthworms and soil microbes. Earthworm biomass can be 80 percent of the weight of surface residue. The physical action of the roots and soil fauna, and the glues they produce, promote the development of soil structure, aeration and drainage, and help break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, which decrease runoff, soil erosion and the risk of flash flooding. The root system also reduces soil erosion by stabilising the soil surface, holding the soil in place during heavy rainfall events. Surface cover reduces soil erosion by intercepting high impact raindrops, thus minimising rain-splash and saltation, and serves as a sponge, retaining rainwater long enough for it to infiltrate the soil. Water storage for plant use thus increases, and water quality downstream is improved through lower sediment loading, and nutrient and coliform content.

The adoption of conservation tillage practices with good surface cover can reduce soil erosion by up to 90 percent and water runoff by up to 40 percent. The surface needs to have at least 70 percent cover to give good protection while \leq 30 percent cover provides poor protection. In addition, surface cover markedly reduces the risk of wind erosion by protecting the soil surface. The practice of 'pasture cropping' where annual crops are direct-drilled into perennial pastures was developed in part to utilise the benefits of maintaining a good surface cover.

PLATE 21 Visual scoring (VS) of surface cover and surface crusting



GOOD CONDITION VS = 2
 Surface cover is ≥ 70 percent with little or no surface crusting.

MODERATE CONDITION VS = 1
 Surface cover is ≥ 30 percent and < 70 percent.
 Surface crusting is 2–3 mm thick and is broken by significant cracking.

POOR CONDITION VS = 0
 Surface cover is ≤ 30 percent.
 Surface crusting is ≥ 5 mm thick and is virtually continuous with little cracking.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and on your knowledge of what the site looked like in the past relative to the three photographs and criteria given Plate 22.



Importance

SOIL EROSION reduces the productive potential of soils through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Over-cultivation can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be water eroded by gullying, rilling and sheet wash. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability of water through the soil;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of over-cultivation can also give rise to significant soil loss by wind erosion of exposed ground.

PLATE 22 Visual scoring (VS) of soil erosion

**GOOD CONDITION VS = 2**

Little or no *water erosion*. Topsoil depths in the footslope areas are < 150 mm deeper than on crest.

Wind erosion is not a concern; only small dust plumes emanate from the cultivator on a windy day. Most wind-eroded material is contained in the field.

**MODERATE CONDITION VS = 1**

Water erosion is a moderate concern with a significant amount of rilling and sheet erosion. Topsoil depths in the footslope areas are 150–300 mm greater than on crests, and sediment input into drains/streams may be significant.

Wind erosion is of moderate concern where significant dust plumes can emanate from the cultivator on windy days. A considerable amount of material is blown off the field but is contained within the farm.

**POOR CONDITION VS = 0**

Water erosion is a major concern with severe gully, rilling and sheet erosion occurring. Topsoils in footslope areas are more than 300 mm deeper than on the crests, and sediment input into drains/streams may be high.

Wind erosion is a major concern. Large dust clouds can occur when cultivating on windy days. A substantial amount of topsoil can be lost from the field and deposited elsewhere in the district.

FIGURE 3 Plant scorecard – visual indicators to assess plant performance in maize

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Crop establishment pg. 36		x 3	
Crop height at maturity pg. 38		x 3	
Leaf colour pg. 40		x 3	
Variability of crop performance along the row pg. 44		x 3	
Root development pg. 46		x 3	
Root diseases pg. 48		x 2	
Weeds pg. 50		x 2	
Ear size pg. 54		x 3	
Crop yield pg. 58		x 3	
Production costs pg. 60		x 1	
PLANT QUALITY INDEX (sum of VS rankings)			

Plant Quality Assessment	Plant Quality Index
Poor	< 20
Moderate	20–37
Good	> 37

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:



Assessment

- 1 Assess the degree and uniformity of crop establishment within a month of sowing by comparing the number and height of established plants with the three photographs and criteria in Plate 23. In making the assessment, consideration must be given to the possible influence of disease, insect attack, poor seed viability, residual herbicides, surface scouring by water erosion, and grazing by ducks, hares, rabbits, etc.



Importance

GOOD SEED GERMINATION, PLANT EMERGENCE AND CROP ESTABLISHMENT depend on factors that include the quality of soil tilth at the time of sowing and during the weeks immediately following. Soils that have poor structure through compaction and over-cultivation can resettle and consolidate rapidly after the seed bed has been prepared. Impeded water and air movement through the soil can give rise to small areas low in oxygen (anaerobic zones). These produce chemical and biochemical reduction reactions, the by-products of which are toxic to plants. These anaerobic zones and poor soil aeration reduce seed germination and plant emergence. As a result, bare patches and poor and uneven early growth are commonly observed throughout paddocks that have poor soil structure. Young plants can also show discolouration of leaves and moisture stress.

The loss of soil structure can reduce crop establishment of barley from 315 to 130 plants/m² and grain yields from 6.7 to 3.9 tonnes per hectare. Seedling mortality of winter cereals can be high if the soil is waterlogged for more than 3–4 days between germination and emergence. Corn germination also slows, and plant populations decrease. Maize plants can decrease from approximately 100 000/ha to 60 000–80 000/ha.

PLATE 23 Visual scoring (VS) of crop establishment

**GOOD CONDITION VS = 2**

Good crop establishment, with few gaps along the row. Crop showing a good, even height.

**MODERATE CONDITION VS = 1**

Moderate crop establishment, with a significant number of gaps along the row and a significant variation in seedling height. Emergence may also be moderately slow but recovers somewhat.

**POOR CONDITION VS = 0**

Poor crop establishment, with a large number of gaps along the row and a large variation in seedling height. Emergence may also be slow with limited recovery.



Assessment

- 1 Measure crop height when the crop has reached maturity and compare with the three photographs and criteria in Plate 24. Your observations of crop growth and vigour during the growing season may also provide a useful indication of seedbed condition. In a good season, under non-limiting conditions, a cultivar should grow to a particular height, with about a 10–15 percent variation. Allowances should be made for exceptionally good seasons and for poor seasons.



Importance

CROP HEIGHT AT MATURITY, while dependent on climatic factors, the cultivar, soil fertility and time of sowing, can be a useful visual indicator of soil quality and plant performance. Crop height is particularly useful if agronomic factors have not limited crop emergence and development during the growing season. The growth and vigour of crops depend in part on the ability of the seedbed to maintain an adequate soil tilth throughout the growing season. Poor soil aeration and resistance to root penetration as a result of structural degradation reduce plant growth and vigour, and delay maturity.

PLATE 24 Visual scoring (VS) of crop height at maturity

**GOOD CONDITION VS = 2**

Crops are at or near maximum height at crop maturity. Maize crops, for example, are generally between 2.3 and 2.7 m at maturity.

**MODERATE CONDITION VS = 1**

Crop heights are significantly below maximum at crop maturity. Crop height for maize, for example, is generally between 1.8 and 2.2 m at maturity.

**POOR CONDITION VS = 0**

Crop heights are well below maximum height at crop maturity. Crop height for maize, for example, is generally between 1.2 and 1.7 m at maturity (chest height).

Assessment

- 1 Note the leaf colour of the crop when all other factors favour rapid growth, and compare with the three photographs and criteria in Plate 25. In making the assessment, consideration must be given to the cultivar, the stage of growth, the soil moisture and temperature conditions, and the presence of pests and diseases (e.g., nematodes). The best time to carry out the assessment is 4–6 weeks after plant emergence, avoiding very cold and wet weather.

Importance

LEAF COLOUR can provide a good indication of the nutrient status and condition of the soil and the crop. The colour of the foliar and blemishes on the leaf are dependent on a number of factors including a deficiency or excess of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B). Chlorosis (or yellowing of crops) due to the loss or inadequate formation of chlorophyll, commonly occurs as a result of low N, S, Mg, Fe, Mn, Cu and Zn levels in the soil, low soil and air temperatures, prolonged cloudy days and poor soil aeration due to compaction and waterlogging.

A deficiency in N and S is a common cause of the yellowing of leaves. Sulphur and N can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form. If the soil is, or becomes poorly aerated and waterlogged, plant-available forms of N and S reduce to plant unavailable forms as discussed on pp. 6, 13 and 26. Soils therefore need to be adequately aerated to enable N and S to remain in a plant available form thereby enabling maximum uptake and utilisation of the N and S present. Plants can also only utilize N if S is present in the oxygenated sulphate form. Put simply, poorly aerated and waterlogging soils reduce the amount of plant-available N and S (and Zn).

The frequent and excessive application of N (especially during dry conditions) and certain types of fertilisers and pesticides to crops can adversely affect the biological regime and nitrogen cycle of the soil, and also suppress the supply and utilisation of other elements. As a result, crops can become dependent on an additional 'fix' of nitrogen or fertiliser to stimulate the colour of the crop and growth. In other words, the engine room of the soil, as discussed on p. 21, has become rusty and no longer has the 'horse power' to produce the yield required without the significant addition of N and fertiliser.

In addition to a yellowing of the crop, discolorations or blemishes on the leaf can also indicate mineral deficiencies (Plates 26–31). Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of S, Zn and Cu, while high S levels can suppress the uptake of P and Mg. Excess N can strip Ca from the soil, block Mn, Zn, B and Cu uptake, and cause the plant to luxury feed on K, which in turn can also tie up Mn and B, and suppress the utilisation of Ca and Mg by the animal.

PLATE 25 Visual scoring (VS) of leaf colour

**GOOD CONDITION VS = 2**

Leaf colour is uniformly deep green. The odd colour blemish on leaves may be apparent within a broad area.

**MODERATE CONDITION VS = 1**

Leaf colour is yellowish green; i.e. has a distinct yellowish tinge. Few colour blemishes on leaves may occur within a wide area.

**POOR CONDITION VS = 0**

Leaf colour is quite yellow over a wide area. Colour blemishes on leaves may commonly occur.

PLATE 26–28 Common symptoms of leaf discoloration due to nutrient deficiencies in maize



26. Phosphorus deficiency – purpling of leaves.



27. Nitrogen deficiency on left.



28. Potassium deficiency.

PLATE 29-31 Common symptoms of leaf discolouration due to nutrient deficiencies in maize



29. Sulphur deficiency on the right.



30. Magnesium deficiency.
Red and purple tints on leaves with
interveinal chlorosis and necrosis.



31. Zinc deficiency.

Assessment

- 1 Cast your eye along the row at crop maturity and observe any variability in crop performance in terms of crop height, stem numbers, stem thickness, leaf colour, leaf density etc. (Plates 32–35), and compare with the class limits in Table 5. In making the assessment, consideration must also be given to other factors that may affect the performance of a crop, such as pest and disease attacks that are not related to the condition of the soil.

Importance

VARIABILITY OF CROP PERFORMANCE ALONG THE ROW can be a good visual indicator of the condition of the soil. In particular, the linear variability in crop performance can be strongly related to the availability of water and nutrients, and the texture of the soil (e.g., whether clayey, silty, loamy or sandy). Also, soils in good condition with good structure and porosity, and a deep, well-aerated root zone enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and consequently the growth and vigour of the crop.

The spatial variability of crop performance along the row is also a useful indicator because it highlights those areas of the field that are under-performing, thus enabling a specific investigation as to why and what remedial action may be taken.

PLATE 32 Variable crop performance due to differences in rooting depth to an iron pan



Variable crop performance due to differences in rooting depth to an iron pan.

PLATE 33 Variable crop performance due to soil compaction



Variable crop performance due to soil compaction.

PLATE 34 Variable crop performance due to differences in soil aeration and soil wetness



Variable crop performance due to differences in soil aeration and soil wetness.

PLATE 35 Variable crop performance due to differences in the degree of water repellency



Variable crop performance due to differences in the degree of water repellency (i.e. hydrophobicity).

TABLE 5 Visual scoring (VS) of variability of crop performance along the row

Visual score (VS)	Variability of crop performance along the row
2 [Good]	Crop performance is good and even along the rows
1 [Moderate]	Crop performance is moderately variable along the rows
0 [Poor]	Crop performance is extremely variable along the rows



Assessment

- 1 Determine the size and development of the root system by carefully prising the plant out of the soil with a spade and gently shaking it or tapping the sample against the edge of the hole to remove adhering soil from the roots. Use the point of a knife to help loosen the soil if required. Assess both the length and the density of the roots and compare against the three photographs and criteria in Plate 36. Root length and root density is best assessed at or just before crop maturity.



Importance

ROOT LENGTH AND ROOT DENSITY provide a good indications of the development of the plant root system. Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared to crops with a shallow, thin root system. Shoot and leaf growth, kernel development and grain filling is therefore likely to be greater, crops are less likely to suffer windthrow, and they will be less susceptible to drought stress. Crops with a dense, deep, vigorous root system will also add (sequester) greater amounts of organic matter to the soil and increase the level of soil life. The physical action of the roots and soil fauna, and the glues they produce, further promote the development of soil structure, soil aeration and drainage.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up reducing losses by leaching into the groundwater and waterways.

Root length, root density, plant growth and vigour can be restricted by the mechanical impediment of roots and the reduction of soil pores as a result of soil compaction or a hardpan. High mechanical resistance to roots limits plant uptake of water and nutrients, restricts the production of several plant hormones in roots necessary for growth, and increases the susceptibility of the crop to windthrow. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, nutrient deficiencies, the application of excess nitrogen causing lazy plants, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and poor soil aeration. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions (p. 8, 12 and 26).

PLATE 36 Visual scoring (VS) of root development



GOOD CONDITION VS = 2

Unrestricted root development with the main large root bulb up to 250 mm wide and 200–250 mm deep.



MODERATE CONDITION VS = 1

Vertical and lateral root development is moderately restricted with right-angle syndrome not uncommon. The main root bulb is commonly 150 mm wide and 150–180 mm deep.



POOR CONDITION VS = 0

Vertical and lateral root development is severely restricted with root systems showing either stunted growth, right-angle syndrome, over-thickening, or growth down coulter channels.

Assessment

- ① Assess the presence of root diseases by pulling a number of stems out of the soil and carefully examining the root system for evidence of root diseases at, or any time before, crop maturity (Plates 37–38).
- ② Consider also how commonly root diseases occur in the field from season to season and make your assessment based on the class limits in Table 6.

Importance

POOR SOIL AERATION, soil saturation and high mechanical resistance to root development due to soil structural degradation can increase root rot and soil-borne pathogens. They can also reduce the ability of the root system to overcome the harmful effects of pathogens resident in the topsoil. Root diseases that commonly occur as a result of the loss of soil quality include take-all (*G. graminis* var. *tritici*), Rhizoctonia crown and brace root rot (*Rhizoctonia solani*), and Pythium root rot (*Pythium* spp.). *Fusarium* spp. root rot can also occur when the plant is stressed because of poor aeration and the inadequate allocation of photosynthate to the roots. The presence of root diseases can cause severe yield loss and reduction in grain quality. Symptoms include pre- and post-emergence plant death in seedlings resulting in crop thinning, stunting and reduced tillering/leaf growth, discolouration of and blemishes (lesions) on stems, tillers and leaves, bleached heads, and premature death. Plants may also lean or lodge because the root system is anchored poorly in the soil. Infected plants have sparse root development and characteristically a brown-black rot can be seen at the crown and extending to the base.

The conservation of soil moisture, amelioration of soil compaction, the build up of organic matter and the promotion of good soil life (in terms of microbial biomass, diversity and activity) are factors that contribute to the development of healthy plants and the suppression of soil-borne diseases. They also help enable the plant to better resist the pressure of disease and insect attack. Soil biota, and especially those micro-organisms that enhance cellulytic breakdown and decomposition of maize/straw residues, further limit pathogen survival.

TABLE 6 **Visual scoring (VS) of root diseases**

Visual score (VS)	Occurrence of root diseases due to soil conditions
2 [Good]	Root diseases are rare
1 [Moderate]	Root diseases are common
0 [Poor]	Root diseases are very common

PLATE 37 **Pythium root rot**



Pythium root rot where the rotted cortex has pulled away from the stele. (White DG, 1999. Compendium of Corn Diseases).

PLATE 38 **Rhizoctonia root rot**



Root rot resulting from rhizoctonia fungal infestation on compacted, poorly aerated soils on the left. Healthy root development on uncompacted, well aerated soils on the right.

 **Assessment**

- 1 Assess the degree of weed infestation by visually estimating the number of weeds between rows before canopy closure. Consider also how often a given level of weed infestation occurs in the paddock from season to season, and at what level it is perceived to be a problem. Make your assessment according to the photos and criteria given in Plate 39 on the basis of what the field would look like without significant weed control measures.

In making the assessment, consider those factors that can contribute to weed infestation including, for example, the introduction of seeds from cultivation and harvesting machinery. The timing of sowing, whether early or late, may also play a significant role. Weeds are often less of a problem if the crop is sown early enough and a good, early canopy cover is established. Warmer climate weeds such as those of summer crops respond directly to temperature and light so they germinate and grow faster in warmer conditions with more light. On the other hand, the growth of cooler climate weeds of both winter and summer cereal crops is independent of temperature and the weeds usually grow best when soil moisture is high. Consider also the use and timing of weed control measures, including shallow inter-row cultivation and pre- and post-emergent herbicide sprays. Weed control measures should be implemented at an early stage when the young weeds are easy to control, i.e. before they get to the seedling stage. In addition, consider whether weeds have become more resistant to a herbicide, and whether the persistence of herbicides is reduced, for example, by their strong absorbance by clayey, allophanic, humic or peaty soils. Soils with a high microbial activity can also give rise to a faster than normal dissipation of herbicides. Herbicides can also degrade quicker if applied at higher temperatures, which renders them less effective. They are also less effective when applied to cloddy than to a fine soil tilth.

 **Importance**

A HIGH WEED population uses a lot of the water and nutrients that would otherwise be available to the crop. Actively growing weeds can also grow over and smother the crop, intercepting light and shading the crop, resulting in suppressed growth and poor crop quality with small, stressed kernels and ears (Plate 40). The rampant growth of tall woody and grass weeds (such as broomcorn millet) interfere with harvesting by contaminating the grain with seed heads and berries (Plate 41). In addition, the extra growth is difficult to pass through the knife rolls, overloading the harvester and damaging the nose cones.

While weeds can occur for a number of reasons, they can be useful indicators of the condition of the soil, including level of compaction, soil aeration and waterlogging, nutrient fertility, pH, the amount and type of organic matter, and the microbial biomass. It is commonly believed healthy soils support weeds and crops equally well. In the same way that insect infestation indicates unhealthy plants with a nutritional imbalance, a weed infestation indicates something is not right with the soil, which is suppressing the growth of crops and providing an environment favouring weeds. Soil structural degradation resulting from over-cultivation, wheel traffic, or soil dispersion due to a low Ca:Mg ratio

PLATE 39 Visual scoring (VS) of weeds



GOOD CONDITION VS = 2

Weeds are not common in most seasons and are not considered to be a problem. Inter-rows may be protected by a mulch or short grass.



MODERATE CONDITION VS = 1

Weeds are common in most seasons and are a moderate problem.
Photo: Courtesy of Trevor James



POOR CONDITION VS = 0

Weeds are extremely common in most seasons and are a serious problem.
Photo: Courtesy of Trevor James

or high Na levels, reduces soil aeration, soil drainage, available water-holding capacity, nutrient uptake, and the rooting potential of the crop, allowing weeds to establish and compete with the crop. Warmer climate weeds also use water more efficiently than the crop itself, and so are very competitive when there is reduced moisture. Lighter soils with a coarser textural class can have more weeds than heavier soils with a finer textural class, while acidic soils can have a greater variety of weeds than non-acid soils.

Weeds will also develop and thrive in soils that have a poor mineral and microbial balance. Weeds will grow and proliferate where there is a Ca and P deficiency and an excess of K and Zn. They will develop where there is an imbalance of Fe to Mn, a lack of biologically available Ca, a lack of biologically active carbon including humus and humic acids, and where there are high nitrate levels, and a lack of bacteria or fungi. Cropping soils need to maintain a good, active microbial biomass with a fungal to bacteria ratio of approximately 3:1 for maize, and 2:1–3:1 for wheat and barley. Such ratios are necessary to preserve and promote a good biological environment for crops. An imbalance of these ratios along with poor soil nutrition could explain why crops may show poor growth and a tendency to be infested with weeds.

Bristle-grass may become prominent in compacted soils and where soils are deficient in Ca, P, Se, vitamin C, and have excess Mg with a narrow Ca:Mg ratio. Their occurrence is exacerbated by Mg, Zn, and the excessive use of K (muriate of potash), which also further suppresses Ca levels. Excess Zn along the maize plant row can cause the proliferation of Shepherds purse. Barnyard grass, goosegrass (crowfoot grass), summer grass and broomcorn millet like a soil environment that is low in Ca, P, humus and soil microbes, and high in K. Witch grass likes heavier, sticky soils with very low Ca levels and possibly high Al.

The condition and properties of the soil have a major bearing on whether the crop is able to grow in a sufficiently vigorous way to out-compete, and prevent or restrict the establishment and growth of weeds. Competitive suppression by vigorous crop growth plays a major role in preventing weed establishment. Weed suppression can also occur after a crop is sown by the production of auxins (or plant growth hormones) when the seed germinates. Auxins limit or stop the germination of seeds from other weeds. While this suppression lasts for only 1–2 days in poor quality soils, it can last for 6–8 weeks in biologically active, well-aerated soils, thus providing an effective, natural weed control. The application of liquid calcium incorporating a form of organic carbon such as molasses, or humic/fulvic acids (to act as a food supply for soil microbes), along with the addition of an organic form of phosphorus and selected trace elements such as B, Co and Se, can help alter the soil environment in such a way that weeds do not want to grow. Changing the soil environment can successfully deal with any weed problem and can provide a more effective solution than the application of straight herbicides, which gives a short-term and often limited response. However, where weeds are an initial problem, the incorporation of herbicides into a solution containing ammonium humate or fulvic/humic acids with a pH modifier, can provide good weed control. Such a mixture enables the amount of herbicide used to be reduced by 25–35 percent, and also helps buffer the effect of the herbicide on soil life. The regular use of herbicides and pesticides have an adverse effect on soil microbes

(including mycorrhizal fungi), which are responsible for maintaining the nutrient balance and availability of nutrients in the soil. The quick-kill approach using chemical herbicides only addresses the symptoms and does nothing to rectify the underlying cause.

PLATE 40 Severe weed infestation



Severe weed infestation of Rough bristle-grass suppressing maize growth.

PLATE 41 Severe weed infestation



Severe weed infestation of Broomcorn millet reducing crop yield and preventing harvesting.



Assessment

- 1 Assess the size of the ears just before harvesting and compare them with the photographs and criteria in Plate 42.

While there is a strong association between kernel number and yield, ear size and dry weight are also strong determinants of the final yield. In making the assessment, consideration must be given to the hybrid and crop agronomy including plant population, soil fertility, weather conditions and in particular the rainfall, temperature, and sunlight hours. High plant populations will reduce the size of the ears, and dry conditions and prolonged cloudy weather will reduce photosynthesis and the subsequent formation of carbohydrates and starch required for grain filling.



Importance

EAR SIZE is governed by a number of factors, including the availability of water, nitrogen and other nutrients, and the production of carbohydrate, starch and protein (Plate 43). It is essential that these be maintained during the crop cycle, particularly avoiding any shortage especially during the grain filling period. Small ears are often a sign of poor soil quality, including low fertility. They may also be due to asynchrony between pollen shed and silking caused by high rainfall, low temperatures, drought, or earworm damage. Soils in good condition with good structure, porosity, organic matter levels, soil life, soil fertility, and rooting depth help ensure the supply and availability of water and nutrients, and the duration of photosynthate producing green leaves. The grain-filling period is prolonged as a result and an increase in ear size is achieved.

Ear size is a useful determinant of grain quality in terms of grain size and shape distribution, grain hardness, grain weight, broken (or damaged) corn, moisture content, and the number of grains affected by disease.

PLATE 42 Visual scoring (VS) ear size

**GOOD CONDITION VS = 2**

Ears are large, varying in length between 180–220 mm. Ears show good grain filling of kernels and tips, and few stress features are apparent

**MODERATE CONDITION VS = 1**

Ears are of medium size, varying in length between 150–180 mm. Ears often show incomplete filling of kernels and tips, and stress features are often apparent.

**POOR CONDITION VS = 0**

Ears are small, varying in length from 100–150 mm. Kernels are often undeveloped and poorly filled at the tips. Stress features are very common.

ear size
PLATE 43 Small ears due to nutrient and water deficiency

Ears with poorly filled tips and loose chaffy kernels due to potassium deficiency.



Small ears with twisted and undeveloped kernels due to phosphate deficiency interfering with pollination and kernel fill.

PLATE 43 **Small ears due to nutrient and water deficiency** (*continued*)



Small ears with a low protein content and kernels at the tip not filling because of a nitrogen deficiency at critical times. Nitrogen is essential throughout the growing season.



Dry weather slows silking behind tasseling; kernels are not pollinated.

Assessment

- Assess crop yield based on the criteria given in the Table 7. Crop yields are best assessed by noting the harvested dry weight (Plate 44). Maize yields can also be estimated by counting the number and size of ears per square metre and the degree of grain filling. The yield of cereal crops can also be estimated by noting the number and size of ears (spikes) per square metre, the number of kernels (grains) per ear, and the degree of grain filling. In making the assessment, consideration must be given to the variety of the crop, the number of plants per square metre, the soil moisture, air temperature and sunshine hours during the growing season, and pests and diseases not associated with the condition of the soil.

Importance

WITH A DECLINE IN SOIL QUALITY, crops can come under stress as a result of poor soil aeration, water-logging, moisture stress (due to either soil saturation or a reduced available water-holding capacity), a lack of available nutrients, and adverse temperatures. Toxic chemicals can also build up and root growth be impeded owing to chemical reduction reactions (pp. 8 & 26) and a high penetration resistance to root development. This results in poor germination and emergence, poor plant growth and vigour, the need for re-drilling, delays in drilling, root diseases, pest attack, and consequently lower crop yields. Plant stress induced by structural degradation can further affect the quality of grain by changing the amount and type of protein and starch formed, and the enzymic potential. These affect the amount of fermentable carbohydrate, the baking quality of wheat, and the malting potential of barley. Under good soil conditions with adequate water and nutrients, the ripening period is prolonged and the starch accumulation inside the kernel is delayed and more gradual. This increases yield with a higher starch and protein percentage and quality.

Compacted, poorly aerated soils can be partially ameliorated by artificial aeration (Plates 46 & 47, p. 63). Aerating the soil can increase crop production by 10–20 percent on moderately compacted ground, and by up to 40 percent on severely compacted ground. Spending money on diesel to aerate compacted soils instead of additional fertiliser will often give better crop yields.

For good crop yields, the plant requires the following nutrients in adequate amounts:

- ❖ N, S, Mg, Fe, Mn, Zn, and Cu for chlorophyll production
- ❖ N, P, K, Fe, Mn, Cu for photosynthesis
- ❖ N, P, K, Zn, Cu and B to aid the production and use of carbohydrates and starch
- ❖ N, K, S, Fe, Cu – to form amino acids, essential for protein synthesis
- ❖ N, P, K, S, Mg, Fe, Mn, Zn, Cu and Mo, constituents of several enzyme systems involved in building and converting amino acids to proteins.
- ❖ N and P to supply the source of energy, energy storage and transfer in the plant
- ❖ N, P, Ca, Fe and B for cell division and enlargement, vital for plant growth
- ❖ Ca and Co for growth of shoots and shoot tips
- ❖ Ca, P and B for root formation and growth

PLATE 44 Harvesting maize for silage and grain



Harvesting a 20 t/ha maize silage crop (top) and a good maize grain crop with a yield of 15.2 tonnes/ha (bottom).

TABLE 7 Visual scoring (VS) crop yield

Visual score (VS)	Crop yield
2 [Good]	Crops have 40 ears per square metre. The ears are large (180–220 mm in length) and show complete grain filling and few signs of stress, pests or diseases. Harvested yield is 14 tonnes/ha for maize grain and 25 tonnes/ha for maize silage.
1 [Moderate]	Crops have 20–30 ears per square metre. The ears are of medium size (150–150 mm in length), with moderate grain filling, but are often poor at the tips. Stress, pest, and disease evidence is moderately common. Harvested yield is 10–12 tonnes/ha for maize grain and 19–22 tonnes/ha for maize silage.
0 [Poor]	Crops have < 20 ears per square metre. The ears are generally small (100–180 mm in length) and show uneven and poor grain filling, particularly at the tips. Stress, pest and disease features are very common. Harvested yield is < 8 tonnes/ha for maize grain and < 16 tonnes/ha for maize silage.

Assessment

- 1 Assess whether production costs have increased because of increased tillage, fertiliser, herbicide and fungicide requirements over the years (Figure 4) and refer to the class limits given in Table 8. This assessment can be based on perceptions but reference to annual balance sheets will give a more precise answer.

Importance

FERTILISER, GROUND PREPARATION, HERBICIDE AND PESTICIDE INPUTS account for some of the highest costs in any cropping operation, and can increase significantly with increasing soil degradation. While fertiliser is one of the major costs associated with cropping, the amount, type and therefore cost of applied fertiliser can be significantly influenced by the condition of the soil. Soil condition can have a major effect on fertiliser use efficiency, including the up-take of N and S. For example, poorly aerated and waterlogged soils reduce plant available nitrate-nitrogen (NO_3^- -N) to nitrite (NO_2^-) and N_2 gas, and sulphate-sulphur (SO_4^{2-} -S) to sulphite (SO_3^{2-}) and sulphides, rendering the N and S unavailable to the plant. The N cycle also cannot work if the S cycle is not working, i.e. plants need sulphur in sulphate form to utilize N. It is partly for this reason that farmers commonly apply more N and S than would otherwise be the case in an attempt to overcome the losses incurred by the chemical reduction effect of soils in poor condition.

Poorly aerated and waterlogged soils also decrease the uptake of phosphorus. Degraded soils with relatively high Olsen P levels (40–50 mg/L) can show a positive yield response to applied P. Again, to boost production, farmers will often apply more phosphorus than normally would be required.

In addition, continuous cropping using conventional cultivation techniques can give rise to a significant loss of organic matter (see Figs 6 & 7, p. 77) and, as a result, can substantially reduce soil fertility and the ability of the soil to supply nutrients. Higher amounts of fertiliser are needed to compensate for the loss of these nutrients. Moreover, the loss of organic carbon could incur a possible carbon tax, further increasing costs.

Reductions in crop yield are often not recognised as the result of the degradation of soil structure, the loss of organic matter, and a reduction in the number and activity of soil microbes. Rather, growers assume that soil fertility is at fault and increase their production costs by applying extra fertiliser.

Do you use fertiliser to grow the plant, or do you use fertiliser to feed the soil to grow the plant?

FIGURE 4 Assessment of production costs

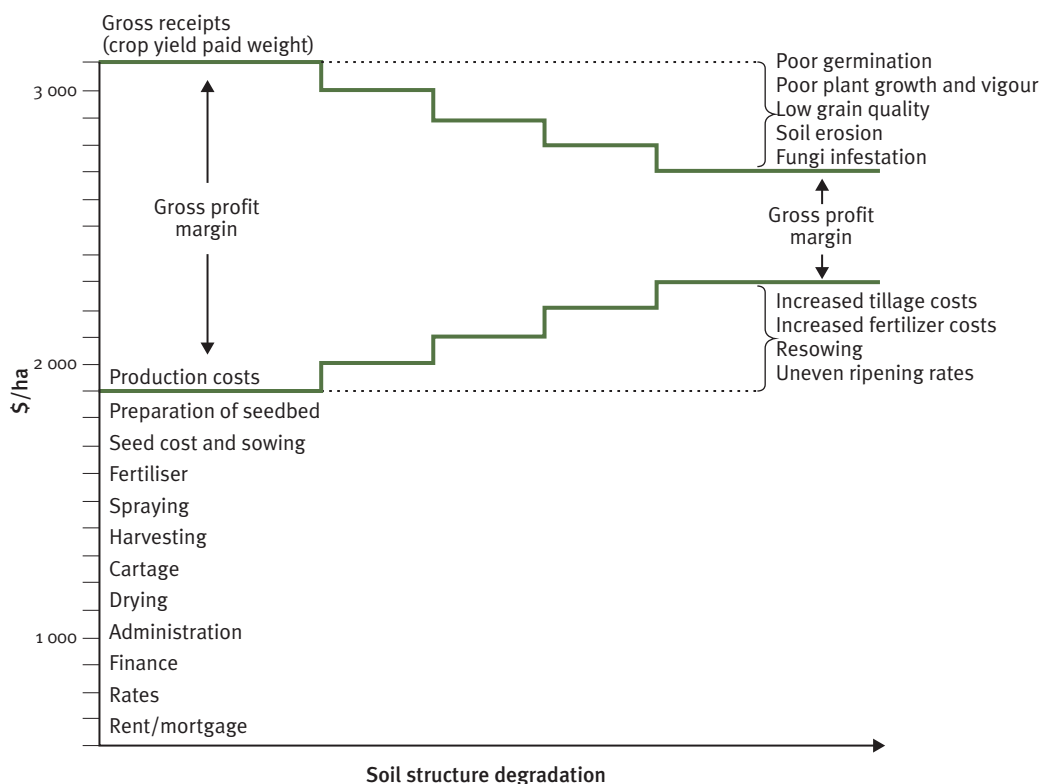


TABLE 8 How to score production costs

Visual score (VS)	Production costs
[Good]	Production costs including fertiliser, ground preparation, herbicide and pesticide requirements have not increased.
1 [Moderate]	Production costs including fertiliser, ground preparation, herbicide and pesticide requirements have increased moderately.
0 [Poor]	Production costs including fertiliser, ground preparation, herbicide and pesticide requirements have increased greatly.

In addition to soil fertility issues, soils in poor physical condition can have a significant effect on the cost of preparing a seedbed. As degradation increases, the density and strength of the soil increases and, as a result, the soil becomes more resistant to tillage forces, effectively creating ‘Sunday Soils’ – too wet to cultivate on Saturday and too dry on Monday. Plough resistance increases so that larger (more costly) tractors are required to avoid excessive wheel slip and to operate at lower ground speeds in a lower gear. The size, density, and strength of soil clods also increase with increasing loss of soil structure, and careful timing and additional energy are needed to break them down to a seedbed. This energy is generally applied by using more intensive methods of cultivation and by making a greater number of passes (often referred to as ‘recreational tillage’). As a result, tillage costs can increase by over 300 percent using conventional cultivation. No-till technology can reduce overall costs by 40–50 percent.

Production costs can be reduced if soils are well aerated and the seedbed is prepared with a minimum number of passes. Cultivating at the optimum water content for maximum breakdown of soil clods to form a seedbed not only reduces the number of passes required, but helps preserve the structure of the soil (Plate 45). Compacted soils should also be artificially aerated when they are sufficiently moist and crumbly to give maximum fracturing (Plate 46). Cultivating and aerating the soil at the optimum water content to give the best results can be achieved by applying the ‘worm test’ (Plate 47).

PLATE 45 Cultivating the soil at the right water content



Cultivating at the optimum water content to achieve maximum breakdown of soil clods to form a seedbed in one pass.

PLATE 46 Artificial aeration

Photo: Courtesy of James Engineering



Artificial aeration of a compacted topsoil at the optimum water content to achieve maximum fracturing of the soil profile.

PLATE 47 The worm test



- a) Roll a soil worm between the palms of your hands.
- b) For **silty soil**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to aerate. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to aerate.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 2

Maize

Visual indicators
of environmental performance
under cropping

A GUIDE



Maize

Visual indicators
of environmental performance
under cropping

A GUIDE

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List of acronyms

AEC	Adenylate energy charge	Mn²⁺	Manganous ions
Al	Aluminium	Mo	Molybdenum
ASC	Anion storage capacity	N	Nitrogen
ATP	Adenosine triphosphate	N₂	Nitrogen gas
B	Boron	NO₃⁻	Nitrate
C	Carbon	NO₃⁻-N	Nitrate-nitrogen
Ca	Calcium	NO₂⁻	Nitrite
Ca²⁺	Calcium cation	N₂O	Nitrous oxide
CEC	Cation exchange capacity	Na	Sodium
CH₄	Methane	Na⁺	Sodium cation
CO₂	Carbon dioxide	NH₃	Ammonia
qCO₂	Metabolic quotient	NH₄⁺	Ammonium
Co	Cobalt	O₂	Oxygen
Cu	Copper	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂S	Hydrogen sulphide	SO₄²⁻	Sulphate
K	Potassium	SO₃²⁻	Sulphide
K⁺	Potassium cation	VS	Visual score
Mg	Magnesium	VSA	Visual Soil Assessment
Mg²⁺	Magnesium cation	WFPS	Water-filled pore space
Mn	Manganese	Zn	Zinc
Mn³⁺	Manganic ions	ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER CROPPING

A GUIDE

Courtesy of Pioneer® brand products



1. Potential for nutrient loss into the groundwater and waterways



2. Carbon sequestration



3. Green house gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways



Assessment

- ① To assess the susceptibility of soils under crops to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 71), the visual scores (VS) for Textural group, Soil colour, Soil smell, and Potential rooting depth from the Soil Scorecard, and the visual score (VS) for Root development from the Plant Scorecard. Also add a ranking score for the amount and solubility of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.



Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals¹, have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is greater than 7:1, P is limiting growth. If the N:P is less than 7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

¹ Non-crystalline iron and aluminium hydroxide oxides and amorphous aluminosilicate clay minerals such as ferrihydrite and allophane.

PLATE 48 Nutrient loss into waterways



a) A field with a moderate potential for nutrient loss into the groundwater and lake. While it has a coarse loamy textural group and moderately good structure with a moderately rapid permeability, it has moderately high carbon levels and CEC in the topsoil, good potential rooting depth, good root development, and received moderate amounts of water-soluble fertiliser and nitrogen.



b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly assessed from five of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^- -N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain more clay and generally more humus as well. Hence their CECs are higher and more able

to adsorb and retain positively charged nutrients such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+ , etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic silty clay*, *peaty silt loam*) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P can also readily leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root development** (p. 46) – Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with crops with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root development and the potential rooting depth.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light,

well-structured soils, particularly when applied in large amounts. High rates of fertiliser are also applied to crops in an attempt to overcome sparse root systems and maximise yield. The over-use of highly soluble granulated N products readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^- . Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching. Nitrate and H^+ ions are produced following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should always be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes. In contrast to urea and other highly soluble fertiliser products, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of high analysis, highly soluble forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can have a negative affect on soil life. The microbial biomass and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–65 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^- -N) from soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+ -N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the

soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reduction in white clover. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical cropping practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Any one of the above indicators provides an estimate of the susceptibility of the soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 20 , certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 20 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching into the environment. Crops are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth.

FIGURE 5 Scorecard – visual indicators to assess the potential for nutrient loss

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of nutrient loss	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹) pg. 2		x 3	
Soil structure (Scoring protocol is given below ²) pg. 4		x 2	
Potential rooting depth (mm) pg. 22		x 3	
Root development pg. 46		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 3	
NUTRIENT LOSS INDEX (sum of VS rankings)			

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 11
Moderate potential for nutrient loss	11–20
Low potential for nutrient loss	> 20

1 Textural group (Figure 2b, p. 3):

VS = 2 for Clayey; VS = 1.5 for Fine silty; VS = 1.0 for Fine loamy; VS = 0.5 for Coarse silty; VS = 0 for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 respectively to the VS score. Note VS scores cannot exceed a value of 2.

2 Soil structure – Is the land most susceptible to a) leaching, or b) runoff?

a) *Land susceptible to leaching – Flat land with little or no runoff (overland flow)*

VS = 2 for Poor soil structure; VS = 1.5 for Moderately poor soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately good soil structure; VS = 0 for Good soil structure.

b) *Land susceptible to runoff – Gently undulating to rolling land*

VS = 2 for good soil structure; VS = 1.5 for Moderately good soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately poor soil structure; VS = 0 for Poor soil structure

3 Amount and form of fertiliser and N applied

VS = 2 if using liquid foliar sprays or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 80 kg N/ha/yr are applied; VS = 1.0 if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 160–240 kg N/ha/yr, using highly soluble, salt-based and nitrogenous fertilisers; VS = 0 if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 320 kg N/ha/yr are applied.

2. Visual indicators to assess the potential for carbon sequestration



Assessment

- Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 8, p. 79) the visual scores (VS) for Soil texture, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root development and Crop yield from the Plant Scorecard. Add also a ranking score for the clay mineralogy, the amount and form of fertiliser and nitrogen applied per annum, and for the method of cultivation (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.



Importance

THE AMOUNT OF C in a soil = C inputs – decomposition rates. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition, leaching and volatilization (Plate 49). A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than the decomposition rates (Plate 50). Farmers can reduce their ecological and carbon footprint and ‘grow’ their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture’s contribution to greenhouse gas emissions, providing a cost-effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, two indicators of plant performance, and from the method of cultivation and the amount and form of fertilisers and nitrogen used, as described below. Crops such as maize silage where most of the plant is removed are C negative.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of organic C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are < 2 µm and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

PLATE 49 A carbon positive field

Photo: Courtesy of Baker No-Tillage Ltd



A carbon positive field using no-till technology to sow directly into maize residue left on the surface. The field has good soil colour compared with the fenceline, good root development, potential rooting depth, and crop yields, moderate earthworm numbers, and 80 kg N/ha/yr are applied in a carbon-friendly form.

PLATE 50 A carbon negative field



A carbon negative field under continuous conventional cultivation. The field has moderately poor soil colour compared with the fenceline, poor earthworm numbers, moderate potential rooting depth, root development, and crop yields, and 200 kg N/ha/yr are applied in a non-carbon friendly form. Total organic C in the upper 200 mm of soil declined from 90.8 tonnes/ha under permanent pasture to 41.2 tonnes/ha after 35 yrs of continuous conventional cultivation (Figure 6, p. 77).

Clay mineralogy (see scorecard, p. 79) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and aluminosilicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle-size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under 20 yrs continuous barley contain about 229 t C/ha in the top 1m, of which 159 t C/ha (69 percent) occurs in the upper 300 mm, and 70 t C/ha (31

percent) between 300 and 1000 mm. Compare this with non-allophanic soils below. The amount of C in the upper 300 mm of allophanic soils under cropping is only 4 t/ha less than under permanent pasture, illustrating its relative stability despite continuous, long-term conventional cultivation.

Soil colour compared with that under the fenceline (p. 10) can provide a good indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present. With the exception of poorly aerated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C (Fig. 10, p. 86).

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. The number and activity of soil microbes at depth is much less than in the topsoil and so the carbon is more protected and able to build up because it is less likely to be mineralised. Deep burrowing earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil C.

Potential rooting depth (p. 22) and the **Root development** (p. 46) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 128 tonnes C/ha after 23 yrs cereal and maize cropping: 85 t C/ha (67 percent) occur in the upper 300 mm, and 42 t C/ha (33 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good potential rooting depth of 1 m contain about 134 t C/ha after 22 yrs maize cropping, of which 64 t C/ha (48 percent)

occur in the upper 300 mm, and 70 t C/ha (52 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme. Note the significantly lower C levels of these soils under conventional cultivation compared with pasture (Fig. 6, p. 77).

Crop yield (p. 58) can provide a further indication whether soil C is increasing, decreasing or at steady state. The greater the crop yield, the greater the root and shoot mass, and therefore the greater the input of C from the root system and the decomposition of the additional surface litter and surface residue. A 14-tonne/ha crop of maize for grain would produce an above-ground C input from the surface litter and residue of approximately 7 t C /ha, and a below-ground C input of 2 t/ha from the roots, a total of 9 t C/ha. An 11- tonne/ha crop of maize adds a total of approximately 7.1 t C/ha to the soil, or 21 percent less than the higher producing crop. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the crop has good root development and potential rooting depth, and the soil is allophanic with a good earthworm population, and doesn't receive high applications of soluble, salt-based nitrogenous products. The application of high rates of granular N to boost yield, promotes the vegetative growth of the shoots relative to the roots. The over-use of N also creates lazy plants, encouraging a shallow root system and therefore less C input. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil. In addition, the microbial decomposition of roots, plant litter and husks produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil. The input of C in the soil from maize for silage is considerably less than maize for grain because much of the above ground vegetative matter is removed at harvest. Maize silage can therefore have a C negative effect.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture and temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing crop growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Amount and form of fertiliser and nitrogen applied to cropping soils (see scorecard, p. 79) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, compost teas,

animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and crop management, good crop yields and C levels can be sustained and increased over the long term. The form in which essential elements are applied can also have an effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and is the preferred form for improving crop quality, and if the seedlings or crop are sensitive to chlorine.

Similarly, while nitrogen promotes crop growth and therefore the input of C into the soil, certain forms of N are more effective than others at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic carbon and carbohydrate such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N. The excessive use of soluble granular forms of N and high analysis nitrogenous fertilisers also cause the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 10:1–100:1. The oversupply of N stimulates bacteria to mineralise 2–3 times the amount of humus they would ordinarily mineralise. Moreover, the high use of granular forms of N such as urea, reduce the earthworm and microbial biomass, further reducing C levels in the soil.

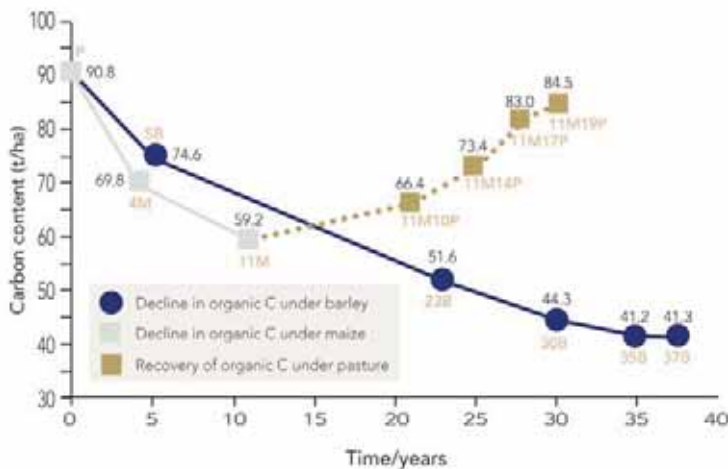
The plant converts CO₂ in the atmosphere into sugar (carbon) by photosynthesis in the leaves of the plant. The sugar dissolves as liquid glucose in the sap of the plant and is subsequently transferred to the soil through the roots to feed the soil microbes. The microbes in turn bring trace elements to the plant in exchange for the sugar. This process of C transfer from the plant to the soil, and the rate of photosynthesis, is disrupted by the over-use of high analysis, highly soluble forms of N and P. These include urea and anhydrous ammonia, and di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (e.g., humates), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70 percent). The utilization of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root development, and crop yield.

The addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

The **method of cultivation** (see scorecard, p. 79) can have a significant effect on soil C levels. Soil organic C can decline markedly under continuous conventional cultivation because the high level of soil disturbance aerates the soil, increasing the rate of mineralisation of soil organic C by microbial respiration and its oxidation to CO₂. The rate of C loss is particularly rapid in the first 4–5 years of cropping, followed by a slower rate of decline, eventually reaching an equilibrium where only the more stable and physically protected carbon remains in the soil (Fig. 6). Total soil C is seen in Fig. 6 to decline by 31.6 t/ha in the upper 200 mm of soil after 11 yrs continuous maize, and by 49.6 t/ha after 35 yrs continuous barley; an average loss of 2.9 and 1.7 t/ha/yr respectively. Note the initial slow rate of recovery of total C after 10 years of pasture following 11 yrs of maize. After 19 yrs of ryegrass/clover pasture, the total C had not recovered to pre-cropping pasture levels of 90.8 t/ha. The significant loss of C under both maize and barley, and the slow rate of C recovery under pasture are due in part to the poor management practices that prevailed. The slow rate of recovery of C under pasture was also due to the extremely compacted, poorly aerated state of the soil.

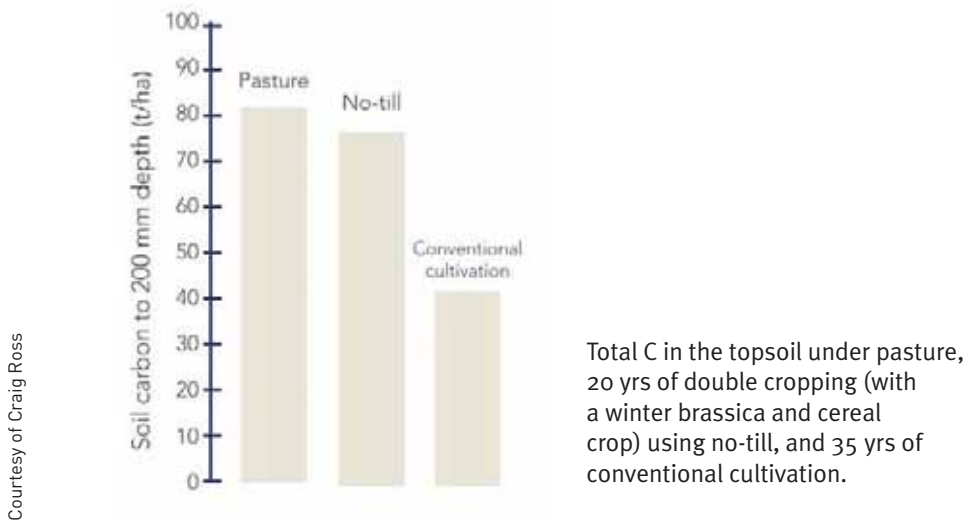
FIGURE 6 Total C in the topsoil under pasture and continuous cropping



Total C in the topsoil (0–200 mm) after 11 yrs and 37 yrs of continuous maize and barley respectively under conventional cultivation.

Note the rate of recovery of total C after 10, 14, 17 and 19 years of pasture following 11 yrs of maize.

FIGURE 7 Total C in the topsoil under pasture, no-till and conventional cultivation



In comparison, the loss of soil C under no-tillage is significantly less than under conventional cultivation (Fig. 7). In some instances, C levels have increased in the upper 150 mm of soil under no-tillage compared with pasture. The greatest increases in soil C can occur at a depth of 300–600 mm under ‘pasture cropping’ practices where no herbicides or insecticides have been applied. The substantial loss of C under conventional cultivation and the slow rate of C recovery under pasture are due to the non-adoption of carbon capture and storage (CCS) management practices.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore ‘grow’ the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 32), certain management practices and specific types of fertiliser need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 32) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits.

FIGURE 8 Scorecard – visual indicators to assess the potential for carbon sequestration

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Topsoil depth:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____ **Date:** _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of soil carbon	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g. 2	x 2	
Clay mineralogy (Scoring protocol is given below ²)		x 2	
Soil colour	g. 10	x 2	
Earthworms (Number =) (Av. size =)	g. 14	x 3	
Potential rooting depth (mm)	g. 22	x 3	
Root development	g. 46	x 3	
Crop yield	g. 58	x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 2	
Method of cultivation (Scoring protocol is given below ⁴)		x 3	
SOIL CARBON INDEX (sum of VS rankings)			

Soil Carbon Assessment	Soil Carbon Index
Potentially poor carbon levels	< 17
Potentially moderate carbon levels	17–32
Potentially good carbon levels	> 32

- Textural group:** VS = 2 for Clayey; VS = 1.5 for Fine loamy and Fine silty; VS = 1.0 for Coarse silty; VS = 0.5 for Coarse loamy; VS = 0 for Sandy.
- Clay mineralogy:** VS = 2 if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; VS = 1 if the soil has moderate levels of Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an ASC of 60–75 percent; VS = 0 if the soil has little or no Fe & Al hydroxides and amorphous aluminio-silica minerals; ASC is < 45 percent.
- Amount and form of fertiliser and N applied:** VS = 2 if “smart” fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based N fertilisers.
- Method of cultivation:** VS = 2 if using ‘pasture cropping’ and no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous mouldboard ploughing with intensive secondary cultivation.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions

Assessment

- 1 Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 12, p. 89) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual score for Crop yield from the Plant Scorecard. Also add a ranking score for the method of cultivation used and the amount and form of N applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.

Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C; without them the earth's average temperature would be around -18°C. However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Solar radiation



Agriculture can provide a significant source of CH₄ and N₂O and is responsible for 15 percent of worldwide greenhouse gas emissions. CO₂ is emitted under arable cropping, however it is reabsorbed as photosynthate by the crop and is therefore greenhouse neutral. While high emission levels of GHGs are more to do with the way we farm, climate friendly and smart agricultural management can significantly reduce emissions.

GHG emissions from cropping result from a number of sources, including the soil, the burning of fossil fuels by farm machinery, and the production and application of nitrogenous fertilisers. The level of emissions varies according to a number of factors, including the condition of the soil, the method of cultivation, and the amount and form of fertiliser N applied, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO₂ to soil C, and by promoting the soil as a CH₄ sink. The C credits gained can help off-set their GHG emissions.

PLATE 51 Field with a low potential for greenhouse gas emission

Field with a low potential to emit GHGs due to the soil being a well-drained, coarse loamy soil with good porosity under a no-tillage regime. In addition, good crop growth and yield remove a large amount of CO_2 from the atmosphere and CO_2 escaping from the soil by photosynthesis.

PLATE 52 Field with a high potential for greenhouse gas emission

Field with a high potential to emit GHGs due to the soil being an imperfectly to poorly drained, clayey soil with poor porosity under continuous conventional cultivation. In addition, poor crop growth and yield remove only small amounts of CO_2 from the atmosphere and CO_2 escaping from the soil by photosynthesis.

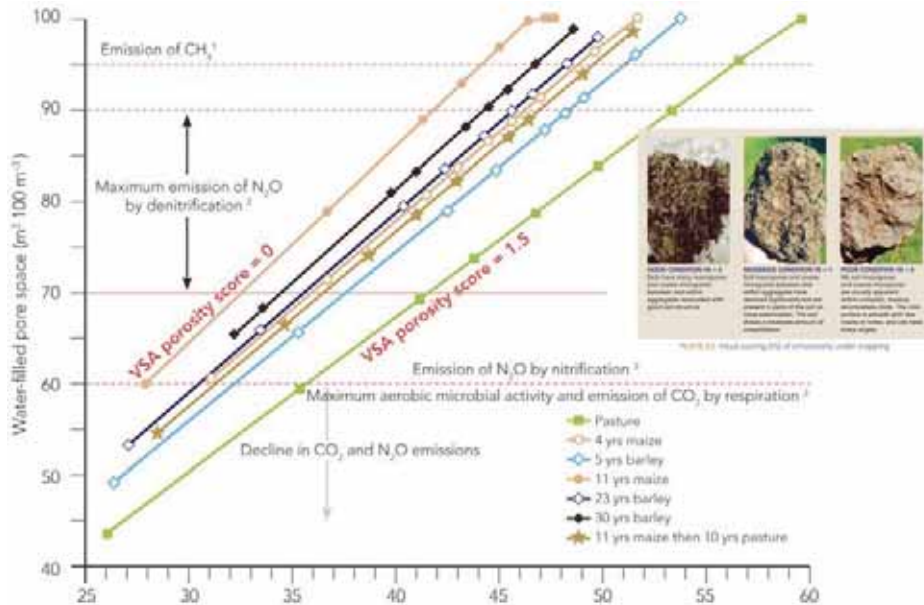
The potential of a site to emit GHGs can be roughly assessed from four indicators of soil quality, one indicator of plant performance, the amount and form of nitrogen applied, and the method of cultivation, as described below.

Soil textures (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major ‘driver’ of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs.

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O , and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 9); emissions of N_2O are lowest when the WFPS is < 50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 9) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O . In contrast, a severely compacted soil after 11 yrs of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 9) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2 . While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is

FIGURE 9 Affect of water-filled pore space and water content on greenhouse gas emissions

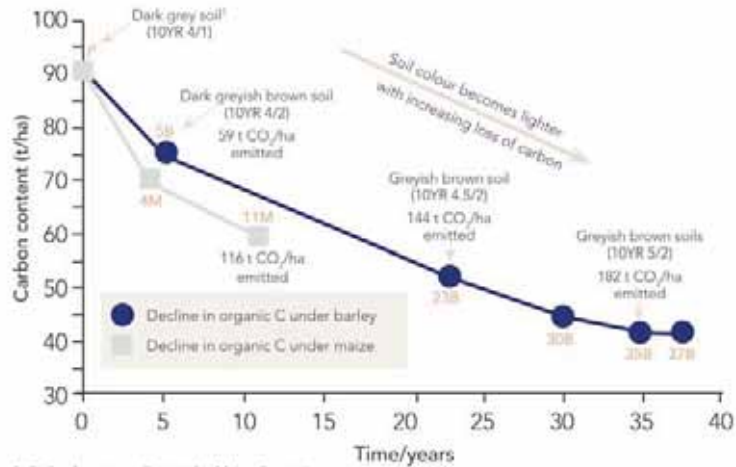


¹ After MacDonald *et al.* (1996); ² After Dobbie *et al.* (1999); ³ After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

hence an effective means of reducing GHG emissions. The relationship between the WFPS and the visual assessment of the porosity of the soil, as shown in Fig. 9, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH₄ from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Well-drained soils are also able to take up and oxidize CH₄ because of the greater number of methanotrophic bacteria present, significantly reducing CH₄ in the atmosphere. Such soils would therefore act as a more effective CH₄ sink. A lighter soil colour compared with soil under the fenceline can also indicate the loss of soil C and the emission of significant amounts of CO₂ into the atmosphere (Figure 10).

FIGURE 10 Soil C loss and associated CO₂ emissions under continuous cropping

Soil C loss, associated soil colour, and CO₂ emissions under continuous maize and barley cropping using conventional cultivation.

Crop yields (p. 58) can provide an indication of the potential to reduce GHG emissions. The greater the crop yield, the greater the amount of CO₂ removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO₂ emitted by microbial respiration, the emission of GHGs from the consumption of the crop by stock, the burning of fossil fuels by farm machinery, and the application of nitrogenous fertilisers. As CO₂ escapes from the soil, most, if not or all, is absorbed by the stomata on the crop leaves, which have an insatiable appetite for CO₂. The greater the canopy cover (leaf area index) and the quicker the canopy closure, the greater the amount of CO₂ removed. Furthermore, if we assume that one kilogram of carbon in a maize crop removes 3.67 kg CO₂ from the atmosphere, a field growing 25 tonnes of maize silage/ha (or 10.3 t C/ha) will remove approximately 38 tonnes of atmospheric CO₂/ha. A field growing just 20 tonnes of maize silage/ha (or 8.2 t C/ha) will remove 30 tonnes of atmospheric CO₂/ha, 22 percent less than the higher producing field. While CO₂ is the least potent of the GHGs with a Global Warming Potential that is 21 and 310 times less than CH₄ and N₂O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO₂ into sugars and oxygen, and subsequently into soil C, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Poor crop yield and the associated reduced crop cover would also reduce insulation from the sun, thereby increasing soil temperatures and reducing the uptake of available N and plant-available water, stimulating N₂O emissions by microbial nitrification and denitrification.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 89) can provide a further indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 9). The nitrification of urea and ammonium-based fertilisers, and particularly the denitrification of nitrates in the soil resulting from the excessive application of salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Fertiliser N applications stimulate emissions in the spring, while crop residues and their incorporation into the soil stimulate emissions in autumn and winter. The highest emissions occur following each fertiliser application, particularly when associated with major rainfall events. Seventy-five to eighty percent of the N_2O emitted can occur within 4 weeks of N application. While N_2O emissions can often account for up to 3 percent of the N applied as fertiliser in small-grain cereal crops and up to 8 percent in maize crops, compact, wet soils can increase N_2O emissions by denitrification 3–4-fold, resulting in a loss of up to 20 percent of fertiliser N, and also decreasing wheat yields by 25 percent. Yield reductions can be attributed in part to N deficiency by high denitrification activity and low mineralization. In addition, the excessive use of nitrogenous products can reduce the capacity of soils to take up and oxidise atmospheric CH_4 , thereby reducing the ability of the soil to act as a CH_4 sink.

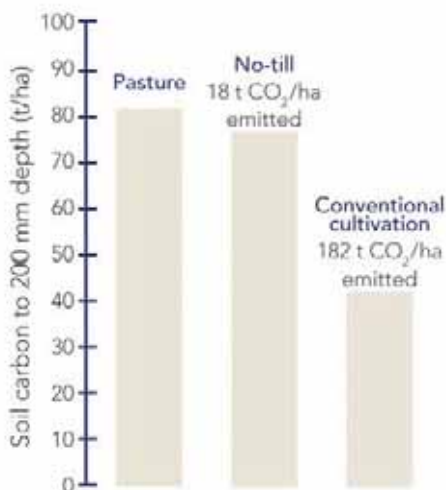
Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied to crops could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic and fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70%) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides microsites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root development, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70%, they can increase NH_3 emissions and potential NH_4^+ -N leaching losses. The jury is also still out as to their long-term impact on soil biology, in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be

applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reductions in white clover. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

The **method of cultivation** (see scorecard, p. 89) can have a marked effect on the level of GHG emissions. Carbon dioxide emissions are significantly greater under conventional cultivation than other forms of ground preparation because of the greater loss of soil C (Figs 10 & 11). The high level of soil disturbance under conventional cultivation aerates the soil, increasing the mineralisation and oxidation of organic C to CO_2 by microbial respiration which subsequently volatilises into the atmosphere. If we assume that one tonne of organic C oxidises to 3.67 tonnes of CO_2 , the loss of 31.6 t C/ha after 11 yrs of conventionally cultivated maize gives rise to the emission of approximately 116 t CO_2 /ha (Fig. 10). The loss of 49.6 t C/ha after 35 yrs of continuous barley produces 182 t CO_2 /ha. These figures do not, however, take into account the C added to the soil from the plant over the 11- and 35-year cropping period, C that would also have oxidised and potentially contributed to CO_2 emissions. However, as mentioned above, after CO_2 escapes from the

FIGURE 11 Soil C loss and associated CO_2 emissions under no-till and conventional cultivation



Soil C loss and associated CO_2 emissions under 20 yrs of double cropping using no-tillage and 35 yrs conventional cultivation.

soil, almost all of it is absorbed by the stomata on the crop leaves and is therefore recycled back into the soil. In addition to the major period of CO₂ emissions when the soil is tilled using conventional cultivation, a certain amount of CO₂ would be emitted after the harvest or senescence of one crop, and canopy closure of the next crop.

In comparison, the loss of soil organic C under no-tillage is significantly less than under conventional cultivation, producing as a result, less emissions of CO₂ (Fig. 11). Adopting carbon capture and storage (CCS) management practices including those cultivation practices that minimise C loss or even promoting C sequestration, is an effective means of reducing the emissions of CO₂ into the atmosphere.

Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by the Emissions Trading Schemes. If the GHG Emission Index is ≤ 22 , certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of > 22 provides significant environmental benefits because less GHGs would be emitted into the atmosphere.

FIGURE 12 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g.2	x 2	
Soil porosity	g.6	x 3	
Number and colour of soil mottles	g.8	x 3	
Soil colour	g.10	x 2	
Crop yield	g.58	x 2	
Amount and form of N applied (Scoring protocol is given below ²)		x 1	
Method of cultivation (Scoring protocol is given below ³)		x 3	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 12
Moderate potential GHG emissions	12–22
Low potential for GHG emissions	> 22

1 Textural group (Figure 2b, p. 3):

VS = 2 for Sandy and Coarse loamy; VS = 1.5 for Coarse silty; VS = 1.0 for Fine loamy; VS = 0.5 for Fine silty; VS = 0 for Clayey.

2 Amount and form of N applied:

VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 Method of cultivation:

VS = 2 if using no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous conventional (mouldboard plough) cultivation with intensive secondary cultivation.

Soil management of maize crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, include ‘pasture cropping’ where annual crops are direct-drilled into perennial pastures, and no-tillage and minimum tillage practices that incorporate the establishment of temporary cover crops and crop residues on the surface. They provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage can also maintain soil life and biological activity (including earthworm numbers), and can increase micro-organism biodiversity above levels commonly found under conventional cultivation. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO₂) and enables the soil to operate as a sink for CO₂. Soil organic matter levels can build up as a result and create the potential to gain ‘carbon credits’, thereby providing an offset to greenhouse gas emissions. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

Where possible, put in place management strategies that don’t require the use of herbicides. Avoid a monochemical herbicide strategy and manage the use of herbicides in association with crop rotations, including the use of livestock, to avoid the development of herbicide tolerance and residual effects. Ensure the soil has adequate levels of available Ca because herbicides are generally more effective when Ca levels in the plant are good. Also ensure that P levels aren’t too high; the higher the P level, the harder it is to deal to snails and slugs. The inappropriate and over-use of various herbicides can significantly change nutrient availability and the efficient uptake of nutrients by binding up micronutrients (chelation immobilization), and through toxic effects on soil organisms important for nutrient turnover and supply.

Continuous conventional cultivation can impact negatively on the environment with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO₂), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades

PLATE 53 A good maize crop



Photo: Courtesy of Kenneth G. Cassman

A good maize crop producing a grain yield in excess of 20 t/ha due in part to the adoption of good management practices that promote a good root system. Note the good potential rooting depth and root development to > 2m. Compare with Plate 16, p. 23

soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. Conventional cultivation should be practiced on a rotational basis with 2 years of cropping followed by 5–7 years pasture.

The fundamental difference between continuous conventional cultivation and conservation tillage is their relative environmental and economic sustainability. The long-term affects of continuous conventional cultivation can be cumulatively negative whereas the long-term affects of conservation tillage can be cumulatively positive. This is provided that good residue management practices are applied and the herbicides used are 100% biodegradable and have no adverse effects on soil or human health.

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for maize*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproducible results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

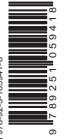
part 2

Visual indicators
of environmental performance
under cropping
A GUIDE

Maize



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Maize

Visual indicators
of environmental performance
under cropping

A GUIDE

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List of acronyms

AEC	Adenylate energy charge	Mn²⁺	Manganous ions
Al	Aluminium	Mo	Molybdenum
ASC	Anion storage capacity	N	Nitrogen
ATP	Adenosine triphosphate	N₂	Nitrogen gas
B	Boron	NO₃⁻	Nitrate
C	Carbon	NO₃⁻-N	Nitrate-nitrogen
Ca	Calcium	NO₂⁻	Nitrite
Ca²⁺	Calcium cation	N₂O	Nitrous oxide
CEC	Cation exchange capacity	Na	Sodium
CH₄	Methane	Na⁺	Sodium cation
CO₂	Carbon dioxide	NH₃	Ammonia
qCO₂	Metabolic quotient	NH₄⁺	Ammonium
Co	Cobalt	O₂	Oxygen
Cu	Copper	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂S	Hydrogen sulphide	SO₄²⁻	Sulphate
K	Potassium	SO₃²⁻	Sulphide
K⁺	Potassium cation	VS	Visual score
Mg	Magnesium	VSA	Visual Soil Assessment
Mg²⁺	Magnesium cation	WFPS	Water-filled pore space
Mn	Manganese	Zn	Zinc
Mn³⁺	Manganic ions	ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER CROPPING

A GUIDE

Courtesy of Pioneer® brand products



1. Potential for nutrient loss into the groundwater and waterways



2. Carbon sequestration



3. Green house gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways



Assessment

- ① To assess the susceptibility of soils under crops to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 71), the visual scores (VS) for Textural group, Soil colour, Soil smell, and Potential rooting depth from the Soil Scorecard, and the visual score (VS) for Root development from the Plant Scorecard. Also add a ranking score for the amount and solubility of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.



Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals¹, have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is greater than 7:1, P is limiting growth. If the N:P is less than 7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

¹ Non-crystalline iron and aluminium hydroxide oxides and amorphous aluminosilicate clay minerals such as ferrihydrite and allophane.

PLATE 48 Nutrient loss into waterways



- a) A field with a moderate potential for nutrient loss into the groundwater and lake. While it has a coarse loamy textural group and moderately good structure with a moderately rapid permeability, it has moderately high carbon levels and CEC in the topsoil, good potential rooting depth, good root development, and received moderate amounts of water-soluble fertiliser and nitrogen.
- b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly assessed from five of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^- -N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain more clay and generally more humus as well. Hence their CECs are higher and more able

to adsorb and retain positively charged nutrients such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+ , etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic silty clay*, *peaty silt loam*) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P can also readily leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root development** (p. 46) – Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with crops with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root development and the potential rooting depth.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light,

well-structured soils, particularly when applied in large amounts. High rates of fertiliser are also applied to crops in an attempt to overcome sparse root systems and maximise yield. The over-use of highly soluble granulated N products readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^- . Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching. Nitrate and H^+ ions are produced following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should always be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes. In contrast to urea and other highly soluble fertiliser products, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of high analysis, highly soluble forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can have a negative affect on soil life. The microbial biomass and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–65 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^- -N) from soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+ -N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the

soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reduction in white clover. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical cropping practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Any one of the above indicators provides an estimate of the susceptibility of the soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 20 , certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 20 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching into the environment. Crops are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth.

FIGURE 5 Scorecard – visual indicators to assess the potential for nutrient loss

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of nutrient loss	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹) pg. 2		x 3	
Soil structure (Scoring protocol is given below ²) pg. 4		x 2	
Potential rooting depth (mm) pg. 22		x 3	
Root development pg. 46		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 3	
NUTRIENT LOSS INDEX (sum of VS rankings)			

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 11
Moderate potential for nutrient loss	11–20
Low potential for nutrient loss	> 20

1 Textural group (Figure 2b, p. 3):

VS = 2 for Clayey; VS = 1.5 for Fine silty; VS = 1.0 for Fine loamy; VS = 0.5 for Coarse silty; VS = 0 for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 respectively to the VS score. Note VS scores cannot exceed a value of 2.

2 Soil structure – Is the land most susceptible to a) leaching, or b) runoff?

a) *Land susceptible to leaching – Flat land with little or no runoff (overland flow)*

VS = 2 for Poor soil structure; VS = 1.5 for Moderately poor soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately good soil structure; VS = 0 for Good soil structure.

b) *Land susceptible to runoff – Gently undulating to rolling land*

VS = 2 for good soil structure; VS = 1.5 for Moderately good soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately poor soil structure; VS = 0 for Poor soil structure

3 Amount and form of fertiliser and N applied

VS = 2 if using liquid foliar sprays or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 80 kg N/ha/yr are applied; VS = 1.0 if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 160–240 kg N/ha/yr, using highly soluble, salt-based and nitrogenous fertilisers; VS = 0 if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 320 kg N/ha/yr are applied.

2. Visual indicators to assess the potential for carbon sequestration



Assessment

- Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 8, p. 79) the visual scores (VS) for Soil texture, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root development and Crop yield from the Plant Scorecard. Add also a ranking score for the clay mineralogy, the amount and form of fertiliser and nitrogen applied per annum, and for the method of cultivation (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.



Importance

THE AMOUNT OF C in a soil = C inputs – decomposition rates. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition, leaching and volatilization (Plate 49). A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than the decomposition rates (Plate 50). Farmers can reduce their ecological and carbon footprint and ‘grow’ their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture’s contribution to greenhouse gas emissions, providing a cost-effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, two indicators of plant performance, and from the method of cultivation and the amount and form of fertilisers and nitrogen used, as described below. Crops such as maize silage where most of the plant is removed are C negative.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of organic C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are < 2 µm and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

PLATE 49 A carbon positive field

Photo: Courtesy of Baker No-Tillage Ltd



A carbon positive field using no-till technology to sow directly into maize residue left on the surface. The field has good soil colour compared with the fenceline, good root development, potential rooting depth, and crop yields, moderate earthworm numbers, and 80 kg N/ha/yr are applied in a carbon-friendly form.

PLATE 50 A carbon negative field



A carbon negative field under continuous conventional cultivation. The field has moderately poor soil colour compared with the fenceline, poor earthworm numbers, moderate potential rooting depth, root development, and crop yields, and 200 kg N/ha/yr are applied in a non-carbon friendly form. Total organic C in the upper 200 mm of soil declined from 90.8 tonnes/ha under permanent pasture to 41.2 tonnes/ha after 35 yrs of continuous conventional cultivation (Figure 6, p. 77).

Clay mineralogy (see scorecard, p. 79) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and aluminosilicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle-size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under 20 yrs continuous barley contain about 229 t C/ha in the top 1m, of which 159 t C/ha (69 percent) occurs in the upper 300 mm, and 70 t C/ha (31

percent) between 300 and 1000 mm. Compare this with non-allophanic soils below. The amount of C in the upper 300 mm of allophanic soils under cropping is only 4 t/ha less than under permanent pasture, illustrating its relative stability despite continuous, long-term conventional cultivation.

Soil colour compared with that under the fenceline (p. 10) can provide a good indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present. With the exception of poorly aerated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C (Fig. 10, p. 86).

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. The number and activity of soil microbes at depth is much less than in the topsoil and so the carbon is more protected and able to build up because it is less likely to be mineralised. Deep burrowing earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil C.

Potential rooting depth (p. 22) and the **Root development** (p. 46) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 128 tonnes C/ha after 23 yrs cereal and maize cropping: 85 t C/ha (67 percent) occur in the upper 300 mm, and 42 t C/ha (33 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good potential rooting depth of 1 m contain about 134 t C/ha after 22 yrs maize cropping, of which 64 t C/ha (48 percent)

occur in the upper 300 mm, and 70 t C/ha (52 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme. Note the significantly lower C levels of these soils under conventional cultivation compared with pasture (Fig. 6, p. 77).

Crop yield (p. 58) can provide a further indication whether soil C is increasing, decreasing or at steady state. The greater the crop yield, the greater the root and shoot mass, and therefore the greater the input of C from the root system and the decomposition of the additional surface litter and surface residue. A 14-tonne/ha crop of maize for grain would produce an above-ground C input from the surface litter and residue of approximately 7 t C /ha, and a below-ground C input of 2 t/ha from the roots, a total of 9 t C/ha. An 11- tonne/ha crop of maize adds a total of approximately 7.1 t C/ha to the soil, or 21 percent less than the higher producing crop. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the crop has good root development and potential rooting depth, and the soil is allophanic with a good earthworm population, and doesn't receive high applications of soluble, salt-based nitrogenous products. The application of high rates of granular N to boost yield, promotes the vegetative growth of the shoots relative to the roots. The over-use of N also creates lazy plants, encouraging a shallow root system and therefore less C input. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil. In addition, the microbial decomposition of roots, plant litter and husks produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil. The input of C in the soil from maize for silage is considerably less than maize for grain because much of the above ground vegetative matter is removed at harvest. Maize silage can therefore have a C negative effect.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture and temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing crop growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Amount and form of fertiliser and nitrogen applied to cropping soils (see scorecard, p. 79) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, compost teas,

animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and crop management, good crop yields and C levels can be sustained and increased over the long term. The form in which essential elements are applied can also have an effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and is the preferred form for improving crop quality, and if the seedlings or crop are sensitive to chlorine.

Similarly, while nitrogen promotes crop growth and therefore the input of C into the soil, certain forms of N are more effective than others at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic carbon and carbohydrate such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N. The excessive use of soluble granular forms of N and high analysis nitrogenous fertilisers also cause the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 10:1–100:1. The oversupply of N stimulates bacteria to mineralise 2–3 times the amount of humus they would ordinarily mineralise. Moreover, the high use of granular forms of N such as urea, reduce the earthworm and microbial biomass, further reducing C levels in the soil.

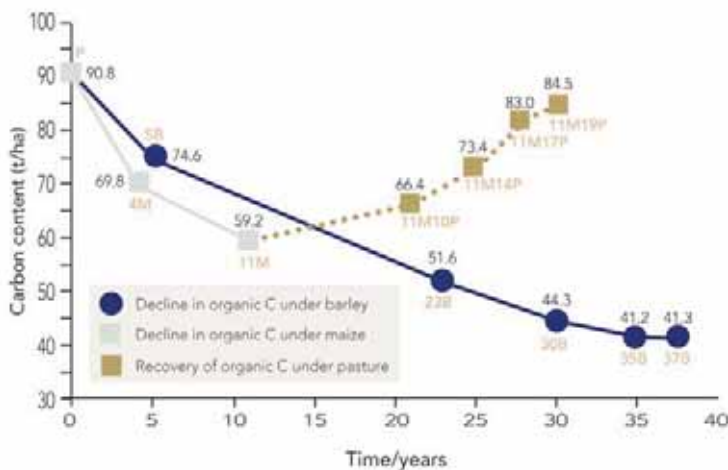
The plant converts CO₂ in the atmosphere into sugar (carbon) by photosynthesis in the leaves of the plant. The sugar dissolves as liquid glucose in the sap of the plant and is subsequently transferred to the soil through the roots to feed the soil microbes. The microbes in turn bring trace elements to the plant in exchange for the sugar. This process of C transfer from the plant to the soil, and the rate of photosynthesis, is disrupted by the over-use of high analysis, highly soluble forms of N and P. These include urea and anhydrous ammonia, and di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (e.g., humates), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70 percent). The utilization of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root development, and crop yield.

The addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

The **method of cultivation** (see scorecard, p. 79) can have a significant effect on soil C levels. Soil organic C can decline markedly under continuous conventional cultivation because the high level of soil disturbance aerates the soil, increasing the rate of mineralisation of soil organic C by microbial respiration and its oxidation to CO₂. The rate of C loss is particularly rapid in the first 4–5 years of cropping, followed by a slower rate of decline, eventually reaching an equilibrium where only the more stable and physically protected carbon remains in the soil (Fig. 6). Total soil C is seen in Fig. 6 to decline by 31.6 t/ha in the upper 200 mm of soil after 11 yrs continuous maize, and by 49.6 t/ha after 35 yrs continuous barley; an average loss of 2.9 and 1.7 t/ha/yr respectively. Note the initial slow rate of recovery of total C after 10 years of pasture following 11 yrs of maize. After 19 yrs of ryegrass/clover pasture, the total C had not recovered to pre-cropping pasture levels of 90.8 t/ha. The significant loss of C under both maize and barley, and the slow rate of C recovery under pasture are due in part to the poor management practices that prevailed. The slow rate of recovery of C under pasture was also due to the extremely compacted, poorly aerated state of the soil.

FIGURE 6 Total C in the topsoil under pasture and continuous cropping



Total C in the topsoil (0–200 mm) after 11 yrs and 37 yrs of continuous maize and barley respectively under conventional cultivation.

Note the rate of recovery of total C after 10, 14, 17 and 19 years of pasture following 11 yrs of maize.

FIGURE 7 Total C in the topsoil under pasture, no-till and conventional cultivation



In comparison, the loss of soil C under no-tillage is significantly less than under conventional cultivation (Fig. 7). In some instances, C levels have increased in the upper 150 mm of soil under no-tillage compared with pasture. The greatest increases in soil C can occur at a depth of 300–600 mm under ‘pasture cropping’ practices where no herbicides or insecticides have been applied. The substantial loss of C under conventional cultivation and the slow rate of C recovery under pasture are due to the non-adoption of carbon capture and storage (CCS) management practices.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore ‘grow’ the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 32), certain management practices and specific types of fertiliser need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 32) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits.

FIGURE 8 Scorecard – visual indicators to assess the potential for carbon sequestration

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of soil carbon	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g. 2	x 2	
Clay mineralogy (Scoring protocol is given below ²)		x 2	
Soil colour	g. 10	x 2	
Earthworms (Number =) (Av. size =)	g. 14	x 3	
Potential rooting depth (mm)	g. 22	x 3	
Root development	g. 46	x 3	
Crop yield	g. 58	x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 2	
Method of cultivation (Scoring protocol is given below ⁴)		x 3	
SOIL CARBON INDEX (sum of VS rankings)			

Soil Carbon Assessment	Soil Carbon Index
Potentially poor carbon levels	< 17
Potentially moderate carbon levels	17–32
Potentially good carbon levels	> 32

- Textural group:** VS = 2 for Clayey; VS = 1.5 for Fine loamy and Fine silty; VS = 1.0 for Coarse silty; VS = 0.5 for Coarse loamy; VS = 0 for Sandy.
- Clay mineralogy:** VS = 2 if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; VS = 1 if the soil has moderate levels of Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an ASC of 60–75 percent; VS = 0 if the soil has little or no Fe & Al hydroxides and amorphous aluminio-silica minerals; ASC is < 45 percent.
- Amount and form of fertiliser and N applied:** VS = 2 if “smart” fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based N fertilisers.
- Method of cultivation:** VS = 2 if using ‘pasture cropping’ and no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous mouldboard ploughing with intensive secondary cultivation.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions

Assessment

- 1 Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 12, p. 89) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual score for Crop yield from the Plant Scorecard. Also add a ranking score for the method of cultivation used and the amount and form of N applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.

Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C; without them the earth's average temperature would be around -18°C. However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Solar radiation



Agriculture can provide a significant source of CH₄ and N₂O and is responsible for 15 percent of worldwide greenhouse gas emissions. CO₂ is emitted under arable cropping, however it is reabsorbed as photosynthate by the crop and is therefore greenhouse neutral. While high emission levels of GHGs are more to do with the way we farm, climate friendly and smart agricultural management can significantly reduce emissions.

GHG emissions from cropping result from a number of sources, including the soil, the burning of fossil fuels by farm machinery, and the production and application of nitrogenous fertilisers. The level of emissions varies according to a number of factors, including the condition of the soil, the method of cultivation, and the amount and form of fertiliser N applied, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO₂ to soil C, and by promoting the soil as a CH₄ sink. The C credits gained can help off-set their GHG emissions.

PLATE 51 Field with a low potential for greenhouse gas emission

Field with a low potential to emit GHGs due to the soil being a well-drained, coarse loamy soil with good porosity under a no-tillage regime. In addition, good crop growth and yield remove a large amount of CO₂ from the atmosphere and CO₂ escaping from the soil by photosynthesis.

PLATE 52 Field with a high potential for greenhouse gas emission

Field with a high potential to emit GHGs due to the soil being an imperfectly to poorly drained, clayey soil with poor porosity under continuous conventional cultivation. In addition, poor crop growth and yield remove only small amounts of CO₂ from the atmosphere and CO₂ escaping from the soil by photosynthesis.

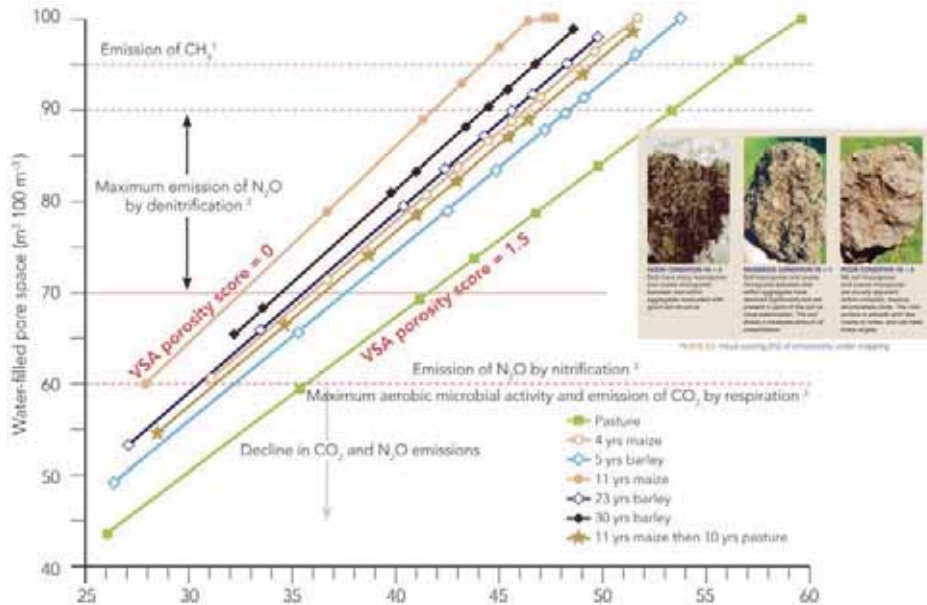
The potential of a site to emit GHGs can be roughly assessed from four indicators of soil quality, one indicator of plant performance, the amount and form of nitrogen applied, and the method of cultivation, as described below.

Soil textures (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major ‘driver’ of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs.

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O , and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 9); emissions of N_2O are lowest when the WFPS is < 50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 9) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O . In contrast, a severely compacted soil after 11 yrs of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 9) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2 . While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is

FIGURE 9 Affect of water-filled pore space and water content on greenhouse gas emissions

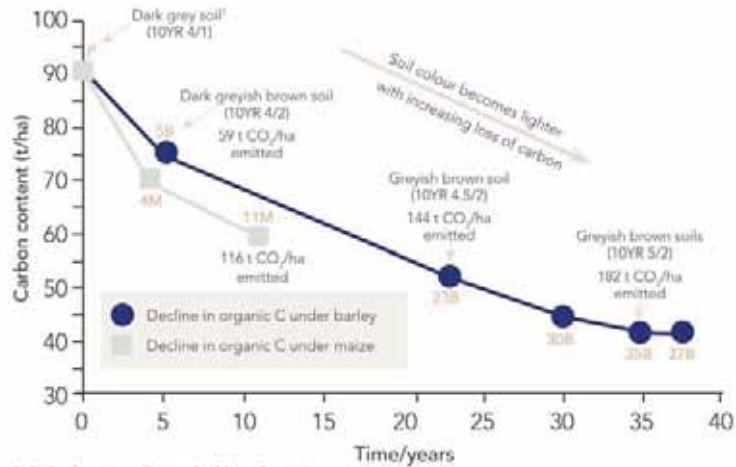


¹ After MacDonald *et al.* (1996); ² After Dobbie *et al.* (1999); ³ After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

hence an effective means of reducing GHG emissions. The relationship between the WFPS and the visual assessment of the porosity of the soil, as shown in Fig. 9, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink. A lighter soil colour compared with soil under the fenceline can also indicate the loss of soil C and the emission of significant amounts of CO_2 into the atmosphere (Figure 10).

FIGURE 10 Soil C loss and associated CO₂ emissions under continuous cropping

Soil C loss, associated soil colour, and CO₂ emissions under continuous maize and barley cropping using conventional cultivation.

Crop yields (p. 58) can provide an indication of the potential to reduce GHG emissions. The greater the crop yield, the greater the amount of CO₂ removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO₂ emitted by microbial respiration, the emission of GHGs from the consumption of the crop by stock, the burning of fossil fuels by farm machinery, and the application of nitrogenous fertilisers. As CO₂ escapes from the soil, most, if not or all, is absorbed by the stomata on the crop leaves, which have an insatiable appetite for CO₂. The greater the canopy cover (leaf area index) and the quicker the canopy closure, the greater the amount of CO₂ removed. Furthermore, if we assume that one kilogram of carbon in a maize crop removes 3.67 kg CO₂ from the atmosphere, a field growing 25 tonnes of maize silage/ha (or 10.3 t C/ha) will remove approximately 38 tonnes of atmospheric CO₂/ha. A field growing just 20 tonnes of maize silage/ha (or 8.2 t C/ha) will remove 30 tonnes of atmospheric CO₂/ha, 22 percent less than the higher producing field. While CO₂ is the least potent of the GHGs with a Global Warming Potential that is 21 and 310 times less than CH₄ and N₂O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO₂ into sugars and oxygen, and subsequently into soil C, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Poor crop yield and the associated reduced crop cover would also reduce insulation from the sun, thereby increasing soil temperatures and reducing the uptake of available N and plant-available water, stimulating N₂O emissions by microbial nitrification and denitrification.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 89) can provide a further indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 9). The nitrification of urea and ammonium-based fertilisers, and particularly the denitrification of nitrates in the soil resulting from the excessive application of salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Fertiliser N applications stimulate emissions in the spring, while crop residues and their incorporation into the soil stimulate emissions in autumn and winter. The highest emissions occur following each fertiliser application, particularly when associated with major rainfall events. Seventy-five to eighty percent of the N_2O emitted can occur within 4 weeks of N application. While N_2O emissions can often account for up to 3 percent of the N applied as fertiliser in small-grain cereal crops and up to 8 percent in maize crops, compact, wet soils can increase N_2O emissions by denitrification 3–4-fold, resulting in a loss of up to 20 percent of fertiliser N, and also decreasing wheat yields by 25 percent. Yield reductions can be attributed in part to N deficiency by high denitrification activity and low mineralization. In addition, the excessive use of nitrogenous products can reduce the capacity of soils to take up and oxidise atmospheric CH_4 , thereby reducing the ability of the soil to act as a CH_4 sink.

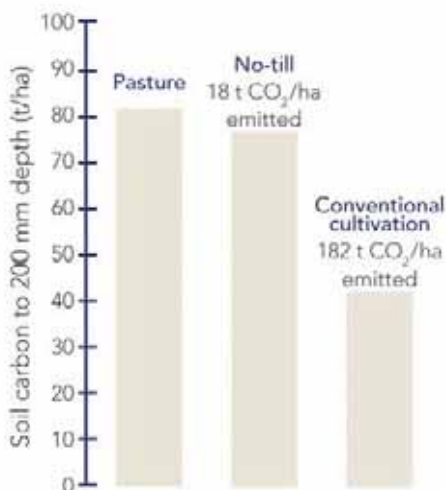
Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied to crops could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic and fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70%) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides microsites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root development, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70%, they can increase NH_3 emissions and potential NH_4^+ -N leaching losses. The jury is also still out as to their long-term impact on soil biology, in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be

applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reductions in white clover. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

The **method of cultivation** (see scorecard, p. 89) can have a marked effect on the level of GHG emissions. Carbon dioxide emissions are significantly greater under conventional cultivation than other forms of ground preparation because of the greater loss of soil C (Figs 10 & 11). The high level of soil disturbance under conventional cultivation aerates the soil, increasing the mineralisation and oxidation of organic C to CO_2 by microbial respiration which subsequently volatilises into the atmosphere. If we assume that one tonne of organic C oxidises to 3.67 tonnes of CO_2 , the loss of 31.6 t C/ha after 11 yrs of conventionally cultivated maize gives rise to the emission of approximately 116 t CO_2 /ha (Fig. 10). The loss of 49.6 t C/ha after 35 yrs of continuous barley produces 182 t CO_2 /ha. These figures do not, however, take into account the C added to the soil from the plant over the 11- and 35-year cropping period, C that would also have oxidised and potentially contributed to CO_2 emissions. However, as mentioned above, after CO_2 escapes from the

FIGURE 11 Soil C loss and associated CO_2 emissions under no-till and conventional cultivation



Soil C loss and associated CO_2 emissions under 20 yrs of double cropping using no-tillage and 35 yrs conventional cultivation.

soil, almost all of it is absorbed by the stomata on the crop leaves and is therefore recycled back into the soil. In addition to the major period of CO₂ emissions when the soil is tilled using conventional cultivation, a certain amount of CO₂ would be emitted after the harvest or senescence of one crop, and canopy closure of the next crop.

In comparison, the loss of soil organic C under no-tillage is significantly less than under conventional cultivation, producing as a result, less emissions of CO₂ (Fig. 11). Adopting carbon capture and storage (CCS) management practices including those cultivation practices that minimise C loss or even promoting C sequestration, is an effective means of reducing the emissions of CO₂ into the atmosphere.

Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by the Emissions Trading Schemes. If the GHG Emission Index is ≤ 22 , certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of > 22 provides significant environmental benefits because less GHGs would be emitted into the atmosphere.

FIGURE 12 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g.2	x 2	
Soil porosity	g.6	x 3	
Number and colour of soil mottles	g.8	x 3	
Soil colour	g.10	x 2	
Crop yield	g.58	x 2	
Amount and form of N applied (Scoring protocol is given below ²)		x 1	
Method of cultivation (Scoring protocol is given below ³)		x 3	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 12
Moderate potential GHG emissions	12–22
Low potential for GHG emissions	> 22

1 Textural group (Figure 2b, p. 3):

VS = 2 for Sandy and Coarse loamy; VS = 1.5 for Coarse silty; VS = 1.0 for Fine loamy; VS = 0.5 for Fine silty; VS = 0 for Clayey.

2 Amount and form of N applied:

VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 Method of cultivation:

VS = 2 if using no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous conventional (mouldboard plough) cultivation with intensive secondary cultivation.

Soil management of maize crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, include ‘pasture cropping’ where annual crops are direct-drilled into perennial pastures, and no-tillage and minimum tillage practices that incorporate the establishment of temporary cover crops and crop residues on the surface. They provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage can also maintain soil life and biological activity (including earthworm numbers), and can increase micro-organism biodiversity above levels commonly found under conventional cultivation. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO₂) and enables the soil to operate as a sink for CO₂. Soil organic matter levels can build up as a result and create the potential to gain ‘carbon credits’, thereby providing an offset to greenhouse gas emissions. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

Where possible, put in place management strategies that don’t require the use of herbicides. Avoid a monochemical herbicide strategy and manage the use of herbicides in association with crop rotations, including the use of livestock, to avoid the development of herbicide tolerance and residual effects. Ensure the soil has adequate levels of available Ca because herbicides are generally more effective when Ca levels in the plant are good. Also ensure that P levels aren’t too high; the higher the P level, the harder it is to deal to snails and slugs. The inappropriate and over-use of various herbicides can significantly change nutrient availability and the efficient uptake of nutrients by binding up micronutrients (chelation immobilization), and through toxic effects on soil organisms important for nutrient turnover and supply.

Continuous conventional cultivation can impact negatively on the environment with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO₂), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades

PLATE 53 A good maize crop



Photo: Courtesy of Kenneth G. Cassman

A good maize crop producing a grain yield in excess of 20 t/ha due in part to the adoption of good management practices that promote a good root system. Note the good potential rooting depth and root development to > 2m. Compare with Plate 16, p. 23

soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. Conventional cultivation should be practiced on a rotational basis with 2 years of cropping followed by 5–7 years pasture.

The fundamental difference between continuous conventional cultivation and conservation tillage is their relative environmental and economic sustainability. The long-term affects of continuous conventional cultivation can be cumulatively negative whereas the long-term affects of conservation tillage can be cumulatively positive. This is provided that good residue management practices are applied and the herbicides used are 100% biodegradable and have no adverse effects on soil or human health.

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for maize*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Annual Crops



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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
CO ₂	Carbon dioxide
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of annual cropping. A decline in soil quality has a marked impact on plant growth and yield, grain quality, production costs and the increased risk of soil erosion. Therefore, it can have significant consequences on society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of annual cropping are important tasks for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the character and quality of annual cropping and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing crops, and to make informed decisions that will lead to sustainable land and environmental management. To this end, Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for annual crops. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a scorecard. With the exception of soil texture, the soil indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and as such provide an effective monitoring tool.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality observed when comparing the soil sample with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil indicators are relatively more important in the assessment of soil quality than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index score for the sample you are evaluating. Compare this with the rating scale at the bottom of the scorecard to determine whether your soil is in good, moderate or poor condition.

The VSA tool kit

PLATE 1 The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in fields is site specific. Avoid areas that may have had heavier traffic than the rest of the field and sample between wheel traffic lanes. However, VSA can also be used to assess the effects of high traffic on soil quality by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

Format of the booklet

The soil scorecard is given in Figure 1 and lists the ten key soil ‘state’ indicators required in order to assess soil quality. Each indicator is described on the following pages, with a section on how to assess each indicator and an explanation of its importance and what it reveals about the condition of the soil.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in annual crops

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Date:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 2	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 1	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

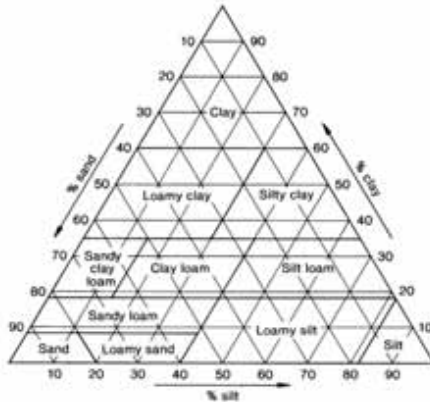


Importance

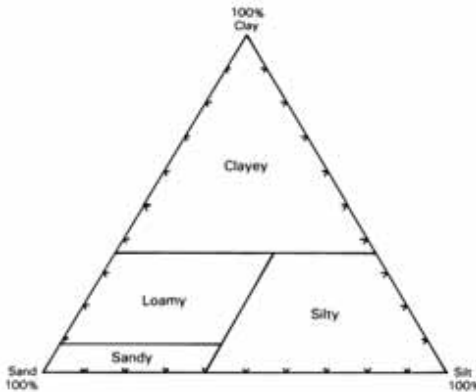
SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil workability and trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for arable cropping. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- ① Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- ② Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and indicates whether the soil is functioning as a carbon 'sink' or as a source of greenhouse gases. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of crops increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe³⁺) and manganic (Mn³⁺) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe²⁺) and manganous (Mn²⁺) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot in soils prone to waterlogging.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.

Assessment

- Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S and Cu. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. In addition, decay and dieback of roots can occur as a result of fungal diseases such as *Rhizoctonia*, *Pythium* and *Fusarium* root rot, foot rot and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

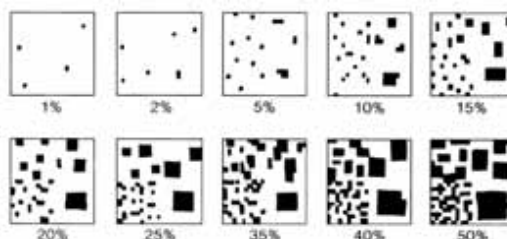


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (>50%) medium and coarse orange and particularly grey mottles.



Assessment

- ① Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 7) and compare with the class limits in Table 2. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in cropping soils and can increase growth rates, crop yield and protein levels significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their

PLATE 6 (a): earthworm casts under crop residue; (b): yellow-tail earthworm (*Octolasion cyaneum*)

biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes can increase crop production markedly while at the same time reducing fertilizer requirements.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the crops grown, the amount and quality of surface residues (Plate 6a), the use of cover crops and the method of tillage. Earthworm populations can be up to three times higher under no-tillage than conventional cultivation. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

Earthworms species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 6b) can indicate adverse soil conditions.

PLATE 7 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present (Plate 8), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also whether there is an over-thickening of roots (a result of a high penetration resistance), and whether the roots are being forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan (pp 16–17). An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated crops. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the crop. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ❖ an abrupt textural change;
- ❖ pH;
- ❖ aluminium (Al) toxicity;
- ❖ nutrient deficiencies;
- ❖ salinity;
- ❖ sodicity;
- ❖ a high or fluctuating water table;
- ❖ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Crops with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce, promote soil structure, porosity, water storage, soil aeration and drainage at depth. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on frequent and high application rates of fertilizer and N to generate growth, and available nutrients are more likely to be taken up, so reducing losses by leaching into the environment.

PLATE 8 Hole dug to assess the potential rooting depth



The potential rooting depth extends to the bottom of the arrow, below which the soil is extremely firm and very tight with no roots or old root channels, no worm channels and no cracks and fissures down which roots can extend.

TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

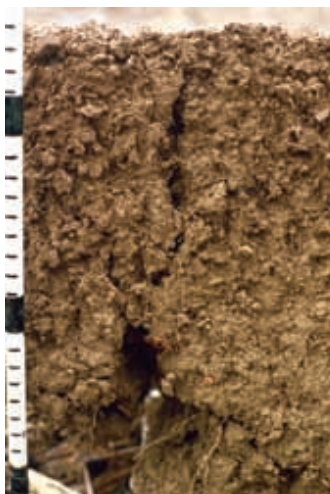
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given in Plate 10.

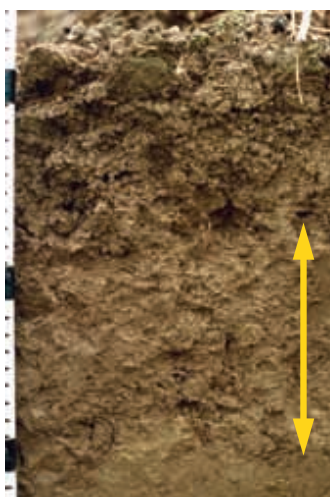
PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth of roots. Roots need oxygen for respiration. They are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are actively growing at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the crop is transpiring actively causes leaf desiccation and the plant to wilt. Prolonged waterlogging also increases the likelihood of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Plant stress induced by poor aeration and prolonged soil saturation can render crops less resistant to insect pest attack such as aphids, armyworm, cutworm and wireworm. Crops decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, become discoloured and die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of the root system to surface ponding and waterlogging is dependent on a number of factors, including the time of year and the type of crop. Tolerance of waterlogging is also dependent on: soil and air temperatures; soil type; the condition of the soil; fluctuating water tables; and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate.

Prolonged surface ponding makes the soil more susceptible to damage under wheel traffic, so reducing vehicle access. As a consequence, waterlogging can delay ground preparation and sowing dates significantly. Sowing can further be delayed because the seed bed is below the crop-specific critical temperature. Increases in the temperature of saturated soils can be delayed as long as water is evaporating.

PLATE 11 Surface ponding in a field



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤1	No surface ponding of water evident after 1 day following heavy rainfall on soils that were at or near saturation.
1 [Moderate]	2–4	Moderate surface ponding occurs for 2–4 days after heavy rainfall on soils that were at or near saturation.
0 [Poor]	>5	Significant surface ponding occurs for longer than 5 days after heavy rainfall on soils that were at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER after harvesting and prior to canopy closure of the next crop helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of conservation tillage can reduce soil erosion by up to 90 percent and water runoff by up to 40 percent. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of soils through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be water eroded by gullying, rilling and sheet wash. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability of water through the soil;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation can also give rise to significant soil loss by wind erosion of exposed ground.

PLATE 13 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no *water erosion*. Topsoil depths in the footslope areas are <150 mm deeper than on the crest.

Wind erosion is not a concern; only small dust plumes emanate from the cultivator on a windy day. Most wind-eroded material is contained in the field.

**MODERATE CONDITION VS = 1**

Water erosion is a moderate concern with a significant amount of rilling and sheet erosion. Topsoil depths in the footslope areas are 150–300 mm greater than on crests, and sediment input into drains/streams may be significant.

Wind erosion is of moderate concern where significant dust plumes can emanate from the cultivator on windy days. A considerable amount of material is blown off the field but is contained within the farm.

**POOR CONDITION VS = 0**

Water erosion is a major concern with severe gully, rilling and sheet erosion occurring. Topsoils in footslope areas are more than 300 mm deeper than on the crests, and sediment input into drains/streams may be high.

Wind erosion is a major concern. Large dust clouds can occur when cultivating on windy days. A substantial amount of topsoil can be lost from the field and deposited elsewhere in the district.

Soil management of annual crops

Good soil management practices are needed in order to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximize water and nutrient utilization. Good soil structure also promotes infiltration and movement of water into and through the soil, minimizing surface ponding, runoff and soil erosion.

Conservation tillage practices, including no-tillage and minimum tillage that incorporate the establishment of temporary cover crops and crop residues on the surface (Plates 14–16), provide soil management systems that conserve the environment, minimize the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface, reducing water runoff and soil erosion. It reduces wheel traffic, which lessens wheel traffic compaction and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimize sowing time, being less dependent on climate conditions in spring and autumn. It improves soil physical characteristics, encourages soil life and biological activity (including earthworm numbers), and increases micro-organism biodiversity. Unlike conventional tillage, conservation tillage also enables the soil to retain a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO_2), enabling the soil to act as a sink for CO_2 . Consequently, soil organic matter levels build up and, therefore, the potential to gain carbon credits. Moreover, conservation tillage uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

On the other hand, conventional tillage can have a negative impact on the environment, with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases greenhouse gas emissions (including the release of 5–times more CO_2), and uses more fossil fuels (i.e., 6–times more consumption of fuel). It degrades soil structure, increases soil erosion, and alters microflora and microfauna adversely by reducing both the number of species and their biomass. The fundamental difference between conventional tillage and conservation tillage is their relative environmental and economic sustainability. The long-term effects of conventional tillage are cumulatively negative whereas the long-term effects of conservation tillage are cumulatively positive.

PLATE 14 No-till drilling an annual crop into an erosion-prone field protected by herbicided pasture [BAKER NO-TILLAGE LTD]



PLATE 15 Strip-tillage planting of an annual crop protected by good residue cover



PLATE 16 Harvesting an annual grain crop followed immediately by no-till seeding the next crop into stubble [BAKER NO-TILLAGE LTD]



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Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for annual crops*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Olive Orchards



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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
CO ₂	Carbon dioxide
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of orchards. A decline in soil quality has a marked impact on tree growth, olive production and the character and quality of olive oil, production costs and the risk of soil erosion. Therefore, it can have significant consequences on society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of olive orchards are important tasks for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance of olive orchards, and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing olives, and to make informed decisions that lead to sustainable land and environmental management. To this end, Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for olives. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a scorecard. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant scorecard. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, the soil quality

assessment is not a combination of the ‘soil’ and ‘plant’ scores. Rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate or poor condition.

Placing the soil and plant assessments side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.

PLATE 1 The VSA tool kit



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the orchard. The condition of the soil in olive orchards is site specific. Sample sites that have had little or no wheel traffic (e.g. near the olive tree). The VSA method can also be used to assess compacted areas by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS rankings in the right-hand column.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required in order to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil and about plant performance.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in olive orchards

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Date: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
 Moisture condition: Dry Slightly moist Moist Very moist Wet
 Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 2	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 1	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 2	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

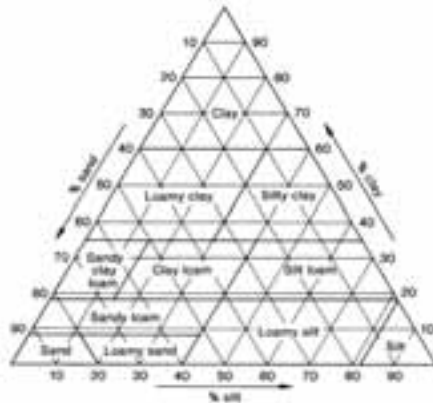


Importance

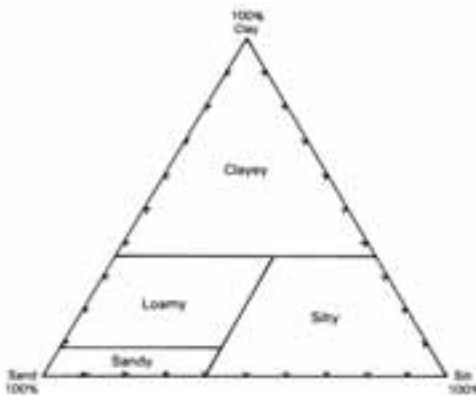
SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for olive orchards. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- ❶ Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- ❷ Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and maintains the soil carbon 'sink'. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of trees increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of fungal diseases such as *Phytophthora* root and crown rot in soils prone to waterlogging. Trees exhibit reduced growth, have thin canopies, and eventually die.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.

Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure decreases and blocks the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K and S. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. Decay and dieback of roots can also occur as a result of fungal diseases such as *Phytophthora* root and crown rot in strongly mottled, poorly aerated soils. Root rot and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. Trees exhibit reduced growth, have thin canopies, and eventually die. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

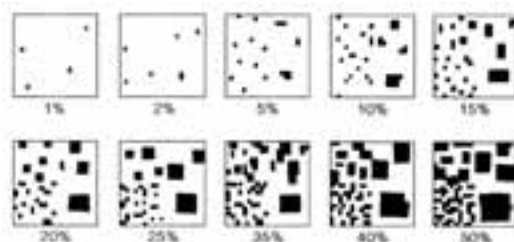


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (>50%) medium and coarse orange and particularly grey mottles.



Assessment

- ① Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 6) and compare with the class limits in Table 2. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in olive orchards and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in

the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes reduce fertilizer requirements and improve trees and olive production.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue, the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 6 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- 1 Dig a hole to identify the depth to a limiting (restricting) layer where present, and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots (Plates 7 and 8) and old root channels, worm channels, cracks and fissures down which roots can extend. Note also the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan. An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting, gully, slip, earth slump or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated olive orchards. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the olives. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases crop yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Olive trees with a deep, dense, vigorous root system raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce promote soil structure, porosity, water storage, soil aeration and drainage at depth. The soil depth should preferably not be less than 600 mm. Heavy clay soils are not recommended. Stony soils are acceptable under artificial irrigation. Furthermore, olive trees need a sufficient rooting depth to provide adequate anchorage for the trees at maturity.

PLATE 7 Root system of an olive tree



PLATE 8 Generic drawing of an olive tree [L. DRAZETA and A. LANG]



TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

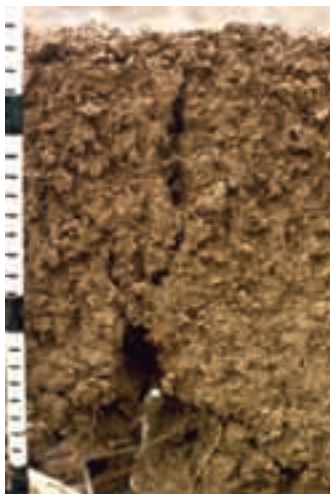
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given Plate 10.

PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Olive trees generally require free-draining soils. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth and development of roots. Roots need oxygen for respiration. While olive trees transpire all year round and do not have a dormant period, they are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are growing actively at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging cause the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the tree is transpiring actively causes leaf desiccation and tip-burn. Prolonged waterlogging also increases the likelihood of infections and fungal diseases such as *Phytophthora* root rot and crown rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Trees decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, have thin canopies, and eventually die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of olive trees to waterlogging is dependent on a number of factors, including the time of year, the rootstock, soil and air temperatures, soil type, the condition of the soil, fluctuating water tables and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the amount of entrapped air and the oxygen consumption rate by plant roots.

Prolonged surface ponding increases the susceptibility of soils to damage under wheel traffic, so reducing vehicle access.

PLATE 11 Surface ponding in an olive orchard [J. GOMEZ]



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤ 1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–4	Moderate surface ponding occurs for 1–3 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	> 5	Significant surface ponding occurs for longer than 3 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare with Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.

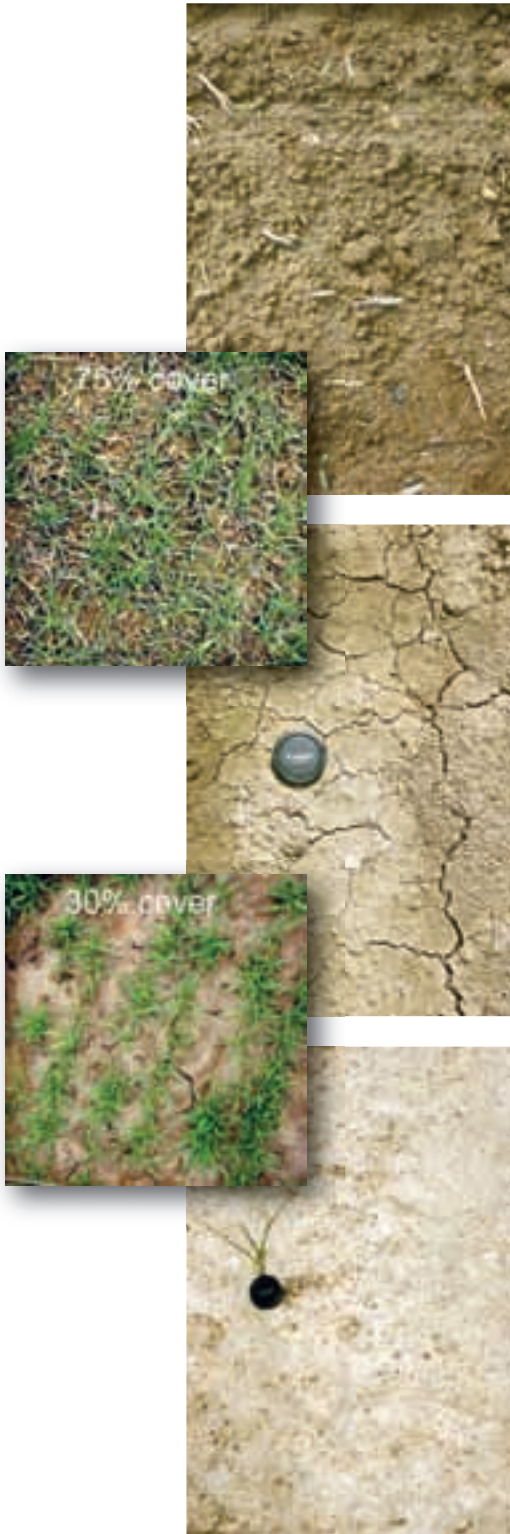


Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of managed cover crops has in some cases reduced sediment erosion rates from 70 tonnes/ha to 1.5 tonnes/ha during single large rainfall events. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Photos of surface cover: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and, more importantly, on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of an olive orchard through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation of interrows can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be removed by slips, flows, gullying and rilling, or it can be relocated semi-intact by slumping. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation between rows can also give rise to significant soil loss by wind erosion of exposed ground where the tree spacing is quite large.

PLATE 13 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no evidence of soil erosion. Little difference in height between the mounded row and interrow. The root system is completely covered.

**MODERATE CONDITION VS = 1**

Moderate soil erosion with a significant difference in height between the interrow and the soil around the base of the tree trunk. Part of the upper root system is occasionally exposed.

**POOR CONDITION VS = 0**

Severe soil erosion with deeply incised gullies or other mass movement features between rows. There is a large difference in height between the interrow and the soil around the base of the tree trunk. The root system is often well exposed and sometimes undermined.

FIGURE 3 Plant scorecard – visual indicators for assessing plant performance in olive orchards

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Canopy volume pg. 26		x 2	
Canopy density pg. 28		x 3	
Shoot length pg. 30		x 3	
Flowering pg. 32		x 3	
Leaf colour pg. 34		x 3	
Yield pg. 36		x 2	
Variability of tree performance along the row pg. 38		x 2	
PLANT PERFORMANCE INDEX (sum of VS rankings)			

Plant Performance Assessment	Plant Performance Index
Poor	< 10
Moderate	10–25
Good	> 25

SUMMARY

Comparison of soil & plant assessments		Do the soil and plant assessments differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:



Assessment

- 1 Assess canopy volume in the late spring to early summer at flowering by comparing the olive tree with Plate 14 and the criteria given. In making the observation, consideration must be given to choosing a representative olive tree in terms of variety, pruning and age. In some cases, orchards are composed of trees of different age and cultivars. Corrections can be made on the basis of previously known annual growth rates as a function of age and cultivars, assigning a hypothetical common age for all trees and subtracting that part of the growth in the canopy volume. Canopy volume can be calculated approximately by applying the simple formula: canopy volume = $w \times b \times h$, where w is the width, b is the breadth and h is the height of the canopy.



Importance

CANOPY VOLUME at the flowering stage is dependent on: the age of the tree, cultivar, pruning, orchard management, disease, and climate factors (including frost damage). However, it can be a useful visual indicator of production and soil quality. Indeed, poor soil structure and soil aeration, limited movement and storage of water, and soil erosion as a result of structural degradation can reduce plant growth and vigour. Canopy volume is a particularly useful assessment of soil quality where climate factors have not limited crop development.

PLATE 14 How to score canopy volume

**GOOD CONDITION VS = 2**

Canopy volume is greater than 100 m^3 (varying from 4–5 m high by 5–6 m wide or more) for mature trees planted at spacings of 5x5 or 6x6 m. Trees have a good distribution of leaves.

**MODERATE CONDITION VS = 1**

Canopy volume is about 50 m^3 (varying from 3–4 m high by 4 m wide) for mature trees planted at spacings of 5x5 or 6x6 m. Trees have a moderate distribution of leaves.

**POOR CONDITION VS = 0**

Canopy volume is less than 23 m^3 (i.e. $\leq 2\text{--}2.5 \text{ m}$ high by 3 m wide) for mature trees planted at spacings of 5x5 or 6x6 m. Trees have a poor distribution of leaves.



Assessment

- 1 Assess the canopy density by comparing with Plate 15 and the criteria given.
- 2 The assessment can be made at any stage after the new growth in the spring and before harvest. In making the assessment, consideration must be given to the pruning and variety of the tree, the presence of pests and diseases, and the weather conditions at bud break (i.e. whether warm and dry, or cold and wet). Poor weather during bud break will promote a high number of leaf buds rather than flowering buds and give rise to many shoots and leaves.



Importance

CANOPY DENSITY is a good indicator of the health and vigour of the tree as reflected by the number of shoots, the number of leaves per shoot and the age of the leaves. In addition to the weather, tree vigour is related strongly to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy, sandy or gravelly). Moreover, soils in good condition with good structure and porosity, and having a deep, well-aerated root zone, enable the unrestricted movement of air and water into and through the soil and the development and proliferation of superficial (feeder) roots. Furthermore, soils with good organic matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, the growth and vigour of the tree. The amount of photosynthate produced by the tree is proportional to the number of leaves and, therefore, influences strongly the growth of the tree and the production and quality of olives.

PLATE 15 How to score canopy density

**GOOD CONDITION VS = 2**

Good canopy density with abundant shoots and leaves per shoot. Many of the leaves are more than two years old.

**MODERATE CONDITION VS = 1**

Moderate canopy density with a moderate number of shoots and leaves per shoot. Most leaves are less than two years old.

**POOR CONDITION VS = 0**

Poor canopy density with few shoots and few leaves per shoot. The canopy appears sparse and spindly. The tree sheds its older leaves prematurely, with only one-year-old leaves being present.



Assessment

- 1 Measure or visually assess shoot length (each month if possible starting from mid-spring to the end of summer) on the mature part of the aerial part of the plant and compare it with Plate 16 and the criteria given. In making the assessment, consideration must be given to the pruning and variety of the tree, and to the weather conditions at bud break and during the spring.



Importance

SHOOT LENGTH determines the number of buds, some of which will bear flowers. It is also strongly related to the physical properties and chemical fertility of the soil, which in turn is influenced by soil management. Shoot length is an expression of plant vigour and general plant growth, which are regulated by the availability of water, nutrients and the aeration status of the soil. Soils in good condition with a deep vigorous root system, good structure, porosity, organic matter levels and soil life show an active chemical and biological process, favouring the release and uptake of nutrients and water, and consequently shoot growth.

PLATE 16 How to score shoot length



GOOD CONDITION VS = 2
Shoots are at least 200 mm (depending on variety) on the external part of the plant.



MODERATE CONDITION VS = 1
Shoot length is moderately below maximum (depending on variety) on the external part of the plant.



POOR CONDITION VS = 0
Shoot length is significantly below maximum (depending on variety) on the external part of the plant.



Assessment

- 1 Assess by visual estimation the number and distribution of flowers at full flowering by comparing with Plate 17 and the criteria given. In making the assessment, consideration must be given to the pruning management of the tree and the weather conditions at bud break and in spring (i.e. whether warm and dry, or cold and wet). Poor weather will promote a high number of leaf buds rather than flowering buds and give rise to lots of shoots and leaves rather than flowers.



Importance

The number and distribution of **FLOWERS** affects fruiting behaviour. The presence of a large number of flowers is also a good indicator of high yields. Flower induction starts in the preceding year of the olive production cycle. Its intensity depends on: weather conditions at the time (e.g. whether wet and cold, or dry and hot); the production of carbohydrate; and the presence of specific hormones necessary to drive the bud apex toward inflorescence production. Carbohydrate production depends on climate conditions, including: the amount of energy from the sun, the number of leaves on the tree, the cultivar, diseases, the availability of water and nutrients, and the physical status of the soil. Once again, soil fertility (physical, chemical and microbiological conditions) is crucial in determining high plant productivity.

PLATE 17 How to score flowering



GOOD CONDITION VS = 2
High number of flowers per shoot and well distributed over the tree.



MODERATE CONDITION VS = 1
Moderate number of flowers occur.



POOR CONDITION VS = 0
Low number of flowers and poorly distributed over the tree.



Assessment

- 1 Assess the colour of the leaves by comparing with Plate 18 and the criteria given. The assessment must be made after the first flush of new growth at the end of the first annual growing period and on leaves exposed to the sunlight. Olive trees have leaves of different ages, varying from one to three years old. Assess only the young leaves, avoiding the deteriorating and immature leaves at the extremities of branches. Consideration must also be given to: the cultivar, the stage of growth, pests and diseases, and recent weather conditions. Prolonged cold and cloudy days with little sunlight can give rise to chlorosis (or yellowing of the leaf) owing to the inadequate formation or loss of chlorophyll.



Importance

LEAF COLOUR can provide a good indication of the nutrient status and condition of the soil. The higher the soil fertility, the greener the leaf colour. Leaf colour is related primarily to water and nutrient availability and especially N. Leaf colour can also be related to a deficiency or excess in phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and boron (B). Chlorosis can further occur as a result of low N, K, S, Fe, Mg and Cu levels in the soil, low soil and air temperatures, and poor soil aeration caused by compaction and waterlogging.

Sulphur is an important element for plant growth and leaf colour and can only be utilized by plants in the sulphate (SO_4^{2-}) form. Under poorly-aerated conditions caused by compaction or waterlogging, S will reduce to sulphur dioxide (SO_2) and sulphides (e.g. H_2S , FeS). Sulphides and SO_2 cannot be taken up by the plant, are toxic to plant roots and micro-organisms, and suppress the uptake of N. Plants can only utilize N where S is present in the oxygenated (sulphate) form. Nitrogen can also only be utilized by the plant in the nitrate (NO_3^-) and ammonium (NH_4^+) forms under aerobic conditions. Under poorly-aerated conditions, N will reduce to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and become plant-unavailable.

PLATE 18 How to score leaf colour



GOOD CONDITION VS = 2
Canopy has an intense green colour.



MODERATE CONDITION VS = 1
Leaves are a medium-green or yellowish-green colour.



POOR CONDITION VS = 0
Leaves are a distinct yellowish colour or turn opaque green.



Assessment

- ❶ Assess relative crop yield by visually estimating the yield per tree and by comparing fruit number and size with Plate 19 and the criteria given. Compare also the percentage of olive oil extracted with that from an ideal crop.
- ❷ In making your assessment, consideration must be given to the amount and type of fertilizer used, disease, and the cultivar, pruning and age of the olive tree. While olive trees can be rejuvenated by good pruning, the greatest yield potential of trees occurs from tree maturity to about 40 years of age on average. Olive trees generally mature in 10 years in humid temperate climates and 15 years in drier Mediterranean climates.
- ❸ Consideration must also be given to the weather conditions (e.g. whether warm and dry, or cold and wet) at pollination, fertilization, flowering and fruit-set. Pollination and fertilization are best when the weather is dry and warm. Cold and wet weather during flowering can give rise to poor fruit-set. Warm weather at fruit-set will give good yields while cold wet weather will give poorer yields. Yield is also influenced by the amount of photosynthate produced by the tree, which is proportional to the number of leaves. Because olive trees are generally biennial bearing, consider the average yield over a 3-year or 4-year period.



Importance

YIELD can be a good visual indicator of the properties and condition of the soil. Olive trees can come under stress from drought (especially during the crucial flowering stage) and from a decline in soil quality caused by reduced water storage and plant-available water, nutrient deficiencies, poor aeration, and restricted root development as a result of soil compaction, a hardpan, a fluctuating water table, etc. This results in disease attack, shorter bud length, a lower number of flowers and poor yield production. Plant stress induced by soil structure degradation during harvesting time also affects the quality of the fruit by changing the amount and type of organic acids and polyphenols.

Appropriate soil management, including the adoption of a managed cover crop between rows and avoiding wheel traffic when the soil is wet, helps to promote the physical condition and overall fertility of the soil, minimize soil erosion, and promote sustainable long-term production.

PLATE 19 How to score yield



GOOD CONDITION VS = 2

Average yield is >0.5 kg of olives/ m^3 of mature trees (10–15 years old).



MODERATE CONDITION VS = 1

Average yield is 0.3 – 0.5 kg of olives/ m^3 of mature trees (10–15 years old).



POOR CONDITION VS = 0

Average yield is <0.3 kg of olives/ m^3 of mature trees (10–15 years old).



Assessment

- 1 Cast your eye along the rows and observe any variability in tree performance (in terms of tree height, trunk thickness, canopy volume, canopy density, leaf colour, etc.) and compare with the class limits in Table 5. In making the assessment, consideration must be given to the variety, pruning and age of the olive tree.



Importance

VARIABILITY OF TREE PERFORMANCE ALONG THE ROW is a good visual indicator of the properties and condition of the soil (Plates 20 and 21). In particular, the linear variability in tree performance is often related to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy, sandy or gravelly). Moreover, soils in good condition with good structure and porosity, and with a deep, well-aerated root zone, enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic-matter levels and soil life (including mycorrhiza) show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, the growth and vigour of the tree.

The spatial variability of tree performance along the row is also a useful indicator because it highlights those trees that are underperforming compared with the majority, enabling a specific investigation as to why those are struggling and what remedial action may be taken.

TABLE 5 **Visual scores for variability of tree performance along the row**

Visual score (VS)	Variability in tree performance along the row
2 [Good]	Tree performance is good and even along the row
1 [Moderate]	Tree performance is moderately variable along the row
0 [Poor]	Tree performance is extremely variable along the row

PLATE 20 Effect of soil texture and available water on tree performance along the row [M. GREVEN]

Variable tree performance along the row owing to differences in soil texture and water-holding capacity. Poor-performing trees occur on gravelly (droughty) soils, while well-performing trees are situated on deeper siltier soils (in the background).

PLATE 21 Effect of soil aeration and drainage on tree performance along the row

Variable tree performance along the row in a four-year-old orchard owing to differences in the aeration and wetness status of the root zone. Poor-performing trees occur in the hollows with a shallow water table, while healthier trees are situated on the humps with a deeper, better-aerated root zone owing to a deeper water table.

Soil management in olive orchards

Olive trees with satisfactory production develop shoot of optimal length, promote flower-bud induction, give good percentage fruiting, and stimulate fruit development. Therefore, it is essential to maintain the availability of water, nutrients and carbohydrate during the crop cycle, avoiding any shortages.

Good soil management practices are needed in order to maintain good growth conditions and productivity to safeguard olive tree functionality especially during the crucial periods of plant development and fructification. To achieve this, management practices need to maintain and promote the condition and, therefore, functionality of the soil, particularly in regard to its aeration status and the supply of nutrients and water to the plant. To this end, the soil needs to have a good rooting environment, including an adequate soil structure to allow an effective root system to develop in order to maximize the utilization of water and nutrients, and to provide sufficient anchorage for the plant. Good soil structure also promotes infiltration and movement of water into and through the soil, so minimizing surface ponding, runoff and soil erosion. The maintenance of good soil health through the implementation of sound management practices further safeguards the environment and minimizes the ecological footprint of olive orchards on a region. A decline in soil quality through soil tillage, compaction, increased fertilizer and chemical inputs, and the loss of soil through erosion contribute to the food eco-footprint of a region and the country.

Where rainfall is not a limiting factor for plant growth, the establishment of cover crops is the most suitable soil management practice to protect the soil surface from erosion, to preserve the environment, to reduce production costs and to enhance the quality of the olive oil. Cover cropping not only helps in reducing water runoff and soil erosion, but it also improves the soil physical characteristics, enriches soil organic matter content, and suppresses soil-borne diseases by increasing micro-organism biodiversity. On the other hand, cover crops compete with olive trees for minerals, water and fertilizer where they are not well managed. In the absence of irrigation in the hottest months in those regions characterized by dry summers, competition for water could occur during flowering, fruit formation and development, so limiting the final yield. To avoid this competition, a temporary cover crop or natural vegetation can be grown during the wetter months and can be controlled during the hottest period by herbicide application or mowing 2–3 times during the period of major nutrient demand.

Different mixes of cover crops, including leguminous species that supply N, should be evaluated in different areas. In addition to legumes, the mix could comprise annual or perennial species, grasses and other broadleaf plants. Winter annuals can be grown to protect the soil from erosion in winter and to improve the ability of the soil to resist compaction when wet. Grasses, with their fibrous root system, are also more effective at improving soil structure, and generally add more organic matter to the soil than do legumes. If allowed to seed in early summer, a seed bank for subsequent regeneration is built up. Where possible, the grass in the interrows and within rows could be kept short by grazing sheep, provided the tree trunks

have protective plastic screens to shield them from strip and ring barking. The advantages of managing a grass cover crop using sheep compared with mowing and herbicide strips include: reduced use of synthetic (herbicide) chemicals, reduced fossil fuel usage, lower CO₂ emissions and, therefore, greater market acceptance. Other advantages include: lower labour and material costs; less compaction along wheel traffic lanes; and improved soil nutrient status and greater soil life (including earthworm numbers) as a result of the dung and urine applied. Stock tend to rest, urinate and defecate most within the tree row, translocating and concentrating nutrients to where the tree roots are greatest. Sheep can also graze grass very short, thereby reducing not only the competition for water and nutrients but also reducing insect and bird numbers and the possibility of fungal diseases.

The traditional management of the interrow is based on one or two cultivations with discs and tine harrows during the hot period following natural weed cover and could be satisfactory in limiting, principally, competition for water. The cultivation should be shallower than 100 mm in order to de-vigorate the cover crop but not to modify the canopy/root ratio of the trees by damaging the root system. The cultivation operations can also be useful for incorporating organic and mineral fertilizers as well as controlling diseases caused by fungi and bacteria in the soil.

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Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for olive orchards*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Orchards



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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of orchards. A decline in soil quality can have a marked impact on tree growth, yield, fruit quality and the operation and running of the orchard. A decline in soil physical properties in particular can take considerable time and cost to correct. Safeguarding soil resources for future generations is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the production performance of orchards and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing orchard crops, and to make informed decisions that will lead to sustainable land and environmental management. To this end, Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. The VSA method can also be used to assess the suitability and limitations of a soil for pipfruit, stonefruit and vine crops. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' indicators of soil quality, presented on a scorecard. With the exception of soil texture, the soil indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and as such provide an effective monitoring tool.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality observed when comparing the soil sample with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil indicators are relatively more important for soil quality than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index score for the sample you are evaluating. Compare this with the rating scale at the bottom of the scorecard to determine whether your soil is in good, moderate or poor condition.

The VSA tool kit

PLATE 1 The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in orchards is site specific. Sample sites that have had little or no wheel traffic (e.g. near the tree). The VSA method can also be used to assess compacted areas by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required. Note that the VSA can be used to assess the suitability of a soil for growing pipfruit and stonefruit trees and vine crops before the orchard is established.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test**Initial observation**

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

Format of the booklet

The soil scorecard is given on Figure 1 and lists the ten key soil ‘state’ indicators required in order to assess soil quality. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in orchards

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Date:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 2	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 1	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 2	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

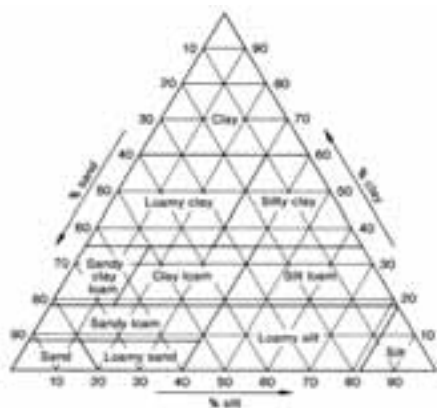


Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for orchards. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and maintains the soil carbon 'sink'. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of trees increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, methane and ethanol that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of fungal diseases such as *Phytophthora* root and crown rot in soils prone to waterlogging. Trees exhibit reduced growth, have thin canopies, and eventually die.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.

Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure decreases and blocks the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K and S. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. In addition, decay and dieback of roots can occur as a result of fungal diseases such as *Phytophthora* root and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. Trees exhibit reduced growth, have thin canopies, and can eventually die. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

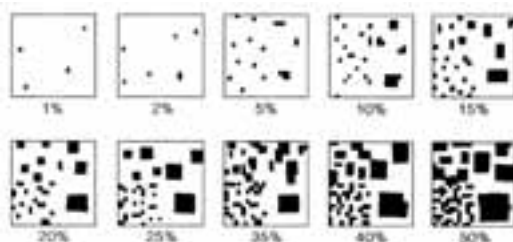


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (> 50%) medium and coarse orange and particularly grey mottles.



Assessment

- 1 Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 6) and compare with the class limits in Table 2. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in orchards and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in

the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes reduce fertilizer requirements and improve the health of the trees and fruit production.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue, the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of:

- (i) surface feeders that live at or near the surface to breakdown plant residues and dung;
- (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and
- (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 6 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- 1 Dig a hole to identify the depth to a limiting (restricting) layer where present (Plate 7), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan (pp 16–17). An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting, gully, slip, earth slump or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated orchards. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the fruit. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Trees with a deep, dense vigorous root system raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce promote soil structure, porosity, water storage, soil aeration and drainage at depth. Soil depth should preferably not be less than 600 mm. Heavy clay soils are not recommended. Stony soils are acceptable under irrigation systems, particularly if the depth of the soil is less than 1 m. An adequate rooting depth is also needed to provide adequate anchorage of the tree at maturity.

PLATE 7 Generic drawing of the root system of a tree [L. DRAZETA and A. LANG]



TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

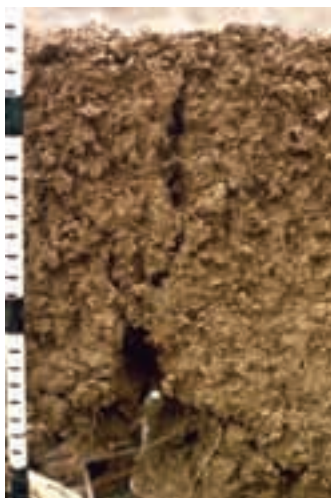
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 8). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 9).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given Plate 9.

PLATE 8 Using a knife to determine the presence or absence of a hardpan



PLATE 9 Identifying the presence of a hardpan



NO HARDPAN

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .



MODERATELY DEVELOPED HARDPAN

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).



STRONGLY DEVELOPED HARDPAN

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 10) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Orchard crops generally require free-draining soils. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth and development of roots. Roots need oxygen for respiration and are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are actively growing at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the tree is transpiring actively causes leaf desiccation and tip-burn, particularly in the outer canopy. Prolonged waterlogging also increases the likelihood of infections and fungal disease such as *Phytophthora* root rot and foot rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Trees decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, have thin canopies, and can eventually die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and manganese to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N, S and Zn. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of trees to waterlogging is dependent on a number of factors, including the time of year, the rootstock and type of tree crop, e.g. pear trees are generally more tolerant than apple trees of saturated soils. Tolerance of waterlogging is also dependent on soil and air temperatures, soil type, the condition of the soil, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate by plant roots.

Prolonged surface ponding increases the susceptibility of soils to damage under wheel traffic, reducing vehicle access.

PLATE 10 Surface ponding in an orchard [A. TOPP]



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤ 1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–4	Moderate surface ponding occurs for 2–4 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	> 5	Significant surface ponding occurs for longer than 5 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare with Plate 11 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of managed cover crops has in some cases reduced sediment erosion rates from 70 tonnes/ha to 1.5 tonnes/ha during single large rainfall events. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 11 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $> 30\%$ and $< 70\%$.

POOR CONDITION VS = 0

Surface crusting is > 5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and, more importantly, on your knowledge of what the site looked like in the past relative to Plate 12.



Importance

SOIL EROSION reduces the productive potential of an orchard through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation of interrows can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be removed by slips, flows, gullying and rilling, or it can be relocated semi-intact by slumping. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation between rows can also give rise to significant soil loss by wind erosion of exposed ground where the tree spacing is quite large.

PLATE 12 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no evidence of soil erosion. Little difference in height between the mounded row and interrow. The root system is completely covered.

**MODERATE CONDITION VS = 1**

Moderate soil erosion with a significant difference in height between the interrow and the soil around the base of the tree trunk. Part of the upper root system is occasionally exposed.

**POOR CONDITION VS = 0**

Severe soil erosion with deeply incised gullies or other mass movement features between rows. There is a large difference in height between the interrow and the soil around the base of the tree trunk. The root system is often well exposed and sometimes undermined.

Soil management in orchards

Trees with satisfactory production develop buds of optimal length, promote flower-bud induction, give good percentage fruiting, and stimulate fruit development. Therefore, it is essential to maintain the availability of water, nutrients and carbohydrates during the crop cycle, avoiding any shortages.

Good soil management practices are needed in order to maintain good growth conditions and productivity to safeguard the functionality of the tree, especially during the crucial periods of plant development and fructification. To achieve this, management practices need to maintain and promote the condition and, therefore, functionality of the soil, particularly in regard to its aeration status and the supply of nutrients and water to the plant. To this end, the soil needs to have a good rooting environment, including an adequate soil structure, to allow an effective root system to develop and so maximize the utilization of water and nutrients, and also provide sufficient anchorage for the plant. Good soil structure also promotes infiltration and movement of water through the soil, minimizing surface ponding, runoff and soil erosion.

Where rainfall is not a limiting factor for plant growth, the establishment of cover crops is the most suitable soil management practice to protect the soil surface from erosion, to preserve the environment, to reduce production costs, and to enhance the quality of the fruit. Cover cropping not only helps in reducing water runoff and soil erosion but also improves soil physical characteristics, enriches soil organic matter content and soil life (including earthworm numbers), and suppresses soil-borne diseases by increasing micro-organism biodiversity. However, cover crops compete for minerals, water and fertilizer where they are not well managed. In the absence of irrigation during the hottest months, competition for water could occur during flowering, fruit formation and development, thereby limiting the final yield. To avoid this competition, a temporary cover crop or natural vegetation can be grown from early autumn to mid-spring (often the wettest period), and it can be controlled during the hottest period by herbicide application or mowing 2–3 times during the period of major nutrient demand.

Different mixes of cover crops, including leguminous species that supply N, should be evaluated in different areas. In addition to legumes, the mix could include annual or perennial species, grasses and other broadleaf plants. Winter annuals can be grown to protect the soil from erosion during the winter and to improve the ability of the soil to resist compaction when wet. With their fibrous root system, grasses are also more effective at improving soil structure, and generally add more organic matter to the soil than do legumes. Where allowed to seed in early summer, a seed bank for subsequent regeneration is built up. Where possible, the grass in the interrows and within rows could be kept short by grazing sheep, provided the tree trunks have protective plastic screens to shield them from strip and ring barking. The advantages of managing a grass cover crop using sheep compared with mowing and herbicide strips include: lower use of synthetic (herbicide) chemicals; reduced fossil fuel use; and lower carbon dioxide emissions and, therefore, greater market acceptance. Other advantages include: lower labour and material costs; less compaction along wheel traffic lanes; improved soil nutrient

status; and greater soil life (including earthworm numbers), as a result of the dung and urine applied. Stock tend to rest, urinate and defecate most within the tree row, translocating and concentrating nutrients to where the tree roots are greatest. Sheep can also graze grass very short, reducing not only the competition for water and nutrients but also reducing insect and bird numbers and the possibility of fungal diseases.

The traditional management of the interrow is based on one or two cultivations with discs and tine harrows during the hot period following natural weed cover and it could be satisfactory in limiting, principally, competition for water. The cultivation should be shallower than 100 mm so as to de-vigorate the cover crop but not to modify the canopy/root ratio of the trees by damaging the root system. The cultivation operations can also be useful for incorporating organic and mineral fertilizers as well as controlling diseases caused by fungi and bacteria in the soil.

The application of mulches along the row in the form of compost, bark chips, cereal straw and grass clippings (spread during mowing) shades the soil, so reducing temperature and soil evaporation in summer. Mulches also encourage biological activity, especially earthworms. They suppress weeds and prevent the breakdown of the soil structure under the impact of rain, thereby enhancing water infiltration.

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The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Vineyards



Vineyards

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of vineyards. A decline in soil quality has a marked impact on vine growth, grape quality, production costs and the risk of soil erosion. Therefore, it can have significant consequences on society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of viticulture are important tasks for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the character and quality of wine, and have profound effects on long-term profits. Land managers need tools that are reliable, quick and easy to use in order to help them assess the condition of their soils and their suitability for growing grapes, and to make informed decisions that lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for viticulture. Soils with good VSA scores will usually give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a scorecard. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant scorecard. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, the soil quality assessment is not a combination of the 'soil' and 'plant' scores. Rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate or poor condition.

Placing the soil and plant assessments side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.

PLATE 1 The VSA tool kit



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the ‘worm test’. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the vineyard. The condition of the soil in vineyards is site specific. Sample sites that have had little or no wheel traffic (e.g. near the vine). The VSA method can also be used to assess compacted areas by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS rankings in the right-hand column.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required in order to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil and about plant performance.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in vineyards

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Date:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 2	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 1	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 2	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

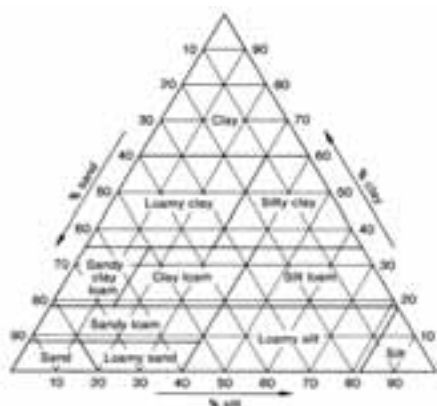


Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size > 0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is < 0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and the potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for vineyards. It regulates:

- ✦ soil aeration and gaseous exchange rates;
- ✦ soil temperature;
- ✦ soil infiltration and erosion;
- ✦ the movement and storage of water;
- ✦ nutrient supply;
- ✦ root penetration and development;
- ✦ soil workability;
- ✦ soil trafficability;
- ✦ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till or conventional cultivation between rows under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Vine roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and maintains the soil carbon 'sink'. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of vines increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of the *Phylloxera* aphid and fungal diseases such as *Phytophthora* root rot and black foot rot in soils prone to waterlogging.

In general, dark-coloured soils are more favourable for red wine quality (owing to an increase in polyphenol and terpens).

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.



Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.



Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure decreases and blocks the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K and S. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. Decay and dieback of roots can also occur as a result of the *Phylloxera* aphid and fungal diseases such as *Phytophthora* root rot and black foot rot in strongly mottled, poorly aerated soils. Root rot and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

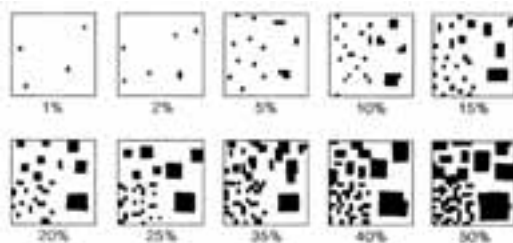


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (> 50%) medium and coarse orange and particularly grey mottles.



Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 6) and compare with the class limits in Table 2. Pay particular attention to the turf mat. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to $1/25 \text{ m}^2$, and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in vineyards and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in

the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases. The collective benefits of microbes reduce fertilizer requirements and improve vine and grape quality.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue, the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

PLATE 6 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present (Plates 7 and 8), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also whether there is an over-thickening of roots (a result of a high penetration resistance), and whether the roots are being forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan (Plate 8), or a natural pan such as an iron, siliceous or calcitic pan. An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting, gully, slip, earth slump or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated vineyards. Under irrigation, the majority of roots are in the top 1 m of soil. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the grapes. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Grapevines with a deep, dense, vigorous root system raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce promote soil structure, porosity, water storage, soil aeration and drainage at depth. For rainfed vineyards, the depth of a restricting layer should ideally be deeper than 2.5 m, with a soil depth of preferably not less than 600 mm. Stony soils are acceptable under irrigation systems, particularly where the depth of the soil is less than 1 m. Furthermore, grapevines need a sufficient rooting depth to provide adequate anchorage for the vines at maturity.

PLATE 7 Potential rooting depth

[L. VAN HUYSTEEN in VAN ZYL 1988]

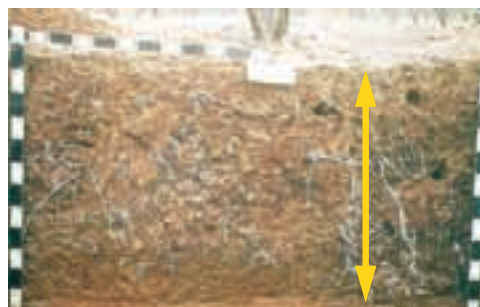


PLATE 8 Restricted root penetration through plough pan at 25 cm [L. VAN HUYSTEEN]



TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

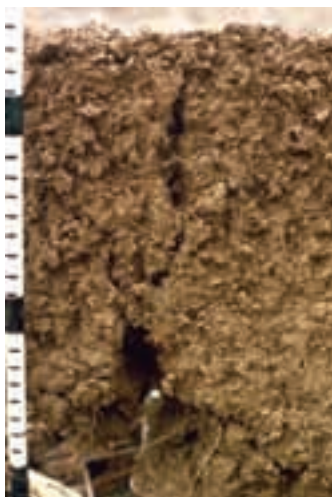
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) rapidly with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given in Plate 10.

PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Grapevines generally require free-draining soils. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth and development of roots. Roots need oxygen for respiration. They are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are growing actively at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the vine is transpiring actively causes leaf desiccation and tip-burn. Prolonged waterlogging also increases the likelihood of pests and diseases, including the *Phylloxera* aphid and *Phytophthora* fungal root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Vines decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, and eventually die.

Waterlogging and deoxygenation also result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of vine roots to waterlogging is dependent on a number of factors, including the time of year, the rootstock, soil and air temperatures, soil type, the condition of the soil, fluctuating water tables and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the amount of entrapped air and the oxygen consumption rate by plant roots. Prolonged surface ponding increases the susceptibility of soils to damage under wheel traffic, so reducing vehicle access.

PLATE 11 Surface ponding in a vineyard [CWi Technical Ltd]



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤ 1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–3	Moderate surface ponding occurs for 2–3 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	> 4	Significant surface ponding occurs for longer than 4 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare with Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of managed cover crops has in some cases reduced sediment erosion rates from 70 tonnes/ha to 1.5 tonnes/ha during single large rainfall events. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Photos of surface cover: courtesy of A. Leys;
Photo of severe crusting: courtesy of M. Speyer



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and, more importantly, on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of a vineyard through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation of interrows can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be removed by slips, flows, gullying and rilling, or it can be relocated semi-intact by slumping. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

PLATE 13 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no evidence of soil erosion. Little difference in height between the mounded row and interrow. The root system is completely covered.

**MODERATE CONDITION VS = 1**

Moderate soil erosion with a significant difference in height between the mounded row and interrow. Part of the upper root system is occasionally exposed.

**POOR CONDITION VS = 0**

Severe soil erosion with deeply incised gullies or other mass movement features between rows. The root system is often well exposed and the vine trunk totally undermined in places.

FIGURE 3 Plant scorecard – visual indicators for assessing plant performance in vineyards

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Wood production pg. 26		x 3	
Shoot lenght pg. 28		x 3	
Leaf colour pg. 30		x 3	
Yield pg. 34		x 2	
Variability of vine performance along the row pg. 36		x 2	
Production costs pg. 38		x 1	
PLANT PERFORMANCE INDEX (sum of VS rankings)			

Plant Performance Assessment	Plant Performance Index
Poor	< 10
Moderate	10–20
Good	> 20

SUMMARY

Comparison of soil & plant assessments		Do the soil and plant assessments differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:



Assessment

- 1 Estimate wood production per metre cord by assessing fresh wood weight at pruning (Plate 14). In making the observation, consideration must be given to the cultivar, pruning and age of the vine.

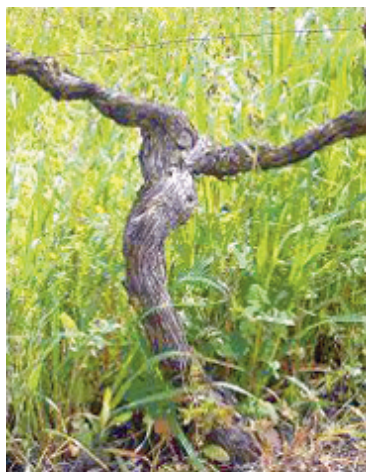


Importance

While climate factors, cultivar and agricultural practices all influence **WOOD PRODUCTION**, wood production at flowering is a good indicator of plant vigour and the fertility and physical condition of the soil (including its nutrient and water status). Therefore, it is a useful indicator of soil quality.

Soil degradation resulting from the loss of organic matter, soil compaction, poor aeration or soil erosion restricts root growth and limits the movement and storage of water, the cycling of nutrients and the efficient uptake of fertilizers. Plant roots either cannot reach the fertilizer, or the applied nutrients remain unavailable in the compacted soil because of impaired water movement or preferential flow through the soil, by-passing much of the soil volume. As a result, plant growth and vigour are poor.

PLATE 14 How to score wood production

**GOOD CONDITION VS = 2**

Depending on the cultivar, vineyards of seven years of age have 0.8 kg of vine-shoots per metre cord at pruning.

**MODERATE CONDITION VS = 1**

Depending on the cultivar, vineyards of seven years of age have 0.6–0.8 kg of vine-shoots per metre cord at pruning.

**POOR CONDITION VS = 0**

Depending on the cultivar, vineyards of seven years of age have <0.6 kg of vine-shoots per metre cord at pruning.



Assessment

- 1 Measure or visually assess shoot length and compare with the criteria given (Plate 15) at veraison. In making your assessment, consideration must be given to the cultivar, pruning and age of the vine, and the weather conditions at bud break. Poor weather will promote a high number of leaf buds rather than flowering buds and give rise to many shoots and leaves rather than flowers.



Importance

SHOOT LENGTH is also influenced by the bud position on the trunk and cordon, and by bud orientation with respect to the vertical direction. It is related strongly to the physical and chemical fertility of the soil, which in turn is influenced by soil management. Shoot length is an expression of plant vigour and general plant growth, which are also regulated by the availability of water and nutrients and by the aeration status of the soil. Waterlogging and poor drainage can restrict spring growth and give rise to poor shoot growth and dieback. Soils in good condition with good structure and porosity, and with a deep, well-aerated rootzone, enable the unrestricted movement of air and water into and through the soil and the development and proliferation of superficial (feeder) roots. Furthermore, soils with good organic-matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, shoot growth.

PLATE 15 How to score shoot length

**GOOD CONDITION VS = 2**

Vine-shoots are at or near the maximum length, with a little variability depending on the position of the shoot on the branch.

**MODERATE CONDITION VS = 1**

Vine-shoot length is moderately below maximum and shows moderate variability depending on the position of the shoot on the plant.

**POOR CONDITION VS = 0**

Vine-shoot length is significantly below the maximum length.



Assessment

- 1 Assess the colour of the mature leaves at the base of the vine-shoots by comparing with Plate 16 and the criteria given. In making the observation, consideration must be given to the cultivar, the stage of growth, pests and diseases, and recent weather conditions. Prolonged cold and cloudy days with little sunlight can give rise to chlorosis (or yellowing of the leaf) owing to the inadequate formation or loss of chlorophyll.



Importance

LEAF COLOUR can provide a good indication of the nutrient status and condition of the soil. The higher is the soil fertility, the greener is the leaf colour. Leaf colour is related primarily to water and nutrient availability, especially N. Leaf colour can also indicate a deficiency or excess of P, K, S, Ca, Mg, Fe, Mn, zinc (Zn), copper (Cu) and boron (B). Chlorosis can further occur as a result of low N, K, S, Fe, Mg and Cu levels in the soil, low soil and air temperatures, and poor soil aeration caused by compaction and waterlogging. A deficiency or excess of one or more essential elements in a plant can also produce visual symptoms of necrosis of leaf margins, stunted growth of shoots, irregular fruit-set and small berries. Premature leaf senescence can further indicate plant stress.

Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of Zn and Cu. Excess N can suppress B and Cu and cause the plant to luxury feed on K, which in turn can suppress the utilization of Ca and Mg. Sulphur can also only be utilized by plants in the sulphate (SO_4^{2-}) form. Under poorly aerated conditions, S will reduce to sulphur dioxide (SO_2) and sulphides (e.g. hydrogen sulphide [H_2S], and ferrous sulphide [FeS]). Sulphides and SO_2 cannot be taken up by the plant, are toxic to plant roots and micro-organisms, and suppress N uptake. Plants can only utilize N where S is present in the oxygenated (sulphate) form. Like S, N can also only be utilized by the plant under aerobic conditions in the nitrate (NO_3^-) or ammonium form (NH_4^+).

Plate 17 shows some of the most common symptoms of nutrient deficiencies.

PLATE 16 How to score leaf colour



GOOD CONDITION VS = 2

Leaves have an intense dark green colour.



MODERATE CONDITION VS = 1

Leaves have a yellowish-green or medium green colour.



POOR CONDITION VS = 0

Leaves have a distinct yellowish colour or turn opaque green.

PLATE 17 Visual symptoms of nutrient deficiency in vines



Phosphorus



Potassium



PLATE 17 Visual symptoms of nutrient deficiency in vines *(continued)*



Boron



Iron



Zinc





Assessment

- ① Assess relative crop yield by visual estimation of fruit number and size and by comparing with Plate 18 and the criteria given, or alternatively estimate or measure the weight of grapes per metre cord. In making your assessment, consideration must be given to the cultivar, pruning and age of the vine. Consideration must also be given to the weather conditions (e.g. whether warm and dry, or cold and wet) at pollination, fertilization, flowering and fruit-set. Pollination is best when the weather is dry, while fertilization is most successful when temperatures are warm. Poor weather during flowering can give rise to poor fruit-set. Warm weather at fruit-set will give good yields while cold wet weather will give poorer yields. Compare your assessment or measurement against the mean of the last 3 or 4 years.



Importance

YIELD can be a good visual indicator of the properties and condition of the soil. The physical condition of the soil (in terms of its texture, structure, porosity, aeration and drainage) has a significant effect on the root system, aeration status and water and nutrient availability at critical times of the year. It also plays an important role in vine growth and vigour, grape quality and yield.

Appropriate soil management, including the adoption of a managed cover crop between rows, and avoiding wheel traffic when the soil is wet, helps to promote the physical condition and overall fertility of the soil and sustainable long-term production.

PLATE 18 How to score yield



GOOD CONDITION VS = 2

Depending on the cultivar, pruning and age of the vine, yields are good.



MODERATE CONDITION VS = 1

Depending on the cultivar, pruning and age of the vine, yields are moderate.



POOR CONDITION VS = 0

Depending on the cultivar, pruning and age of the vine, yields are poor.

Assessment

- 1 Cast your eye along the rows and observe any variability in vine performance (in terms of vine height, stem thickness, canopy volume and density, leaf colour, early senescence of leaves, etc.) and compare with the class limits in Table 5. In making the assessment, consideration must be given to pruning and to diseases that are not soil-related (Plates 19–22).

Importance

VARIABILITY OF VINE PERFORMANCE ALONG THE ROW can be a very good visual indicator of the properties and condition of the soil. In particular, the linear variability of vine performance is often related to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy, sandy or gravelly). Moreover, soils in good condition with good structure and porosity, and with a deep, well-aerated rootzone, enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic-matter levels and soil life (including mycorrhizae) show an active biological and chemical process, favouring the release and uptake of water and nutrients and, consequently, the growth and vigour of the vine.

The spatial variability of vine performance along the row is also a useful indicator because it highlights those vines that are underperforming compared with the majority, enabling a specific investigation as to why those are struggling and what remedial action may be taken.

PLATE 19 Effect of soil texture, organic matter and mycorrhizae on vine performance [D. MUNDY]



Poor-performing vines on the left are on coarse-textured soils with low organic matter and a low mycorrhizal colonization of 40%. Well-performing vines on the right are the result of better utilization of water and nutrients on a siltier soil with more organic matter and a 90% colonization of mycorrhizae.

PLATE 20 Effect of soil aeration and drainage on vine performance [D. MUNDY]



Poor-performing vines in the hollows are due to root (black foot) rot associated with poor drainage, while the better-performing vines on higher ground further along the row are on freer-draining, better-aerated soil.

PLATE 21 Effect of soil-borne pathogens on vine performance [D. MUNDY]



Poor-performing vines in the centre row owing to a soil-borne pathogen.

PLATE 22 Variable crop vigour and leaf colour [S. GREEN]



Variable crop vigour and leaf colour along the row owing to differences in water and nutrient availability associated with differences in soil texture and soil depth.

TABLE 5 Visual scores for variability of vine performance along the row

Visual score (VS)	Variability of vine performance along the row
2 [Good]	Vine performance is good and even along the row
1 [Moderate]	Vine performance is moderately variable along the row
0 [Poor]	Vine performance is extremely variable along the row



Assessment

- 1 Assess whether production costs have increased because of increased tillage/subsoiling, fertilizer requirements and pesticide application over the years (Figure 4 and Table 6). This assessment can be based on perceptions, but reference to annual balance sheets will give a more precise answer.



Importance

Continuous tillage between rows using conventional cultivation techniques can give rise to a marked decline in soil structure, porosity and organic matter. The result is a reduction in root growth owing to a decline in soil aeration, an increase in penetration resistance to root development, a reduction in water storage and plant-available water, and a reduction in soil fertility and the ability of the soil to supply nutrients. Higher amounts of fertilizer are required in order to compensate for the loss of these nutrients and the decline in soil quality. Higher and more frequent applications of chemical sprays are also needed because of increased disease and pest attack in vineyards with degraded soils. The quantity and quality of the final product can often be reduced, with a lower income as a consequence.

Soil compaction under wheel traffic between rows increases the size, density and strength of soil clods, and increases the penetration resistance to lateral root development. Apart from decreasing infiltration and increasing runoff, the increased tillage resistance of compacted lanes often requires a greater number of passes and careful timing with the cultivator in order to break down the large clods. Subsoiling may also be necessary to ameliorate compaction in the subsoil in order to improve aeration and root development.

FIGURE 4 Assessment of production costs

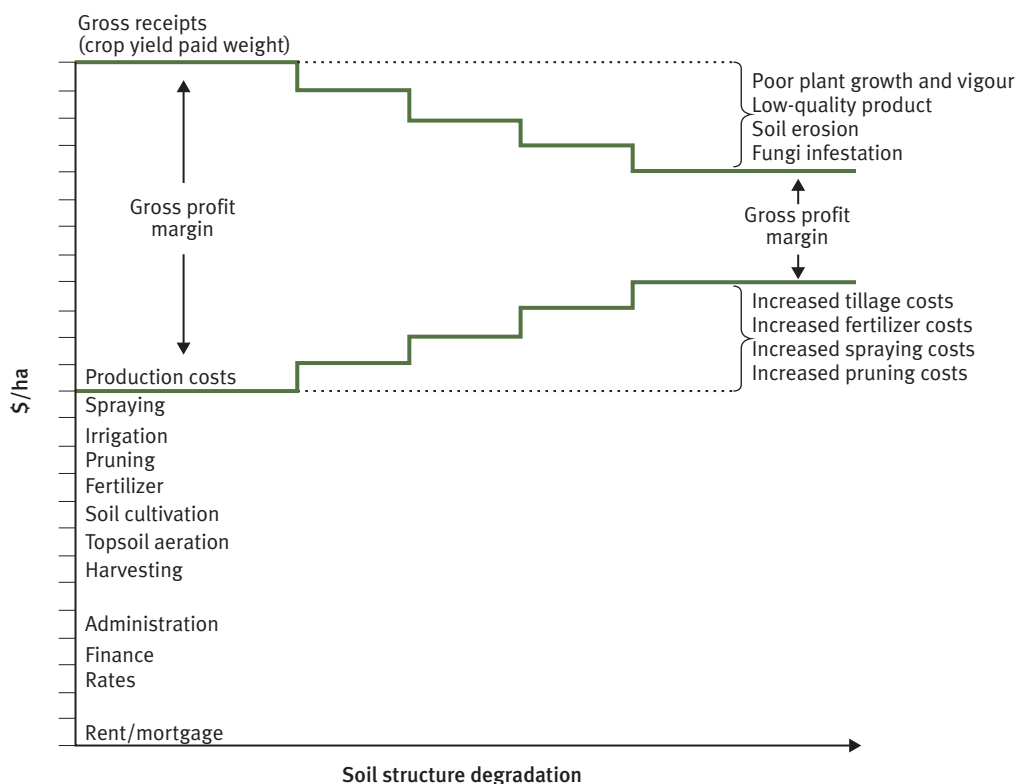


TABLE 6 Visual scores for production costs

Visual score (VS)	Production costs
2 [Good]	Spraying, fertilizer and tillage/subsoiling requirements have not increased significantly
1 [Moderate]	Spraying, fertilizer and tillage/subsoiling requirements have increased moderately
0 [Poor]	Spraying, fertilizer and tillage/subsoiling requirements have increased greatly

Soil management in vineyards

Soil management plays a key role in achieving good high-quality vineyard production while at the same time safeguarding the environment and minimizing the ecological footprint of viticulture on a region and the country.

One of the aims of the farmer should be soil conservation. This does not only mean having healthy plants and high grape quality, but achieving this with less fertilizer, chemical input and soil tillage. In general, conventional soil management in vineyards can have a negative impact on the environment. It enhances chemical residues, alters microflora and microfauna by reducing both the number of species and their biomass, reduces soil organic matter content and exposes the soil to accelerated soil erosion. Thus, the loss of soil and soil quality in vineyards contributes to the food eco-footprint.

Cover crops play an important role in protecting the soil surface and enhancing soil quality, so preserving the environment, reducing production costs and enhancing the quality of wine. Recent experiments have shown that the nutritional status of vineyards can have a strong influence on the chemical and organoleptic characteristics of wine.

Cover cropping not only helps in reducing water runoff and soil erosion but also improves soil physical characteristics, enriches soil organic matter content, reduces inorganic fertilization and root mortality, and suppresses soil-borne disease by increasing micro-organism activity and biodiversity.

One of the limiting factors of cover crops in vineyards is the competition for nutrients and plant-available water where the management is inadequate. This can affect the amount of available N to the plant and the N content and alcoholic fermentation of the wine. In order to solve this problem, a different mix of cover crops including leguminous species such as clover and lucerne that supply N (fixed from the atmosphere) should be evaluated in different areas, reducing the problem of N deficiency. The input of biologically fixed N is also an important component of the N cycle.

In addition to legumes, the mix of cover crops in the interrows could include annual and perennial species, grasses and other broadleaf plants. Winter annuals can be grown in order to protect the soil from erosion during winter and to improve the ability of the soil to resist compaction when wet. Grasses, with their fibrous root system, are also more effective at improving soil structure, and generally add more organic matter to the soil than do legumes. Where allowed to seed in early summer, a seed bank for subsequent regeneration is built up. In order to reduce competition, cover crops or natural weeds can be controlled by herbicide application or by mowing 2–3 times during the period of major water and nutrient demand. Grass should also be kept short in order to reduce insect and bird numbers. Where the grass cover crop extends along and under the vine row, ensure that the length of grass is kept short in order to reduce not only the competition for water and nutrients but also the possibility of fungal diseases.

In addition to the adoption of managed cover crops, the physical condition and overall fertility of the soil can be promoted by avoiding wheel traffic between rows when the soils are wet.

The application of mulches along the vine rows in the form of grass mowings, compost, bark chips and cereal straw shade the soil, so reducing temperature and soil evaporation during the summer. Mulches also encourage biological activity, especially earthworms. They suppress weeds and prevent the breakdown of the soil structure under the impact of rain, so enhancing water infiltration. The application of crushed glass as a 'mulch' enhances the availability of understorey light, so providing more energy from the rays of the sun to the ripening fruit, lifting the flavour, and ripening the fruit earlier. However, glass mulch does nothing to enhance the biological life of the soil.

References

Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for vineyards*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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Wheat



Wheat

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ATP	Adenosine triphosphate
B	Boron
Ca	Calcium
CO ₂	Carbon dioxide
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
P	Phosphorus
RSG	Restricted spring growth
S	Sulphur
VS	Visual score
VSA	Visual Soil Assessment
Zn	Zinc

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of wheat cropping. A decline in soil quality has a marked impact on yield and grain quality, production costs and the risk of soil erosion, and can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Safeguarding soil resources for future generations and minimizing the ecological footprint of cropping wheat is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil quality;
- ❖ the effect of land management decisions on soil quality.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance of wheat cropping and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for growing crops, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for wheat. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

The VSA method

Visual Soil Assessment is based on the visual assessment of key soil ‘state’ and plant performance indicators of soil quality, presented on a scorecard. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant scorecard. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. capable of changing under different management regimes and land-use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the ‘soil’ and ‘plant’ scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between score can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2 and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate or poor condition.

Placing the soil and plant assessments side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 mm long x 350 mm wide x 250 mm deep) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260x260 x20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750x500 mm) – on which to spread the soil, after the drop shatter test has been carried out;
- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the potential rooting depth;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the VS for each indicator.

PLATE 1 The VSA tool kit



The procedure

When it should be carried out

The test should be carried out when the soils are moist and suitable for cultivation. If you are not sure, apply the 'worm test'. Roll a worm of soil on the palm of one hand with the fingers of the other until it is 50 mm long and 4 mm thick. If the soil cracks before the worm is made, or if you cannot form a worm (for example, if the soil is sandy), the soil is suitable for testing. If you can make the worm, the soil is too wet to test.

Setting up

Time

Allow 25 minutes per site. For a representative assessment of soil quality, sample 4 sites over a 5-ha area.

Reference sample

Take a small sample of soil (about 100x50x150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in wheat fields is site specific. Avoid areas that may have had heavier traffic than the rest of the field and sample between wheel traffic lanes. VSA can also be used however, to assess the effects of high traffic on soil quality by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicator scorecard.

Carrying out the test

Initial observation

Dig a small hole about 200x200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two samples of 200x200x100 mm with a spade. If the 100–200-mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two samples of 200x200x100 mm. Note that taking a 200-mm cube sample below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and farm management practices.

The drop shatter test

Drop the test sample a maximum of three times from a height of 1 m onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, is dependent on the texture of the soil and the degree to which the soil breaks up, as described in the section on soil structure.

Systematically work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS rankings in the right-hand column.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required in order to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil and about plant performance.

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in wheat

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Date: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____

Textual group (upper 1 m): Sandy Loamy Silty Clayey Other
 Moisture condition: Dry Slightly moist Moist Very moist Wet
 Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Soil colour pg. 8		x 2	
Number and colour of soil mottles pg. 10		x 2	
Earthworms (Number =) pg. 12 (Av. size =)		x 3	
Potential rooting depth (m) pg. 14		x 3	
Surface ponding pg. 18		x 1	
Surface crusting and surface cover pg. 20		x 2	
Soil erosion (wind/water) pg. 22		x 2	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 15
Moderate	15–30
Good	> 30



Assessment

- ❶ Take a small sample of soil (half the size of your thumb) from the topsoil and a sample (or samples) that is (or are) representative of the subsoil.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball.

With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the textural class obtained by reference to the textural diagram (Figure 2).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For example, if the soil has a reasonably high content of organic matter, i.e. is humic with 15–30 percent organic matter, raise the textural score by one (e.g. from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

There are also occasions when the assignment of a textural score will need to be modified because of the specific preference of a crop for a particular textural class. For example, asparagus prefers a soil with a sandy loam texture and so the textural score is raised by 0.5 from a score of 1 to 1.5 based on the specific textural preference of the plant.

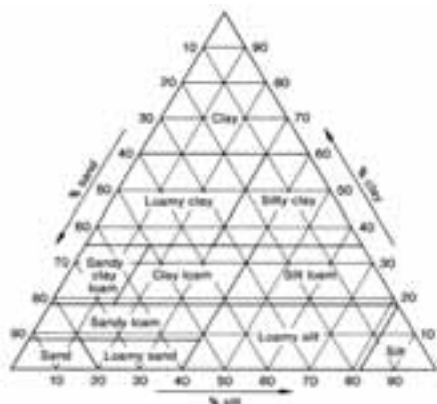


Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size >0.06 mm; silt varies between 0.06 and 0.002 mm; and the particle size of clay is <0.002 mm. Texture influences soil behaviour in several ways, notably through its effect on: water retention and availability; soil structure; aeration; drainage; soil workability and trafficability; soil life; and the supply and retention of nutrients.

A knowledge of both the textural class and the potential rooting depth enables an approximate assessment of the total water-holding capacity of the soil, one of the major drivers of crop production.

FIGURE 2 Soil texture classes and groups



Textural classes.



Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball that fissures when pressed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball that deforms without fissuring.
1 [Moderate]	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball that fissures when pressed flat.
0.5 [Moderately poor]	Loamy sand Silty clay Clay	Loamy sand: Gritty and rasping sound. Will almost mould into a ball but disintegrates when pressed flat. Silty clay, clay: Very smooth, very sticky, very plastic. Moulds into a cohesive ball that deforms without fissuring.
0 [Poor]	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
- ❷ Drop the soil sample a maximum of three times from a height of 1 m onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Do not drop any piece of soil more than three times. For soils with a sandy loam texture (Table 1), drop the cube of soil just once only from a height of 0.5 m.
- ❸ Transfer the soil onto the large plastic bag.
- ❹ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade (once) from a height of just 50 mm, and then roll the spade over, spilling the soil onto the plastic bag.
- ❺ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures. If the clod does not part easily, do not apply further pressure (because the cracks and fissures are probably not continuous and, therefore, are unable to readily conduct oxygen, air and water).
- ❻ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs in Plate 2 and the criteria given. The method is valid for a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for grain crops. It regulates:

- ✦ soil aeration and gaseous exchange rates;
- ✦ soil temperature;
- ✦ soil infiltration and erosion;
- ✦ the movement and storage of water;
- ✦ nutrient supply;
- ✦ root penetration and development;
- ✦ soil workability;
- ✦ soil trafficability;
- ✦ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum-till, controlled traffic or conventional cultivation under optimal soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, subangular and subrounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or subangular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 How to score soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.



Assessment

- ❶ Remove a spade slice of soil (about 100 mm wide, 150 mm long and 200 mm deep) from the side of the hole and break it in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs in Plate 3. Look for the spaces, gaps, holes, cracks and fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).



Importance

It is important to assess **SOIL POROSITY** along with the structure of the soil. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores and coarse micropores within the large clods, restricting their drainage and aeration.

Poor aeration leads to the build up of carbon dioxide, methane and sulphide gases, and reduces the ability of plants to take up water and nutrients, particularly nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Plants can only utilize S and N in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) forms. Therefore, plants require aerated soils for the efficient uptake and utilization of S and N. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and they are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilize the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, it also reduces fertilizer efficiency considerably and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce lower amounts of greenhouse gases. The greater the porosity, the better the drainage, and, therefore, the less likely it is that the soil pores will be water-filled to the critical levels required to accelerate the production of greenhouse gases. Aim to keep the soil porosity score above 1.

PLATE 3 How to score soil porosity**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present on close examination in parts of the soil. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.



Assessment

- 1 Compare the colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area.
- 2 Using the three photographs and criteria given (Plate 4), compare the relative change in soil colour that has occurred.

As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.



Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not assessed so easily and accurately. In general, the darker the colour is, the greater is the amount of organic matter in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, which collectively determine soil health. It promotes infiltration and retention of water, helps to develop and stabilize soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and indicates whether the soil is functioning as a carbon 'sink' or as a source of greenhouse gases. Organic matter also provides an important food resource for soil organisms and is an important source of, and major reservoir of, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; N, P, K and S requirements of crops increase markedly, and other major and minor elements are leached more readily. The result is an increased dependency on fertilizer input to maintain nutrient status.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is influenced markedly by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidized form of ferric (Fe³⁺) and manganic (Mn³⁺) oxides. Grey-blue colours can indicate that the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe²⁺) and manganous (Mn²⁺) oxides. Poor aeration and prolonged waterlogging give rise to a further series of chemical and biochemical reduction reactions that produce toxins, such as hydrogen sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, that damage the root system. This reduces the ability of plants to take up water and nutrients, causing poor vigour and ill-thrift. Decay and dieback of roots can also occur as a result of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot in soils prone to waterlogging.

PLATE 4 How to score soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is not too dissimilar to that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than that under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with that under the fenceline.



Assessment

- 1 Take a sample of soil (about 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and compare with the three photographs (Plate 5) and the percentage chart to determine the percentage of the soil occupied by mottles.

Mottles are spots or blotches of different colour interspersed with the dominant soil colour.



Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also an early warning of a decline in soil structure caused by compaction under wheel traffic and overcultivation. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces Fe and Mn from their brown/orange oxidized ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey owing to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey, mottles predominate. An abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicates the soil is moderately well drained, and the absence of mottles indicates good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S and Cu. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, ethanol, acetaldehyde and ethylene, which are toxic to plant roots. In addition, decay and dieback of roots can occur as a result of fungal diseases such as *Rhizoctonia*, *Pythium* and *Fusarium* root rot, foot rot and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for mottles is ≤ 1 , you need to aerate the soil.

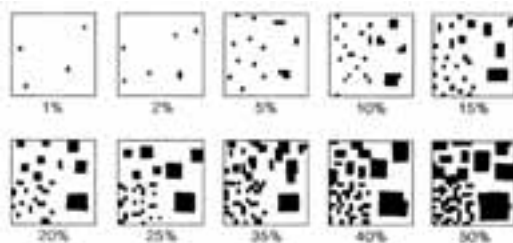


PLATE 5 How to score soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has common (10–25%) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has abundant to profuse (> 50%) medium and coarse orange and particularly grey mottles.



Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 7) and compare with the class limits in Table 2. Pay particular attention to the turf mat. Earthworms vary in size and number depending on the species and the season. Therefore, for year-to-year comparisons, earthworm counts must be made at the same time of year when soil moisture and temperature levels are good. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. A 200-mm cube sample is equivalent to 1/25 m², and so the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.



Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digestion and casting, earthworms have a major effect on the chemical, physical and biological properties of the soil. They shred and decompose plant residues, converting them to organic matter, and so releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter and water content. Moreover, earthworms act as biological aerators and physical conditioners of the soil, improving:

- ✦ soil porosity;
- ✦ aeration;
- ✦ soil structure and the stability of soil aggregates;
- ✦ water retention;
- ✦ water infiltration;
- ✦ drainage.

They also reduce surface runoff and erosion. They further promote plant growth by secreting plant-growth hormones and increasing root density and root development by the rapid growth of roots down nutrient-enriched worm channels. While earthworms can deposit about 25–30 tonnes of casts/ha/year on the surface, 70 percent of their casts are deposited below the surface of the soil. Therefore, earthworms play an important role in arable cropping and can increase growth rates and production significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in the supply of nutrients, digesting soil and fertilizer and unlocking nutrients, such as P, that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant-growth hormones and compounds that

PLATE 6 (a): earthworm casts under crop residue; (b): yellow-tail earthworm (*Octolasion cyaneum*)



stimulate root growth and promote the structure, aeration, infiltration and water-holding capacity of the soil. Micro-organisms further encourage a lower incidence of pests and diseases, and promote a more rapid breakdown of organic herbicides. The collective benefits of microbes can increase crop production markedly while at the same time reducing fertilizer requirements.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the amount and quality of surface residue (Plate 6a), the use of cover crops including legumes, and the cultivation of interrows. Earthworm populations can be up to three times higher in undisturbed soils compared with cultivated soils. Earthworm numbers are also governed by: soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertilizer and N used. The overuse of acidifying salt-based fertilizers, anhydrous ammonia and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep-burrowing species that pull down and mix plant litter and organic matter at depth.

Earthworms species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 6b) can indicate adverse soil conditions.

PLATE 7 Sample for assessing earthworms



TABLE 2 Visual scores for earthworms

Visual score (VS)	Earthworm numbers (per 200-mm cube of soil)
2 [Good]	> 30 (with preferably 3 or more species)
1 [Moderate]	15–30 (with preferably 2 or more species)
0 [Poor]	< 15 (with predominantly 1 species)



Assessment

- ① Dig a hole to identify the depth to a limiting (restricting) layer where present (Plate 8), and compare with the class limits in Table 3. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks and fissures down which roots can extend. Note also whether there is an over-thickening of roots (a result of a high penetration resistance), and whether the roots are being forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed owing to prolonged waterlogging, and whether there is a hardpan present such as a human-induced tillage or plough pan, or a natural pan such as an iron, siliceous or calcitic pan (pp 16–17). An abrupt transition from a fine (heavy) material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.



Importance

The **POTENTIAL ROOTING DEPTH** is the depth of soil that plant roots can potentially exploit before reaching a barrier to root growth, and it indicates the ability of the soil to provide a suitable rooting medium for plants. The greater is the rooting depth, the greater is the available-water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated crops. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the crop. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertilizer efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hardpans impede the movement of air, oxygen and water through the soil profile, the last increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions.

Crops with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce, promote soil structure, porosity, water storage, soil aeration and drainage at depth. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on frequent and high application rates of fertilizer and N to generate growth, and available nutrients are more likely to be taken up, so reducing losses by leaching into the environment.

PLATE 8 Hole dug to assess the potential rooting depth



The potential rooting depth extends to the bottom of the arrow, below which the soil is extremely firm and very tight with no roots or old root channels, no worm channels and no cracks and fissures down which roots can extend.

TABLE 3 Visual scores for potential rooting depth

VSA score (VS)	Potential rooting depth (m)
2.0 [Good]	> 0.8
1.5 [Moderately good]	0.6–0.8
1.0 [Moderate]	0.4–0.6
0.5 [Moderately poor]	0.2–0.4
0 [Poor]	< 0.2

Identifying the presence of a hardpan

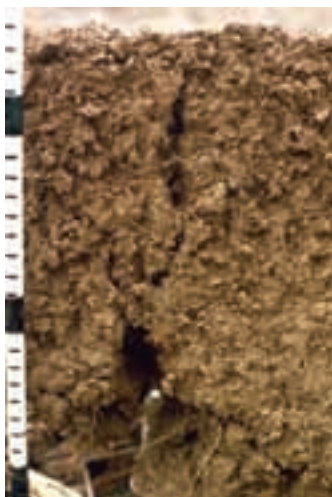
Assessment

- 1 Examine for the presence of a hardpan by rapidly jabbing the side of the soil profile (that was dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically and quickly down to the bottom of the hole (Plate 9). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. A strongly developed hardpan is very tight and extremely firm, and it has a high penetration resistance to the knife. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (Plate 10).
- 2 Having identified the possible presence of a hardpan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hardpan is. Remove a large hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (Plates 2, 3 and 5), and also look for the presence of roots. Compare with the photographs and criteria given in Plate 10.

PLATE 9 Using a knife to determine the presence or absence of a hardpan



PLATE 10 Identifying the presence of a hardpan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding (Plate 11) based on your observation or general recollection of the time ponded water took to disappear after a wet period during the spring, and compare with the class limits in Table 4.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the rate of infiltration into and through the soil, a high water table, and the time the soil remains saturated. Prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress, and restrict root respiration and the growth of roots. Roots need oxygen for respiration. They are most vulnerable to surface ponding and saturated soil conditions in the spring when plant roots and shoots are actively growing at a time when respiration and transpiration rates rise markedly and oxygen demands are high. They are also susceptible to ponding in the summer when transpiration rates are highest. Moreover, waterlogging causes the death of fine roots responsible for nutrient and water uptake. Reduced water uptake while the crop is transpiring actively causes leaf desiccation and the plant to wilt. Prolonged waterlogging also increases the likelihood of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Plant stress induced by poor aeration and prolonged soil saturation can render crops less resistant to insect pest attack such as aphids, armyworm, cutworm and wireworm. Crops decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, become discoloured and die.

Waterlogging and deoxygenation also results in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are toxic to roots. Plant-available nitrate-nitrogen (NO_3^-) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas, and plant-available sulphate-sulphur (SO_4^{2-}) is reduced to sulphide, including hydrogen sulphide (H_2S), ferrous sulphide (FeS) and zinc sulphide (ZnS). Iron is reduced to soluble ferrous (Fe^{2+}) ions, and Mn to manganous (Mn^{2+}) ions. Apart from the toxic products produced, the result is a reduction in the amount of plant-available N and S. Anaerobic respiration of micro-organisms also produces carbon dioxide and methane (also greenhouse gases), hydrogen gas, ethanol, acetaldehyde and ethylene, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The tolerance of the root system to surface ponding and waterlogging is dependent on a number of factors, including the time of year and the type of crop. Tolerance of waterlogging is also dependent on: soil and air temperatures; soil type; the condition of the soil; fluctuating water tables; and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate.

Prolonged surface ponding makes the soil more susceptible to damage under wheel traffic, so reducing vehicle access. As a consequence, waterlogging can delay ground preparation and sowing dates significantly. Sowing can further be delayed because the seed bed is below the crop-specific critical temperature. Increases in the temperature of saturated soils can be delayed as long as water is evaporating.

PLATE 11 Surface ponding in a wheat field



TABLE 4 Visual scores for surface ponding

VSA score (VS)	Surface ponding due to soil saturation	
	Number of days of ponding *	Description
2 [Good]	≤1	No evidence of surface ponding after 1 day following heavy rainfall on soils that were already at or near saturation.
1 [Moderate]	2–3	Moderate surface ponding occurs for 2–3 days after heavy rainfall on soils that were already at or near saturation.
0 [Poor]	>5	Significant surface ponding occurs for longer than 5 days after heavy rainfall on soils that were already at or near saturation.

* Assuming little or no air is trapped in the soil at the time of ponding.



Assessment

- 1 Observe the degree of surface crusting and surface cover and compare Plate 12 and the criteria given. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. Surface crusting also reduces aeration, causing anaerobic conditions, and prolongs water retention near the surface, which can hamper access by machinery for months. Crusting is most pronounced in fine-textured, poorly structured soils with a low aggregate stability and a dispersive clay mineralogy.

SURFACE COVER after harvesting and prior to canopy closure of the next crop helps to prevent crusting by minimizing the dispersion of the soil surface by rain or irrigation. It also helps to reduce crusting by intercepting the large rain droplets before they can strike and compact the soil surface. Vegetative cover and its root system return organic matter to the soil and promote soil life, including earthworm numbers and activity. The physical action of the roots and soil fauna and the glues they produce promote the development of soil structure, soil aeration and drainage and help to break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, decreasing runoff, soil erosion and the risk of flash flooding. Surface cover also reduces soil erosion by intercepting high impact raindrops, minimizing rain-splash and saltation. It further serves to act as a sponge, retaining rainwater long enough for it to infiltrate into the soil. Moreover, the root system reduces soil erosion by stabilizing the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved with a lower sediment loading, nutrient and coliform content. The adoption of conservation tillage can reduce soil erosion by up to 90 percent and water runoff by up to 40 percent. The surface needs to have at least 70 percent cover in order to give good protection, while ≤ 30 percent cover provides poor protection. Surface cover also reduces the risk of wind erosion markedly.

PLATE 12 How to score surface crusting and surface cover



GOOD CONDITION VS = 2

Little or no surface crusting is present; or surface cover is $\geq 70\%$.

MODERATE CONDITION VS = 1

Surface crusting is 2–3 mm thick and is broken by significant cracking; or surface cover is $>30\%$ and $<70\%$.

POOR CONDITION VS = 0

Surface crusting is >5 mm thick and is virtually continuous with little cracking; or surface cover is $\leq 30\%$.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and on your knowledge of what the site looked like in the past relative to Plate 13.



Importance

SOIL EROSION reduces the productive potential of soils through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Overcultivation can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be water eroded by gullying, rilling and sheet wash. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability of water through the soil;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of overcultivation can also give rise to significant soil loss by wind erosion of exposed ground.

PLATE 13 How to score soil erosion

**GOOD CONDITION VS = 2**

Little or no *water erosion*. Topsoil depths in the footslope areas are <150 mm deeper than on the crest.

Wind erosion is not a concern; only small dust plumes emanate from the cultivator on a windy day. Most wind-eroded material is contained in the field.

**MODERATE CONDITION VS = 1**

Water erosion is a moderate concern with a significant amount of rilling and sheet erosion. Topsoil depths in the footslope areas are 150–300 mm greater than on crests, and sediment input into drains/streams may be significant.

Wind erosion is of moderate concern where significant dust plumes can emanate from the cultivator on windy days. A considerable amount of material is blown off the field but is contained within the farm.

**POOR CONDITION VS = 0**

Water erosion is a major concern with severe gullying, rilling and sheet erosion occurring. Topsoils in footslope areas are more than 300 mm deeper than on the crests, and sediment input into drains/streams may be high.

Wind erosion is a major concern. Large dust clouds can occur when cultivating on windy days. A substantial amount of topsoil can be lost from the field and deposited elsewhere in the district.

FIGURE 3 Plant scorecard – visual indicators for assessing plant performance in wheat

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Crop establishment pg. 26		x 2	
Tillering pg. 28		x 3	
Leaf colour pg. 30		x 3	
Variability of crop performance along the row pg. 34		x 3	
Root development pg. 36		x 3	
Root diseases pg. 38		x 2	
Crop growth & height at maturity pg. 40		x 2	
Kernel size pg. 42		x 2	
Crop yield pg. 44		x 3	
Production costs pg. 46		x 1	
PLANT QUALITY INDEX (sum of VS rankings)			

Plant Quality Assessment	Plant Quality Index
Poor	< 15
Moderate	15–30
Good	> 30

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Land use management & history:

Total available water-holding capacity:



Assessment

- 1 Assess the degree and uniformity of crop establishment within a month of sowing by comparing the number and height of established plants with the three photographs provided (Plate 14).



Importance

GOOD SEED GERMINATION, PLANT EMERGENCE AND CROP ESTABLISHMENT depend on factors that include the quality of soil tilth at the time of sowing and during the weeks immediately following. Soils that have poor structure through compaction and over-cultivation can resettle and consolidate rapidly after the seed bed has been prepared. Impeded water and air movement through the soil can give rise to increased soil-borne pathogens and areas low in oxygen (anaerobic zones). Anaerobic zones produce chemical and biochemical reduction reactions, the by-products of which are toxic to plants. Poor soil aeration and soil-borne pathogens can give rise to poor germination, poor pre- and post emergence, poor plant vigour and even death. While emergence may be slow, recovery can also be limited and plants often appear sickly. Poor plant emergence, bare patches and poor and uneven early leaf and tiller growth are commonly observed throughout paddocks and result in crop thinning and low plant populations. Young plants can also show discolouration of leaves, leaf blemishes and moisture stress.

The loss of soil condition can reduce crop establishment from 300 to 130 plants/m² and grain yields from 8 to 5 tonnes per hectare. Seedling mortality can be high if the soil is waterlogged for more than 3 to 4 days between germination and emergence.

PLATE 14 How to score crop establishment

**GOOD CONDITION VS = 2**

Good emergence and crop establishment, with few gaps along the row and crop showing a good even height.

**MODERATE CONDITION VS = 1**

Moderate emergence and crop establishment, with a significant number of gaps along the row and a significant variation in seedling height. Emergence may also be moderately slow but recovers somewhat.

**POOR CONDITION VS = 0**

Poor emergence and crop establishment, with a large number of gaps along the row and a large variation in seedling height. Emergence may also be slow with limited recovery and plants often appear sickly.



Assessment

- 1 Measure the number of tillers at the end of the tillering stage and compare with the photographs (Plate 15) and class limits below.



Importance

THE NUMBER OF TILLERS play a fundamental role in determining the number of ears (spikes) per square metre and consequently the final yield. The potential number of tillers varies with the genotype, particularly among winter genotypes which have the greatest number. The new semi-dwarf wheat varieties normally have 2–3 tillers per plant to permit the development and grouping of tillers and ears that are contemporary, i.e. are equal in all vegetative, reproductive and ripening stages in order to maximise yields. Although this character is genetically determined and strongly influenced by planting density, it is also an expression of plant vigour and general plant growth which are firstly regulated by nutrient and water availability and the condition of the soil.

Soils in good health with good structure, porosity, organic matter levels, soil life, soil fertility and rooting depth favour the release and uptake of water and nutrients and subsequently the development of a greater number of tillers and their contemporary development.

PLATE 15 How to score tillering

**GOOD CONDITION VS = 2**

Depending on the cultivar the plant has 3 well developed tillers with little variability compared to the main stem (i.e., main culm).

**MODERATE CONDITION VS = 1**

Depending on the cultivar the plant has 2–3 tillers with moderate variability compared to the main stem (or culm).

**POOR CONDITION VS = 0**

The plant has 1 or no tillers at all with significant differences in terms of development to the main stem (or culm).



Assessment

- 1 Assess the leaf colour of the crop when all other factors favour rapid growth, and compare with the three photographs (Plate 16). In making the assessment, consideration must be given to the cultivar, the stage of growth, the soil moisture and temperature conditions, and the presence of pests and diseases (e.g. nematodes). The assessment can be done at any time prior to leaf senescence but ideally from four to six weeks after plant emergence to grain filling, avoiding very cold and wet weather.



Importance

LEAF COLOUR prior to completion of grain filling can provide a good indication of the water and nutrient status and condition of the soil. Under normal environmental conditions the higher the soil fertility, the greener the crop. Plant vigour and colour is strongly related to soil water and nutrient availability, especially nitrogen (N). Discolouration of the foliage and blemishes on the leaf can also result from a deficiency or excess of phosphorus (P), potassium (K), sulphur (S), magnesium (Mg), manganese (Mn), zinc (Zn), copper (Cu) and boron (B) – Plate 17. Chlorosis (or yellowing of crops) due to the inadequate formation of chlorophyll, commonly occurs as a result of low N, K, S, Fe, Mg and Cu levels in the soil, low soil and air temperatures, prolonged cloudy days and poor soil aeration due to compaction and waterlogging.

Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of Zn and Cu. Excess N can suppress B and Cu and cause the plant to luxury feed on K. Sulphur can also only be utilised by the plant in the sulphate (SO_4^{2-}) form. Under poorly aerated conditions sulphate-S will reduce to sulphur dioxide (SO_2) and sulphides (eg. hydrogen sulphide [H_2S], and ferrous sulphide [FeS]). Sulphides and SO_2 cannot be taken up by the plant, are toxic to plant roots and micro organisms, and suppress the uptake of N. Plants can also only utilise N if S is present in the oxygenated (sulphate) form. Like S, N can only be utilised by the plant in the oxygenated nitrate (NO_3^-) and ammonium (NH_4^+) form under aerobic conditions.

The aeration status of the soil can further affect the uptake of nutrients. Phosphorus, copper and cobalt for example cannot be efficiently utilised by the plant under anaerobic conditions.

PLATE 16 How to score leaf colour



GOOD CONDITION VS = 2

Leaf colour is uniformly deep green. The odd colour blemish on leaves may be apparent within a broad area.



MODERATE CONDITION VS = 1

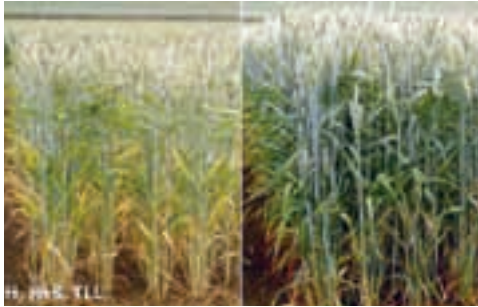
Leaf colour is yellowish green; i.e. has a distinct yellowish tinge. Few colour blemishes on leaves may occur within a wide area.



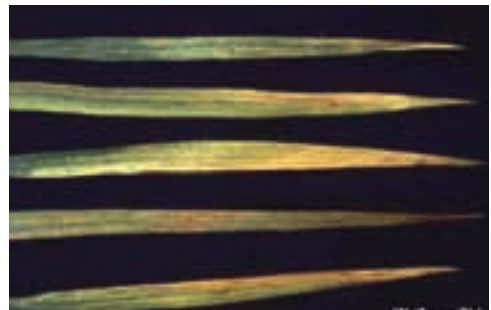
POOR CONDITION VS = 0

Leaf colour is quite yellow over a wide area. Colour blemishes on leaves may commonly occur.

PLATE 17 Common symptoms of leaf discolouration due to nutrient deficiencies in wheat



Nitrogen deficiency on the left



Phosphorus deficiency

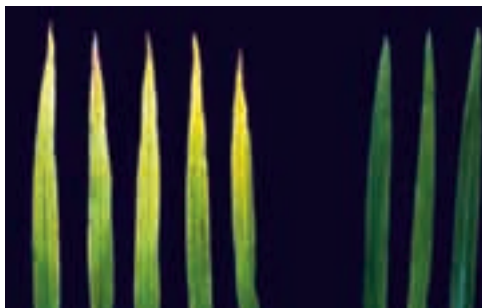


Potassium deficiency



Sulphur deficiency on the right

PLATE 17 Common symptoms of leaf discolouration due to nutrient deficiencies in wheat (*cont'd*)



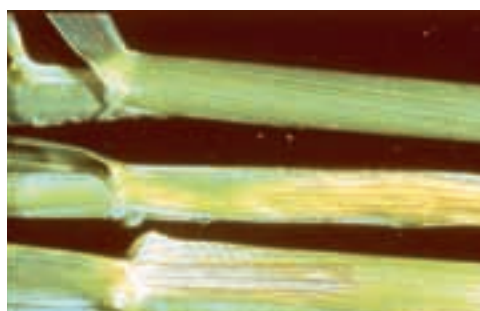
Magnesium deficiency on the left



Manganese deficiency



Copper deficiency



Zinc deficiency

Assessment

- 1 Cast your eye along the row and observe any variability in crop performance (in terms of crop height, plant and leaf density, stem thickness, leaf colour) and compare with the class limits in the Table 5. In making the assessment, consideration must also be given to other factors that may affect the performance of a crop such as pest and disease attack that are not related to the condition of the soil.

Importance

VARIABILITY OF CROP PERFORMANCE ALONG THE ROW can be a good visual indicator of the condition of the soil (Plates 18–21). In particular, the linear variability in crop performance can be strongly related to the availability of water and nutrients, and the texture of the soil (e.g. whether clayey, silty, loamy or sandy). Also, soils in good condition with good structure and porosity, and have a deep, well aerated root zone enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and consequently the growth and vigour of the crop.

The spatial variability of crop performance along the row is also a useful indicator because it highlights those areas of the field that are under-performing enabling a site specific investigation as to why and what remedial action may be taken. This may include variable rate application of fertiliser by GPS guided ground spreaders.

PLATE 18 Variable crop performance due to soil aeration and wetness



Variable crop performance due to differences in soil aeration and soil wetness.

PLATE 19 Variable crop performance due to soil compaction



Variable crop performance due to differences in soil compaction.

PLATE 20 Variable crop performance due to an iron pan



Variable crop performance due to differences in rooting depth to an iron pan.

PLATE 21 Variable crop performance due to water repellency



Concentric rings of poor wheat growth due to severely water repellent (hydrophobic) soils. Areas of stronger wheat growth occur on non-water repellent soils.

TABLE 5 Visual scores for variability of crop performance along the row

Visual score (VS)	Variability of crop performance along the row
2 [Good]	Crop performance is good and even along the row
1 [Moderate]	Crop performance is moderately variable along the row
0 [Poor]	Crop performance is extremely variable along the row



Assessment

- 1 Examine the upper part of the hole dug to assess the potential rooting depth of the soil. With the help of a knife, carefully loosen the soil around the roots to expose the root system *in-situ* (Plate 22). Alternatively, dig out a 250–300 mm deep slice of soil around a group of plants and gently tap the sample against the edge of the hole to expose the root system. Use a knife to help loosen the soil if required. Assess both the length and the density of the roots and compare with the class limits in the Table 6. Root length and root density is best assessed at or just prior to crop maturity.



Importance

THE ROOT LENGTH AND ROOT DENSITY provides a good indication of the condition of the plant root system. Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared to crops with a shallow, thin root system. Tillering, ear development and grain filling is therefore likely to be greater, crops are less likely to suffer wind throw, and they will be less susceptible to drought stress. Crops with a dense, deep, vigorous root system are also more likely to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna, and the glues they produce promote the development of soil structure, soil aeration and drainage.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up reducing losses by leaching into the groundwater and waterways.

Root length and density can be restricted by the mechanical impedance of roots and the lack of soil pores due to soil compaction or a hardpan. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, nutrient deficiencies, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and low oxygen levels. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, carbon dioxide, methane, ethanol, acetaldehyde and ethylene, by-products of chemical and biochemical reduction reactions (see pg 18).

PLATE 22 **Root development**

Photo showing good root development in the upper 150 mm of soil only. The root distribution and root density in the 150–300 mm zone is poor.

TABLE 6 **Visual scores for root development**

Visual score (VS)	Root development
2 [Good]	Good root length and root density in the upper 250–300 mm of soil
1 [Moderate]	Moderate root length & density in the upper 250–300 mm of soil
0 [Poor]	Poor root length & density in the upper 250–300 mm of soil with the root system being restricted to limited areas



Assessment

- 1 Assess the presence of root diseases by pulling a number of stems out of the soil and carefully examining the root system for visual evidence of root diseases at or any time before crop maturity. Make your assessment based on the class limits in Table 7.
- 2 Consider also how commonly root diseases occur in a particular field from season to season.



Importance

ROOT DISEASES encouraged by the degradation of soil quality include take-all (*G. graminis* var. *tritici*), dryland root rot (*Fusarium graminearum* and many others), *Rhizoctonia* root rot (*Rhizoctonia solani*) and *Pythium* root rot (*Pythium* spp.) (Plates 23–26). Their presence can cause severe yield loss and reduction in grain quality. Symptoms of root diseases include pre- and post emergence plant death in seedlings resulting in crop thinning, stunting and reduced tillering, discolouration of and blemishes (lesions) on stems, tillers and leaves, bleached heads and premature death. Infected plants have sparse root development and characteristically a brown-black rot can be seen at the crown and extending to the base.

Poor soil aeration, soil saturation and high penetration resistance to root development due to soil structural degradation can increase root rot and soil-borne pathogens. They can also reduce the ability of the root system to overcome the harmful effects of pathogens resident in the topsoil.

The conservation of soil moisture, amelioration of soil compaction, the build up of organic matter and the promotion of good soil life (in terms of microbial biomass, diversity and activity) are factors that contribute to the development of healthy plants and the suppression of soil-borne diseases. They also help enable the plant to better resist the pressure of disease and insect attack. Soil biota and especially those micro-organisms that enhance cellulytic breakdown and decomposition of straw residues further limit pathogen survival.

PLATE 23 *Pythium* root disease [from Compendium of Wheat Diseases by M.V. WIESE]



Wheat seedlings damaged by *Pythium* species in wet soil.

PLATE 24 **Take-all root disease** [from Compendium of Wheat Diseases by M.V. WIESE]

Root rot and darkened stem bases due to take-all (*G. graminis* var. *tritici*).

PLATE 25 ***Fusarium* root disease** [from Compendium of Wheat Diseases by M.V. WIESE]

Secondary root emerging from crown and invaded by *Fusarium culmorum*.

PLATE 26 **Root rot** [from Compendium of Wheat Diseases by M.V. WIESE]

Wheat crown on the left damaged by common root rot; healthy crown (right).

TABLE 7 **Visual scores for root disease**

Visual score (VS)	Occurrence of root diseases due to soil conditions
2 [Good]	Root disease are rare
1 [Moderate]	Root disease are common
0 [Poor]	Root disease are very common



Assessment

- 1 Assess crop growth and crop height when the crop has reached maturity and preferably two weeks after ear emergence (Plate 27). Compare with the class limits in Table 8. Your observations of crop growth and vigour during the growing season may also provide a useful indication of seedbed conditions. In a good season under non-limiting conditions, a particular cultivar should grow to a certain height with about a 10–15% variation. Allowances should be made for exceptionally good seasons and for poor seasons.



Importance

CROP GROWTH AND CROP HEIGHT AT MATURITY can be useful visual indicators of soil quality. They are also dependent on a number of other factors including climate, cultivar, nitrogen application and soil fertility, time of sowing, fungicide applications and the use of plant growth regulators to reduce straw length. Crop growth and crop height are however particularly helpful indicators of soil quality if agronomic factors have not limited crop emergence and development during the growing season. The growth and vigour of grain crops depend in part on the ability of the seedbed to maintain an adequate tilth throughout the growing season. Poor soil aeration and resistance to root penetration as a result of structural degradation reduce plant growth and vigour, and delay maturity.

PLATE 27 Crop height at maturity

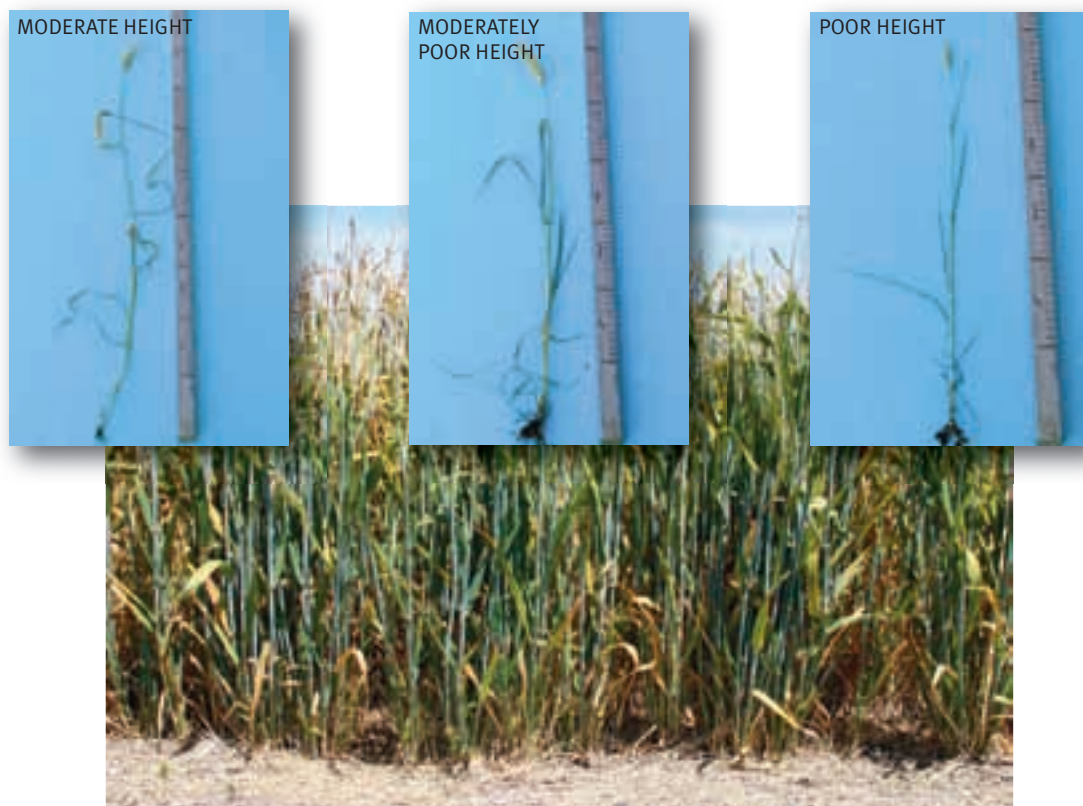


TABLE 8 Visual scores for crop growth and height at maturity

Visual score (VS)	Crop growth and crop height at maturity
2 [Good]	Crop growth is good and crops are at or near maximum height, with little variability in height at maturity. Semi-dwarf varieties commonly have a crop height at maturity of >1000 mm
1 [Moderate]	Crop growth is moderate. Crops show moderate variability in height at maturity and are significantly below maximum (700–900 mm)
0 [Poor]	Crop growth is poor and plants can appear sickly. Crop height is uneven and patchy and well below maximum at maturity (400–600 mm)



Assessment

- ① Measure the size of the kernels just before harvesting and compare them with the photographs and criteria given (Plate 28).

While there is a strong association between kernel number and yield, kernel size and dry weight are also strong determinants of the final yield. In making the assessment, consideration must be given to the plant population, tiller density and weather conditions and in particular the rainfall and sunlight hours. High plant populations and tiller densities will reduce the size of the kernel, and dry conditions and prolonged cloudy weather will reduce photosynthesis and subsequently the formation of carbohydrates and starch.



Importance

KERNEL development starts immediately after floret fertilization with cellular division during which the endosperm cell and amyloplasts are formed. This period is known as the lag phase and lasts for about 20 to 30 percent of the grain filling period. This is followed by a phase of cell growth, differentiation and starch deposition in the endosperm which takes 50 to 70 percent of the grain filling period. Good availability of carbohydrate is essential to be maintained during the crop cycle avoiding any shortage especially during the grain filling period. Soils in good condition with good structure, porosity, organic matter levels, soil life, soil fertility and rooting depth help ensure the supply and availability of water and nutrients. The grain filling period is prolonged as a result and an increase in kernel size is achieved. Good crop management practices including the adoption of widely spaced rows and good residue cover between rows to conserve water in dry zones also help to maximise the size of the kernel.

KERNEL SIZE is a useful determinant of grain quality by measuring the weight of unscreened grain, the screening loss and the weight of 1000 grains of clean seed.

PLATE 28 How to score kernel size

**GOOD CONDITION VS = 2**

Depending on the variety, kernels are large, completely filled and well shaped with few or no moisture stress features apparent.

**MODERATE CONDITION VS = 1**

Kernels are of moderate size, may show occasional incomplete grain filling and stress features are often apparent.

**POOR CONDITION VS = 0**

Kernels are generally very small with an irregular shape and stress features are very common.



Assessment

- ① Assess relative crop yield based on the class limits in Table 9. Assessments can be made for all varieties of crops by counting or estimating the number and size of ears (spikes) per square metre, the number of kernels (grains) per ear, and the degree of grain filling. Harvested yield monitors could also be employed. Compare these with an 'ideal' crop (Plates 29). In making the assessment, consideration must be given to the variety of wheat, the number of plants per square metre, the soil moisture, air temperature and sunshine hours during the growing season, and pests and diseases not associated with the condition of the soil.



Importance

WITH A DECLINE IN SOIL QUALITY, crops can come under stress as a result of poor soil aeration, water-logging, moisture stress (due to either soil saturation or a reduced available water-holding capacity), a lack of available nutrients (Plates 30–31), and adverse temperatures. Toxic chemicals can also build up and root growth be impeded owing to chemical reduction reactions and a high penetration resistance to root development. This results in poor germination and emergence, poor plant growth and vigour, the need for redrilling, delays in drilling, root diseases, pest attack, and consequently lower crop yields. Plant stress induced by structural degradation can further affect the quality of grain by changing the amount and type of protein and starch formed, and the enzymic potential. These affect the amount of fermentable carbohydrate, the baking quality of wheat and the malting potential of barley. Under good soil conditions with adequate water and nutrients, the ripening period is prolonged and the starch accumulation inside the kernel is delayed and more gradual. This increases yield with a higher starch and protein percentage and quality.

PLATE 29 Crop yield



Good crop yield with large ear development and complete grain filling.

PLATE 30 Effect of boron deficiency on crop yield



Small ear development on the left due to boron deficiency.

PLATE 31 Effect of copper deficiency on crop yield



White tipping and incomplete ear development due to copper deficiency.

TABLE 9 Visual scores for crop yield

Visual score (VS)	Crop yield
2 [Good]	Crops have >500 ears per square metre. The ears are large with a spike length >90% of maximum for the variety. Ears have >50 kernels (grains) per ear and show complete grain filling with few signs of stress, pests or diseases. Harvested yield is greater than 8 tonnes per hectare
1 [Moderate]	Crops have 300–400 ears per square metre. The ears are of medium size with the spike length varying from 60–80% of maximum for the variety. Ears have 30–40 kernels (grains) per ear and show moderate and occasional uneven grain filling. Stress, pest and disease evidence is moderately common. Harvested yield is 6–7 tonnes per hectare
0 [Poor]	Crops have <200 ears per square metre. The ears are generally small and vary in length. Spike length is commonly <50% of maximum for the variety. Ears have <20 kernels (grains) per ear and grain filling is poor and often uneven. Stress, pest and disease features are very common. Harvested yield is less than 5 tonnes per hectare



Assessment

- 1 Assess whether production costs have increased because of increased tillage/fertilizer requirements and herbicide/fungicide application over the years (Figure 4 and Table 10). This assessment can be based on perceptions, but reference to annual balance sheets will give a more precise answer.



Importance

Ground preparation, fertiliser, herbicide and pesticide inputs account for some of the highest costs in any cropping operation, and can increase significantly with increasing soil degradation. As degradation increases, the density and strength of the soil increases and, as a result, the soil becomes more resistant to tillage forces. Plough resistance increases so that larger tractors are required to avoid excessive wheel slip and the need to operate at lower ground speeds in a lower gear. The size, density and strength of soil clods also increase with increasing loss of soil structure, and careful timing and additional energy is needed to break them down to a seedbed. This energy is generally applied by using more intensive methods of cultivation and by making a greater number of passes. As a result, conventional tillage costs can increase by over 300 percent.

Continuous cropping using conventional cultivation techniques can also give rise to a significant loss of organic matter and, as a result, can substantially reduce soil fertility and the ability of the soil to supply nutrients. Higher amount of fertilizer are needed to compensate for the loss of these nutrients. The loss of organic carbon under continuous conventional cultivation could further incur a possible carbon tax in the future.

Reductions in crop yield are often not recognised as the result of the degradation of soil structure. Growers often assume that soil fertility is at fault and increase their production costs by applying extra amounts of fertilisers.

FIGURE 4 Assessment of production costs

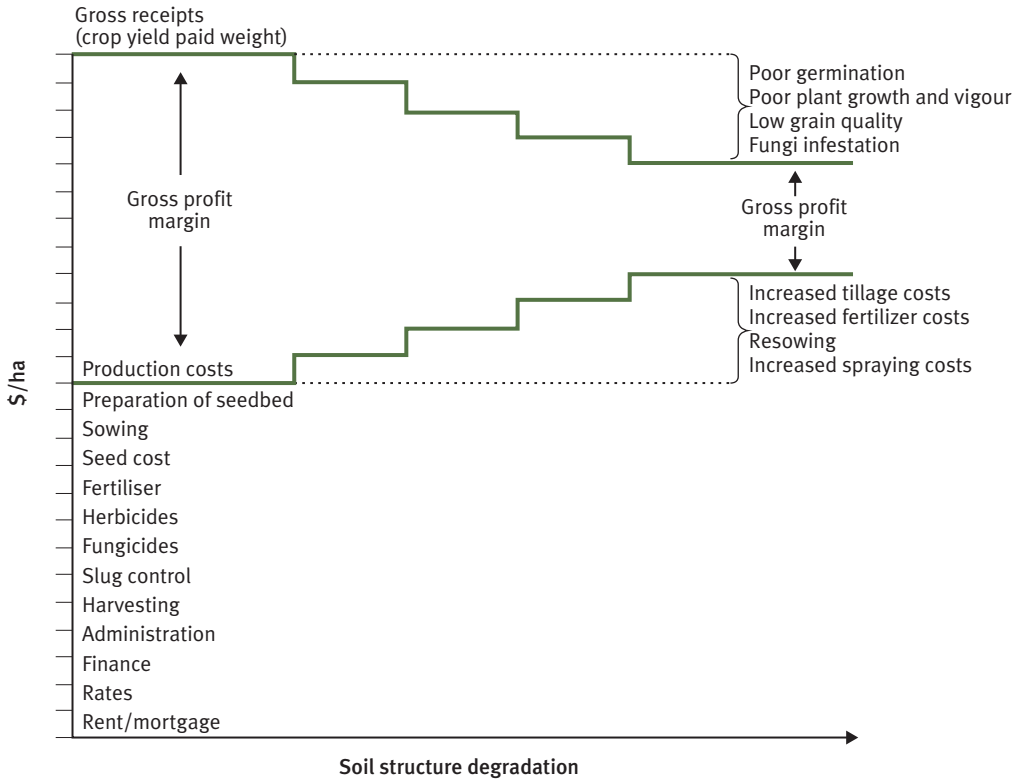


TABLE 10 Visual scores for production costs

Visual score (VS)	Production costs
2 [Good]	Production costs including ground preparation, fertiliser, herbicide & pesticide requirements have not increased
1 [Moderate]	Production costs including ground preparation, fertiliser, herbicide & pesticide requirements have increased moderately
0 [Poor]	Production costs including ground preparation, fertiliser, herbicide & pesticide requirements have increased greatly

Soil management of wheat crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, including no-tillage and minimum tillage that incorporate the establishment of temporary cover crops and crop residues on the surface (Plates 32–34), provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage also encourages soil life and biological activity (including earthworm numbers) and increases micro-organism biodiversity. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO_2) and enables the soil to operate as a sink for CO_2 . Soil organic matter levels build up as a result and create the potential to gain 'Carbon Credits'. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

On the other hand, conventional tillage can impact negatively on the environment, with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO_2), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. The fundamental difference between conventional tillage and conservation tillage is their relative environmental and economic sustainability. The long-term affects of conventional tillage are cumulatively negative whereas the long-term affects of conservation tillage are cumulatively positive.

PLATE 32 No-till drilling a wheat crop into an erosion-prone field protected by herbicided pasture [BAKER NO-TILLAGE LTD]



PLATE 33 Strip-tillage planting of an annual crop protected by good residue cover



PLATE 34 Harvesting a wheat crop followed immediately by no-till seeding the next crop into stubble [BAKER NO-TILLAGE LTD]



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Shepherd, T. G., Stagnari, F., Pisante, M. and Benites, J. 2008. *Visual Soil Assessment – Field guide for wheat*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 1

Pastures



Pastures

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Plates, figures, tables and parts of the text are reproduced from Shepherd, T.G. 2009. Visual Soil Assessment, Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country. Second edition. Horizons Regional Council, Palmerston North. 119 p.; under copyright © Horizons Regional Council and BioAgriNomics Ltd 2009.

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List of acronyms

AEC	Adenylate energy charge	MgO	Magnesium oxide
Al	Aluminium	Mn	Manganese
ASC	Anion storage capacity	Mn³⁺	Manganic
ATP	Adenosine triphosphate	Mn²⁺	Manganous
B	Boron	Mo	Molybdenum
C	Carbon	N	Nitrogen
Ca	Calcium	N₂	Nitrogen gas
Ca²⁺	Calcium cation	NO₃⁻	Nitrate
CEC	Cation exchange capacity	NO₃⁻-N	Nitrate-Nitrogen
CH₄	Methane	NO₂⁻	Nitrite
Cl	Chlorine	N₂O	Nitrous oxide
CO₂	Carbon dioxide	Na	Sodium
qCO₂	Metabolic quotient	Na⁺	Sodium cation
Co	Cobalt	NH₄⁺	Ammonium
CT	Condensed tannins	NH₃	Ammonia
Cu	Copper	O₂	Oxygen
DM	Dry matter	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂	Hydrogen gas	SO₄²⁻	Sulphate
H₂S	Hydrogen sulphide	SO₃²⁻	Sulphide
I	Iodine	Se	Selenium
K	Potassium	VS	Visual score
K⁺	Potassium cation	VSA	Visual Soil Assessment
KCl	Potassium chloride	WFP	Water-filled porosity
LHb	Leghaemoglobin	Zn	Zinc
Mg	Magnesium	ZnS	Zinc sulphide
Mg²⁺	Magnesium cation		
MgCl₂	Magnesium chloride		

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of pastoral land. A decline in soil quality has a marked impact on canopy cover, tiller density, pasture growth, pasture quality, food quality, animal health, production costs, nutrient loss into the groundwater and waterways, carbon sequestration and green-house gas emissions. It can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Soil physical properties control the movement of water and air into and through the soil, the ease with which roots penetrate the soil, the number, type and activity of soil organisms, and the availability and uptake of soil nutrients. Damage to the soil can change these properties and reduce plant growth, food quality and environmental outcomes, regardless of nutrient status. Safeguarding soil resources for future generations and minimizing the ecological footprint of pastoral agriculture is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil/pasture and food quality;
- ❖ the effect of land management decisions on soil quality, plant performance, and environmental outcomes.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance and quality of pastures and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for pasture grazing, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for pastoral agriculture. Scoring is out of 50: the higher the score, the better the condition of the soil and the performance of the plant. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

In addition, the VSA provides a quick, low cost method for estimating the potential for nutrient loss into the groundwater and waterways, C sequestration, and the emission of green house gases.

The VSA method

While the name Visual Soil Assessment implies a focus on the soil, the method is equally about assessing both the soil and the plant. Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a score card. Soil

quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the pasture. This knowledge will facilitate the satisfactory and rapid completion of the plant score card. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. they are capable of changing under different management regimes and land use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the 'soil' and 'plant' scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate, or poor condition.

Placing the soil and plant scores side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ❖ **A SPADE** (flat-faced) – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ❖ **A PLASTIC BASIN** (about 450 x 350 x 250 mm) – to contain the soil during the drop shatter test;
- ❖ **A HARD SQUARE BOARD** (about 260 x 260 x 20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ❖ **A HEAVY-DUTY PLASTIC BAG** (about 750 x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;

PLATE 1 The VSA tool kit



- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A MAGNIFYING HAND LENS** – to assess the clover nodules;
- ❖ **A TAPE MEASURE** – to measure the sample depth, topsoil depth, and potential rooting depth;
- ❖ **A BRUX REFRACTOMETER AND GARLIC CRUSHER** – to measure the sugar content of pasture. Although the VSA method is designed to be instrument free, the refractometer is highly recommended;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the visual score (VS) for each indicator.

The procedure

When should it be carried out?

The test should be carried out when the soils are moist and suitable for grazing. If you are not sure, apply the ‘worm test’ (p. 70). For **silty soils**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to test. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to test.

Setting up

Time

Allow 40 minutes per site. For a representative assessment of soil quality, sample four sites over a 5 hectare area.

Reference sample

Take a small sample of soil (about 100 x 50 x 150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. Avoid areas that may have had heavier wheel and stock traffic than the rest of the field, e.g., around ‘camp’ sites, water troughs and gateways, etc. Also avoid atypical small areas within the field, such as small hollows or mounds, areas adjacent to groves or lines of trees, filled in pits, etc. VSA can also be used to assess the compactive and pugging effects of these high traffic areas on soil quality. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the score card. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicators score card.

Carrying out the test

Initial observation

Dig a small hole about 200 x 200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200-mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If, for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two 200 x 200 x 100 mm samples with a spade. If the 100–200 mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two 200 x 200 x 100 mm samples. Note that taking a 200-mm cube immediately below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and pasture/crop management.

The drop shatter test

Drop the test sample a maximum of three times onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, depends on the texture of the soil, and the degree to which the soil breaks up, as described on pp. 2 and 3.

Systematically work through the score card, assigning a visual score (VS) to each indicator by comparing it to the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS ranking in the right-hand column of the scorecard.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

“Despite mankind’s lofty aspirations and many notable achievements, our survival depends on a six-inch layer of topsoil and the fact that it rains”

anonymous

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality under pasture

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Topsoil depth:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____ **Date:** _____

Textual group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Moisture condition: Dry Slightly moist Moist Very moist Wet

Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Number and colour of soil mottles pg. 8		x 2	
Soil colour pg. 10		x 2	
Earthworms (Number =) (Av. size =) pg. 14		x 3	
Soil smell pg. 18		x 2	
Potential rooting depth (m) pg. 22		x 3	
Surface ponding pg. 26		x 3	
Surface relief pg. 30		x 1	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 20
Moderate	20–35
Good	> 35

Assessment

- ❶ Take a sample of soil half the size of your thumb from the topsoil to assess the *soil texture*. Take also a sample/s that is/are representative of the subsoil to assess the overall *textural group* of the soil profile.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball and then squeezing it between the thumb and forefinger. With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the *textural class* obtained by reference to the textural diagram (Figure 2a). The *textural group* is obtained by comparing the position of the textural class in Figure 2a with Figure 2b (e.g., silt loam = fine silty).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For instance, if the soil has a reasonably high content of organic matter, i.e. is humic with 17–29 percent organic matter, raise the textural score by one (e.g., from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size ≥ 0.06 mm; silt varies between 0.06 and 0.002 mm, while the particle size of clay is < 0.002 mm.

Texture influences soil behaviour in several ways, notably through its effect on water retention and availability, soil structure, aeration, drainage, soil trafficability and workability, soil life, and the supply and retention of nutrients. Knowledge of both the textural class and potential rooting depth (see p. 22) enables an approximate assessment of the total water holding capacity of the soil, one of the major drivers of pasture production.

FIGURE 2 Soil texture classes and groups

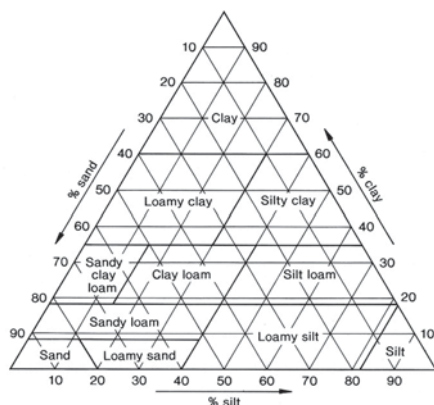


Figure 2a
Textural classes.

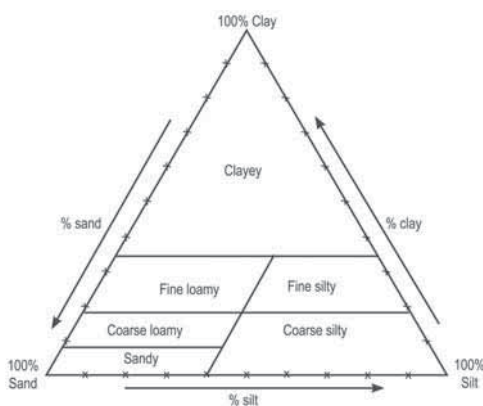


Figure 2b
Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
1 [Moderate]	Loamy silt	Smooth feel, non sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
0.5 [Moderately poor]	Silty clay & Clay	Very smooth, very sticky, very plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
0 [Poor]	Loamy sand	Gritty and rasping sound. Will almost mould into a ball but disintegrates when squeezed between thumb and forefinger
	Sand	Gritty and rasping sound. Cannot be moulded into a ball

Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade. When taking the sample, ensure the blade of the spade is inserted vertically to obtain the true volume of soil required for assessment.
- ❷ Drop the soil sample a maximum of three times from a height of one metre onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Don't drop any piece of soil more than three times. For soils with a sandy loam texture (p. 2), drop the cube of soil once only from a height of 0.5 metres. If the sandy loam is humic (17–29 percent organic matter), drop the soil twice from 1 metre. Transfer the soil onto the large plastic bag.
- ❸ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade once from a height of just 50 mm and then roll the spade over, spilling the soil onto the plastic bag.
- ❹ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures if present. If the clod cannot be easily parted, do not apply further pressure because the cracks and fissures are probably not continuous and therefore unable to readily conduct oxygen, air and water.
- ❺ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs and criteria given in Plate 2. The method is valid over a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.

Importance

SOIL STRUCTURE is important for pastures. It regulates soil aeration and gaseous exchange rates, soil infiltration and erosion, the movement and storage of water, soil temperature, root penetration and development, nutrient supply, and the resistance to structural degradation by compaction and deformation under wheel traffic and stock treading. Good soil structure improves the trafficability of the soil, increasing the window of opportunity for stock grazing and vehicle access without causing compaction. The loss of soil structure can alter seasonal growth patterns and change the botanical composition of pasture including an increase in the number of weeds. Structural degradation can reduce tiller density and canopy cover by 50 percent, pasture production by 30–50 percent in spring, and is often a catalyst for diseases. It also reduces the infiltration of water into and through the soil increasing the potential for erosion by sheet wash on sloping ground.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, sub-angular and sub-rounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or sub-angular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 Visual scoring (VS) of soil structure



GOOD CONDITION VS = 2

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally sub-rounded (nutty) and often quite porous.



MODERATE CONDITION VS = 1

Soil contains significant proportions (50 percent) of both coarse clods and friable fine aggregates. The coarse clods are firm, sub-angular or angular in shape and have few or no pores.



POOR CONDITION VS = 0

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or sub-angular in shape and have very few or no pores.

 **Assessment**

- ❶ Remove a spade slice of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and break in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs and criteria given in Plate 3. Look for the spaces, gaps, holes, cracks, fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides additional information as to the porosity of the individual clods (the intra-aggregate porosity).

 **Importance**

SOIL POROSITY is important to assess along with soil structure. Soil porosity, and particularly macro porosity (or large pores), influence the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores or coarse micropores within the large clods, thus restricting their drainage and aeration.

Poor aeration leads to the build up of methane, sulphide gases and alcohol, and reduces the ability of plants to take up water and nutrients, particularly nitrogen, phosphorus, potassium, sulphur, zinc, copper and cobalt. Poorly aerated and compacted soils reduce plant-available nitrate-nitrogen (NO_3^- -N) and ammonium (NH_4^+) to nitrite (NO_2^-), nitrogen (N_2) gas and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available sulphate-sulphur (SO_4^{2-} -S) is also reduced to sulphite (SO_3^{2-}) and sulphides, rendering N and S unavailable to the plant. Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can also only utilize N if S is present in the oxygenated sulphate form. Moreover, the number, activity and biodiversity of micro-organisms and earthworms are greatest in well-aerated soils and are able to decompose and cycle organic matter and nutrients more efficiently than in poorly aerated soils.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilise the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, but greatly reduces fertiliser efficiency and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce less greenhouse gases. The greater the porosity the better the drainage and therefore the soil pores will be less likely to be water-filled to the critical levels required to generate the production of methane and nitrous oxide greenhouse gases (see pp. 92–93). Aim to keep the porosity score above 1.

PLATE 3 Visual scoring (VS) of soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present in parts of the soil on close examination. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.

Assessment

- Assess the number, size and colour of soil mottles by taking a sample of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and comparing it with the three photographs and criteria given in Plate 4. The percentage chart below will help you determine the percentage of the soil occupied by mottles.

Mottles are patches of different colour interspersed within the dominant (background) soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also early warnings of a decline in soil structure as a result of treading damage and compaction under wheel traffic. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces iron (Fe) and manganese (Mn) from their *brown/orange* oxidised ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey due to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey mottles predominate. The abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicate the soil is moderately well drained, and no mottles indicate good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S, Zn, Cu and Co (p. 6). Depending on soil type and soil condition, Olsen P levels of 22–35 mg/L are generally required for optimum pasture production. However, P levels need to be raised (sometimes to 40–50 mg/L) in compacted, poorly aerated soils to produce a positive dry matter production response. In addition, sulphur and nitrogen are reduced to plant-unavailable forms as described on the previous page. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, alcohol

(ethanol and ethylene), acetaldehyde and formaldehyde, which are toxic to plant roots. Root damage and reduced nutrient and water uptake give rise to poor pasture vigour. If your visual score for the number and colour of soil mottles is one or less, you need to aerate the soil.

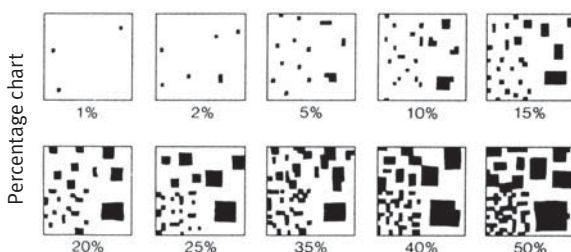


PLATE 4 Visual scoring (VS) of the number and colour of soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has many (10–20 percent) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has profuse (> 50 percent) medium and coarse orange and particularly grey mottles.

Assessment

- 1 Compare the moist colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area (Plate 5). If the soil is dry, pour water over the surface of the sample.
- 2 Using the three photographs and criteria given in Plate 6, compare the *relative change* in soil colour that has occurred. As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.

Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not so easily and accurately assessed; in general, the darker the colour, the greater the amount of organic matter and humus in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, collectively determining soil health. It promotes infiltration, the movement and retention of water, helps develop and stabilise soil structure, cushions the impact of wheel traffic and stock treading, reduces the potential for wind and water erosion, plays a key role in maintaining the cation exchange and buffering capacity of the soil, and indicates whether the soil is

PLATE 5 Soil colour under the fenceline



Soil colour under the fenceline on the left compared with that in the field on the right. The comparative difference in soil structure and porosity is also a useful observation to make.

PLATE 6 Visual scoring (VS) of soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is similar to, or darker than that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with under the fenceline.

functioning as a carbon 'sink' or as a source of green-house gases. Organic matter acts as a major reservoir of organic carbon in the soil, carbon that is sequestered by microorganisms and from CO₂ in the atmosphere by plants. Organic matter also provides an important food resource for soil organisms and is an important source and major reservoir of plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; nitrogen, phosphorus, potassium and sulphur requirements of pastures increase markedly, and other major and minor elements are more readily leached. The result is an increased dependency on fertiliser input to maintain nutrient status.

Dark-coloured soils due to high amounts of organic matter and humus provide a major source of nitrogen and phosphorus. A soil with 1 percent organic carbon in the top 0–100 mm contains about 1200 kg of organically bound N per ha. Over the course of a year, 1–5 percent of the organic N is mineralised by soil microorganisms to plant-available inorganic N in the form of ammonium (NH₄⁺) and nitrate-nitrogen (NO₃⁻-N). A soil with 1200 kg N/ha can therefore potentially provide around 60 kg of plant available N/ha/yr. If we assume soils have an average organic C content of 5 percent, the activity of soil microbes can potentially supply 300 kg N/ha/yr. Ensuring a good, healthy, biologically active soil with average soil C levels can therefore provide the N requirements of a high-producing dairy farm. This is borne out by the fact that dairy farms with good soil life are commonly producing in excess of 17 tonne dry matter/ha/yr with no mineral N applied. Many soils have well in excess of 5 percent organic C in the top 0–100 mm and therefore hold greater amounts of organically bound N that could potentially become plant available. The key is to ensure that management practices, including the type and amount of fertilisers used, encourage rather than suppress the biological life of the soil and therefore the amount of available N present.

Soil colour (compared with that under the fenceline) can be a useful indicator of whether soils on a farm or in a field are becoming darker due to gaining (sequestering) carbon. If the soil is paler, it could possibly be losing carbon, i.e. becoming C negative. If there is no colour difference, the soil carbon regime may be in a steady (C neutral) state, i.e. neither losing nor gaining carbon. Soil colour, along with soil texture, clay mineralogy, earthworm numbers, root length and density, potential rooting depth, pasture growth (dry matter production), pasture colour and growth compared with urine patches, and the amount and form of fertiliser and N applied (see following pages) can collectively provide a clear indication whether a particular management practice or land use is carbon positive, neutral or negative. A farm that has similar or darker coloured topsoils in the field relative to the fenceline, with fine silty or clayey textures, good earthworm numbers, root length and density, potential rooting depth, pasture growth (dry matter production), pasture colour and growth relative to urine patches, and is applying carbon-friendly forms of fertiliser and N will sequester significant amounts of carbon (see carbon sequestration, pp. 80–89). The farm will therefore be C positive and in a position to potentially gain 'carbon credits' rather than possibly pay a carbon tax.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is markedly influenced by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Very dark brown, brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidised form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that along with low pH, reduce the form of Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Ferrous and manganous oxides are more soluble than their oxidised forms and are therefore more readily taken up by the plant. High levels of Fe and Mn in the soil and pasture suppress the availability of cobalt (Co), which in turn reduces the appetite of ruminant stock – as a consequence, stock lose condition.

In addition to the production of toxic levels of Fe^{2+} and Mn^{2+} ions, poor aeration and waterlogging gives rise to a further series of chemical and biochemical reduction reactions that produce toxins such as hydrogen sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde that damage the root system. This reduces the ability of plants to take up water and nutrients (particularly N, P, K, S, Zn, Cu and Co), causing poor pasture growth and vigour. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, pastures typically have low energy levels and are not as palatable because they are unable to take up nutrients such as Na that are necessary to make sugars.

What is more, soil colour can indicate the potential of a soil to convert plant-available forms of nutrients into unavailable forms. Soils that are distinctly grey in colour due to being anaerobic and waterlogged reduce plant-available N in the form of nitrate (NO_3^-) and ammonium (NH_4^+) to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available S in the form of sulphate-sulphur (SO_4^{2-} -S) is reduced to unavailable sulphides. Sulphur and nitrogen can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Plants also need S in the sulphate form to utilise N.

Dark coloured soils further suggest that the microbial biomass is predominantly aerobic, enabling the efficient decomposition of organic matter to humus and the retention, immobilisation and release of soil nutrients.

Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 2, p. 5 & Plate 7). Note also the number of species present (Plates 8–10) and compare with the criteria given in Table 2. Earthworms vary in size and number depending on the species, maturity, and the season. For year-to-year comparisons, therefore, earthworm counts must be made at the same time of year (preferably late winter to early spring), and when soil moisture and temperature levels are good; avoid dry conditions. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. As a 200-mm cube sample is equivalent to 1/25 square metre, the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.

Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digesting, and casting, earthworms have a major effect on the chemical, physical, and biological properties of the soil: they shred and decompose plant residue converting it to humus and releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg, characteristics that are due in part to the higher enzyme activity in

the casts (see p. 20). They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter, and water content. In addition, dead earthworms can contribute significant amounts of N to the soil, being 60–70 percent protein (dry weight) with a N content of 12 percent. Forty-five earthworms per 200-mm cube of soil ($1\ 125/m^3$) are roughly equivalent to a biomass of 4 tonnes of earthworm/ha, and could release 43–50 kg N/ha upon their death. The presence of earthworms also increases the mobilization of nitrate-N by 10 times and that of ammonium-N by 80 times, compared with soils without earthworms.

PLATE 7 Sample for assessing earthworms



Sample for assessing earthworms. Photo shows earthworms present in a 200-mm cube sample of soil.

PLATE 8 *Lumbricus rubellus*

A very active surface litter and dung feeding earthworm; commonly red-brown or red-purple in colour with a paler underside; has a distinctly flattened tail; commonly 25–220 mm long.

PLATE 9 *Aporectodea caliginosa*

A medium-sized (40–90 mm) topsoil dwelling earthworm; commonly grey-pink on both the dorsal and ventral surfaces; does not have a flattened tail.

PLATE 10 *Aporectodea longa*

A long (90–180 mm) deep burrowing earthworm; commonly dark grey-brown with a black head; tail end is paler and slightly flattened. Underside is paler than the dorsal surface.

TABLE 2 Visual scores (VS) for earthworms

Visual score (VS)	Earthworm numbers (per 200 mm cube of soil)
2 [Good]	≥ 45 (with preferably 3 or more species)
1.5 [Moderately good]	35–44
1 [Moderate]	25–34 (with preferably 2 or more species)
0.5 [Moderately poor]	15–24
0 [Poor]	< 15 (with predominantly 1 species)

Earthworms also act as biological aerators and physical conditioners of the soil, improving soil porosity, aeration, soil structure, soil aggregate stability, water retention, water infiltration, and drainage, and reducing surface runoff and erosion. They promote pasture growth by secreting plant-growth hormones and increasing root density and root development through the rapid growth of roots down nutrient-enriched worm channels. They also contribute to nitrogen fixation by promoting nitrogen-fixing microorganisms, nitrogen-fixing nitrogenase enzymes and the availability of Mo. While earthworms can deposit around 25–30 tonnes of casts/ha/yr on the surface (Plate 11), 70 percent of their casts are deposited below the surface of the soil. Earthworms can therefore have a major effect on the overall properties and condition of the soil.

Earthworms also increase the population, activity, and diversity of soil microbes. The number of beneficial bacteria can increase three-fold from 3 million per gram in soils with no worms to 10 million per gram after colonization by worms. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus and the supply of nutrients. Earthworms therefore play an important role in pastoral agriculture and can increase pasture production by 10–30 percent.

Earthworms can increase the depth of topsoil and the carbon content of both topsoil and subsoil by their burrowing, digesting, reworking, and mixing of soil and plant residues (bioturbation), and by the deposition of worm casts. High numbers of earthworms ingest considerable amounts of soil and plant material, building up soil C levels by converting C to more stable organic compounds bonded to clay particles. Organic matter gradually works down to the subsoil and so increases the depth of topsoil. The burrowing, casting,

and incorporation of organic matter into the soil contributes to increasing topsoil depth by decreasing soil density and increasing the porosity, and therefore the volume of soil. Given that 30 percent of worm casts are deposited on the surface and 70 percent below ground, the potential for earthworms to increase soil carbon levels and topsoil depth is substantial. Deposition rates of soil at the surface due mainly to earthworm casts can vary from 2–20 mm/yr.

PLATE 11 Surface of field 'boiling' with worm casts



Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by pasture production and the stocking rate. Their numbers are also governed by soil moisture, temperature, texture, soil aeration, pugging, legume content, pH, soil nutrients (including Ca), and the type and amount of fertiliser and nitrogen used. The over-use of acidifying salt-based fertilisers and ammonia-based products can reduce earthworm numbers.

PLATE 12 Yellow-tail earthworm (*Octolasion cyaneum*)



Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep burrowing species that pull down and mix plant litter and organic matter at depth.

Earthworm species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 12) can indicate adverse soil conditions.

Assessment

- 1 Remove a spade slice of soil (approximately 100 mm wide × 100 mm long × 100 mm deep) and break in half. Place the exposed face of the soil close to your nose, take three deep sniffs, and compare with the criteria given in Table 3. Before sniffing the soil, place a tissue (or mask) over your nose to prevent the inhalation of any harmful microbes. The test is best carried out when the soil is moist, including during or immediately after the wet months of the year.

Importance

SOIL SMELL, while very dependent on the water content and aeration status of the soil, is also a good indicator of the amount and the activity of soil life and therefore soil health. Soil smell is determined principally by the gases given off by the aerobic or anaerobic respiration of soil microbes, and by the type and amount of organic matter and humus present in the soil. Aerobic respiration by soil fungi, bacteria, yeast, protozoa (i.e. single cell animals), nematodes, arthropods (mites, beetles, millipedes, etc.), and earthworms produce distinctive odours. The degree and nature of the odours are determined by the composition and activity of the soil biology which in turn is governed in part by the available food supply in the form of organic matter and humus. Soils rich in fungi, for example, produce aromatic compounds and organic acids that give an earthy, rich, sweet, fresh or sometimes musty smell. These are often the characteristic smells of forest soils, which are generally rich in fungi. The presence of similar fungal smells in a pastoral soil suggests it is not only well aerated but also has a good, active microbial biomass (Plate 14). This is because it must have large numbers of bacteria to maintain a fungal to bacteria ratio of 0.75:1 (or 1:1) that is necessary to preserve and promote pastoral plants. An imbalance of this ratio along with poor soil nutrition could explain why pastures may show poor persistence and a tendency to revert to other plant species such as woody weeds. Pastoral soils that are intensively grazed and fertilised tend to have a greater abundance of bacteria relative to fungi than soils that are less intensively grazed and fertilised. As a consequence, they are more

TABLE 3 How to assess soil smell

Visual score (VS)	Soil smell
2 [Good]	Soil has a distinct rich, earthy, sweet, wholesome or fresh smell.
1 [Moderate]	Soil has a slight earthy, sweet odour or a mineral smell.
0 [Poor]	Soil has a putrid, sour, chemical or unpleasant smell.

sensitive to stress such as droughts, are less efficient in terms of uptake, cycling and retention of nutrients including N, and are more susceptible to N leaching.

Biological regimes are sensitive to intensive land uses with the result that soils can have little or no soil smell. Anaerobic respiration of micro-organisms (including anaerobic bacteria and yeast) in saturated, poorly aerated soils produce methane and nitrous oxide (greenhouse gases), alcohol (ethanol and ethylene), acetaldehyde formaldehyde, and putrid sulphide gases including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS), all of which inhibit root growth when accumulated in the soil (Plate 15). Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

While soils should have good microbial biomass with levels preferably in excess of 1800 mg/kg, and a good microbial quotient (i.e. the ratio of microbial biomass C to total organic C), to be beneficial, soil microbes also need to be active. The level of activity and therefore functionality of the microbial biomass is something that must always be kept in mind when assessing the status of the soil biological community. The activity and energy status of soil microbes can be assessed by measuring their respiration, the level of their respiration relative to their biomass (i.e. the respiration to biomass ratio or the metabolic quotient qCO_2), and their AEC, which should be ≥ 0.8 . Microbial viability is maintained at AEC values between 0.8 and 0.5 – the cells die at values below 0.5.

Soil microbes, including actinomycetes and mycorrhizal fungi, play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important stable organic compound that comprises up to 30 percent or more of the humus fraction in pastoral soils. Soil organisms also play a key role in the promotion and maintenance of soil fertility through nutrient and carbon cycling, and their role in the N and S cycle. Microbes immobilise and retain significant amounts of nutrients in the humus they produce and in their biomass, releasing them when they die. Moreover,

PLATE 13 Sample to assess soil smell



soil microbes, including mycorrhizal fungi, play a major role in the supply of plant-available nutrients, digesting soil and fertiliser, and unlocking nutrients such as phosphorus that are fixed by the soil. Mycorrhizal fungi and bacteria provide a fundamentally important ‘microbial bridge’ that allows the bidirectional flow of liquid C (sugars) from the plant to the soil, and nutrients and plant growth hormones from the soil to the plant. High organic matter and microbial activity further result in a high level of activity of soil enzymes such as urease, protease, phosphatase and sulfatase, which result in a high turnover of N, P and S through the soil organic pool.

In addition, soil microbes and particularly bacteria play a major role in the fixation and supply of nitrogen. *Rhizobium* bacteria in clover nodules fix N directly from the atmosphere. The ammonia produced by N-fixation is taken up by the plant to produce protein and organic N compounds that are then mineralised by a further range of bacteria and fungi, releasing N in the form of plant available ammonium (NH_4^+) when the plant dies. Under aerobic conditions, the ammonium is converted by nitrosomonas and nitrobacter bacteria to nitrate (NO_3^-), another plant available form of N (a process known as nitrification). Free-living aerobic *Azotobacter* bacteria and anaerobic (*Clostridium*) bacteria in the soil further promote the fixation and supply of plant-available N.

Nitrogen fixing bacteria, be they free-living in the rhizosphere, confined to nodules on plant roots, or existing as endophytes in leaves or stems, derive most of their energy from dissolved organic carbon (liquid sugar) produced by photosynthesis. N-fixation is therefore very dependent on the flow of liquid carbon from the leaf to the roots. If plants are mycorrhizal, i.e. have high populations of mycorrhizal fungi and bacteria attached to the roots that form a microbial bridge between the plant and the soil, they don’t require N in a mineralised form such as nitrate or ammonium. In order to transport mineralised N, mycorrhizal fungi have to convert it to glutamate, which represents an energy cost. For this reason, N is preferentially transported in an organic form, generally as amino acids such as glycine and glutamine.

PLATE 14 Soil with a moderately good smell



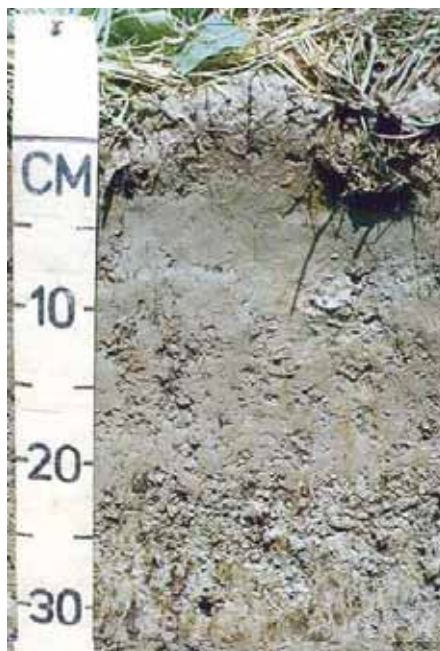
Soil has a moderately rich, earthy, sweet smell with a smell score of 1.5.

Moreover, bacterial- and fungal-feeding protozoa and nematodes release large amounts of N when feeding on their selected prey and are responsible for much of the plant-available N in the majority of soils. The predator-prey interaction of protozoa on bacteria releases 5 units of plant-available N in the form of ammonium for every six bacteria consumed. The feeding of nematodes on bacteria releases 19 units of N for every 20 bacteria consumed. Given that bacterial numbers should be greater than one million per gram for all agricultural soils, and nearer 100 million per gram for productive soils, the potential storage and release of N from bacteria is considerable. Between 40 and 80 percent of the N in plants can come from the predator-prey interaction of protozoa with bacteria.

In addition to adding organic matter to the soil, soil organisms play a key role in soil formation by developing and promoting the structure, aggregate stability, porosity, aeration, infiltration and water-holding capacity of the soil, and reduce waterlogging and runoff from the topsoil. Soil microbes also play an important role in purifying water and filter, buffer, degrade, immobilise, and detoxify organic and inorganic pollutants. Moreover, they suppress pests and diseases, producing compounds that inhibit the growth of, or are toxic to pathogens, reducing the invasion of the plant by a pathogen. *Beauveria* fungi, for example, destroy the adult clover root weevil, providing an effective biological control. Soil microbes also produce plant growth hormones and compounds that stimulate root growth and produce B group vitamins, including vitamin B12 which is important for rumen function.

The collective benefits of microbes can reduce fertiliser requirements and more than double the growth of ryegrass and clover. They can also significantly improve the sugar content, nutrient density, and health of the plant. Soil life can therefore be effectively described as the 'engine room' of the soil, with mycorrhizal fungi being the powerhouse. The trick to smart and sustainable farming is to ensure the engine remains well oiled.

PLATE 15 Soil with a poor smell



Soil has a putrid, unpleasant smell of hydrogen sulphide with a smell score of 0.

Assessment

- 1 Assess the potential rooting depth by digging a hole to identify the depth to a limiting (restricting) layer if present, and compare with the class limits given in Table 4. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks, and fissures down which roots can extend. Note also whether there is an overthickening of roots (a result of a high penetration resistance), and whether the roots are forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed due to prolonged waterlogging, and whether there is a hard pan present such as a strongly developed human-induced tillage or plough pan (p. 24), or a strongly developed natural pan such as an iron, silica or calcitic pan. An abrupt transition from a fine textured material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.

Importance

POTENTIAL ROOTING DEPTH is the depth of soil plant roots can potentially exploit before reaching a barrier to root growth, and indicates the ability of the soil to provide a suitable rooting medium for plants. The greater the rooting depth, the greater the available water-holding capacity of the soil, the greater the availability of soil nutrients, and the greater the resulting dry matter production. Fertilisers applied to pastures with deep rooting systems are more effectively utilised by the plant, resulting in less leaching of nutrients into the groundwater and waterways. During drought periods deep roots can access larger water reserves alleviating water stress and promoting the recovery and survival of the pasture. Conversely, soils with a restricted rooting depth due, for example, to a layer with a high penetration resistance (such as a compacted layer or a hardpan) limit uptake of water and nutrients, reduce fertiliser efficiency, increase leaching of nutrients, and limit pasture growth. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hard pans impede the movement of air, oxygen and water through the soil profile, the latter increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ❖ an abrupt textural change;
- ❖ low pH;
- ❖ aluminium (Al) toxicity;
- ❖ nutrient deficiencies;
- ❖ salinity;
- ❖ sodicity;
- ❖ a high or fluctuating water table;
- ❖ low oxygen levels.

Anaerobic (anoxic) conditions due to deoxygenation and prolonged water-logging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions.

Pastures with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth, thereby contributing to the sequestration of C in the soil. The physical action of the roots and soil fauna and the glues they produce, promotes soil structure, porosity, water storage, aeration and drainage at depth. The presence of nitrogen-fixing clover root nodules at depth also encourages the further development of the root system by supplying nitrogen. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Pastures are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up, so reducing losses by leaching into the environment.

PLATE 16 Potential rooting depth



Photo: Courtesy of Aaron Topp

Hole dug to assess the potential rooting depth.
Photo showing good potential rooting depth with abundant fine roots extending beyond the bottom of the photo at 810 mm depth.

TABLE 4 Visual scoring (VS) of potential rooting depth

VSA score (VS)	Potential rooting depth (mm)
2.0 [Good]	800
1.5 [Moderately good]	600–800
1.0 [Moderate]	400–600
0.5 [Moderately poor]	200–400
0 [Poor]	< 200

Identifying the presence of a hardpan

Assessment

- 1 Examine for the presence of a strongly developed hard pan by rapidly jabbing the side of the soil profile (dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically to the bottom of the hole (Plate 17). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (see photos below).
- 2 Having identified the possible presence of a hard pan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hard pan is. A strongly developed hard pan is very tight and extremely firm and has a high penetration resistance to the knife. Confirm also its presence or absence by removing a large, hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (by referring back to pp. 4, 6 and 8). In addition, look for the presence or absence of roots. Compare with the photos and criteria given in Plate 18. Only a strongly developed hardpan will restrict all root development and its presence will determine the potential rooting depth.

PLATE 17 Identifying the presence or absence of a hardpan with a knife



PLATE 18 Visual assessment of a hard pan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).



Assessment

- 1 Assess the degree of surface ponding based on your observation or general recollection of the time ponded water took to disappear after a wet period during the autumn, spring and summer, and compare with the three photographs and criteria given in Plate 19.



Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the infiltration rate into and through the soil, a high water table, and the time the soil remains saturated. Roots need oxygen for respiration, and prolonged waterlogging depletes oxygen in the soil, causing anaerobic (anoxic) conditions that induce root stress and restrict root respiration and growth. Roots are most vulnerable to surface ponding and saturated soil conditions in the spring when respiration and transpiration rates rise markedly, oxygen demands are high, and plant roots and shoots are actively growing. Such waterlogging causes the death of the fine roots responsible for nutrient and water uptake. Roots are also susceptible to ponding in the summer when transpiration rates are highest – reduced water uptake while the pasture is actively transpiring causes leaf desiccation and the wilting of plants.

Waterlogging causes pasture growth to decline due to poor shoot growth, fewer tillers, poor plant vigour, and chlorosis. In addition, pasture utilisation is reduced as a result of poor palatability, which is a function of:

- ❖ a change in pasture composition;
- ❖ deficiency in nutrients and sugars/carbohydrates;
- ❖ pasture becoming unpalatable and inaccessible by being soiled and trampled into the mud.

Prolonged waterlogging can change the composition of the pasture by stressing the less water-tolerant species and encouraging the development of undesirable water-tolerant species such as pennyroyal, duckweed, buttercup, etc. Prolonged waterlogging also increases root rot and soil-borne pathogens and limits the ability of roots to overcome the harmful effects of pathogens resident in the topsoil.

PLATE 19 Visual scoring (VS) of surface ponding



GOOD CONDITION VS = 2

No surface ponding of water evident after 1 day¹ following heavy rainfall on soils that were at or near saturation.



MODERATE CONDITION VS = 1

Moderate surface ponding occurs for 3–5 days¹ after heavy rainfall on soils that were at or near saturation.



POOR CONDITION VS = 0

Significant surface ponding occurs for longer than 7¹ days after heavy rainfall on soils that were at or close to saturation.

¹ Assuming little or no air is trapped in the soil at the time of ponding.

Waterlogging and deoxygenation result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are either toxic to roots or are in a form that is unable to be taken up by the plant, e.g.:

- ✦ iron is reduced to soluble ferrous (Fe^{2+}) ions and Mn to manganous (Mn^{2+}) ions;
- ✦ plant-available nitrate-nitrogen (NO_3^- -N) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas;
- ✦ plant-available sulphate-sulphur (SO_4^{2-} -S) is reduced to unavailable sulphite (SO_3^{2-}) and sulphides, including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS).

Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form.

In addition to N and S, waterlogging and poor aeration reduces the availability and uptake of P, K, Zn, Cu, and Co. This is partly because prolonged ponding of water kills off mycorrhizal fungi, soil organisms that facilitate the efficient uptake and utilisation of soil nutrients, and P in particular. While Olsen P levels of 22 mg/L are generally adequate for optimum pasture production on most soils in good condition, poorly aerated and waterlogged soils with relatively high Olsen P levels (40–50 mg/L) can show a positive pasture response to applied P. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, pastures typically have low energy levels and are not as palatable because they are unable to take up nutrients such as Na that are necessary to make sugars.

Anaerobic respiration of micro-organisms in waterlogged and poorly aerated soils produces methane (greenhouse gases), hydrogen gas, alcohol (ethanol and ethylene), acetaldehyde, and formaldehyde, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The by-products of anaerobic respiration and the lack of oxygen in poorly aerated and waterlogged soils also prevent the decay of organic material in the soil. As the soil becomes progressively degraded, the amount of CO_2 increases relative to O_2 and reaches a point where plant residues cannot decay; instead they begin to ferment, producing alcohol, formaldehydes and methane, which make proper decay and the turnover of organic matter impossible.

Prolonged surface ponding increases the susceptibility of soils to damage by wheel traffic and stock treading, reducing vehicle access, trafficability, and grazability by stock. Waterlogged topsoils on sloping ground are also prone to erosion by sheetwash and sloughing, the latter process caused by the physical shunting of soil downslope brought about through the treading effect of stock. Soils susceptible to surface ponding therefore need to be carefully managed to minimise the effects of such ponding on soil, pasture growth, utilisation and quality, and the environment.

The tolerance of the root system to surface ponding and waterlogging depends on a number of factors, including the pasture species and the time of year. Tolerance of waterlogging also depends on soil and air temperatures, soil type and condition, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and the oxygen consumption rate of plant roots.



Assessment

- 1 Observe the surface relief (smoothness) of the paddock at the end of the winter and compare it with the three photographs and criteria given in Plate 20.

Although soils are most susceptible to treading damage (pugging) during wet winter months, observations of surface relief at any time of the year will give useful information on damage caused by past grazing and its likely effects on soil quality.



Importance

SURFACE RELIEF shows the severity of pugging under stock treading, and can indicate structural damage below the surface. Wet soils can pug severely under intensive grazing by heavy weight animals when the load-bearing capacity of the soil is insufficient to support the weight of the animal. This damages the soil structure and reduces the pores in the soil, which are important for water, nutrient and air movement, and root penetration. Infiltration rates and the movement of water through the soil decreases, increasing runoff, soil erosion, and the risk of flash flooding. Very broken and deeply incised soil as a result of severe pugging can also damage the pasture root system and increase the area of bare ground. It can further induce surface ponding and anaerobic conditions, reducing pasture utilisation and impairing pasture growth as a result of poor shoot growth, fewer tillers and poor plant vigour (see p. 26). In addition, the decay and turnover of organic matter is impaired by the production of methane, alcohol and aldehydes as described on p. 19.

PLATE 20 Visual scoring (VS) of surface relief



GOOD CONDITION VS = 2
Surface is relatively smooth and unbroken.



MODERATE CONDITION VS = 1
Surface terrain is somewhat broken up and incised by occasional heavy treading events but it is not difficult to walk over.



POOR CONDITION VS = 0
Surface is very broken and deeply incised by severe repeated treading. The terrain is difficult to walk across and care must be taken to avoid twisting ankles.

FIGURE 3 Plant scorecard – visual indicators to assess plant performance in pasture

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Pasture quality (Brix=) pg. 34		x 3	
Clover nodules pg. 42		x 3	
Weeds pg. 46		x 2	
Pasture growth pg. 50		x 3	
Pasture colour and growth relative to urine patches pg. 52		x 3	
Pasture utilisation pg. 58		x 3	
Root length and root density pg. 60		x 3	
Area of bare ground pg. 62		x 2	
Drought stress pg. 64		x 2	
Production costs to maintain stock-carrying capacity pg. 66		x 1	
PLANT PERFORMANCE INDEX (sum of VS rankings)			

Plant Quality Assessment	Plant Quality Index
Poor	< 20
Moderate	20–35
Good	> 35

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:

Assessment

- 1 Assess the amount of green grass leaf, legume and dead matter (using the percentage chart on p. 36), and the botanical composition of the pasture during the time of year when pasture growth is strong due to favourable moisture and temperature conditions, and compare with the photographs and criteria given in Plate 21. Also measure the Brix (sugar) content of the pasture during the middle part of a sunny day using a simple refractometer. While not essential, measuring the Brix level is highly recommended.

In making the assessments, consider the original sowing mix, grazing management, competition and shading by other plants, fertiliser regime, and seasonal climatic conditions including air temperature and sunlight. Note there is a tendency to overestimate the amount of clover and underestimate the amount of dead matter.

Importance

PASTURE QUALITY varies according to the amount of green leaf and grass stem, legume content, dead matter, botanical composition, and sugar (energy) content of the pasture. While the stem is often considered to be lower quality than the leaf, it can have high concentrations of carbohydrates. Dead material has a very low nutritive value. Although pasture quality is governed by a number of factors, it can be a good indicator of the condition of the soil.

Pasture species is governed in part by the fertility of the soil and whether the plant is a high, moderate or low fertility species. High fertility species include perennial and Italian ryegrass, tall and meadow fescue, prairie grass, timothy, phalaris and white clover. Moderate fertility species include cocksfoot, crested dogstail, Yorkshire fog, sweet vernal, Kentucky bluegrass, creeping bent, and brome. Low fertility species include browntop, Chewing's fescue, paspalum, ratstail, danthonia, goosegrass, hairgrass, and needlegrass.

Pasture species also vary in their tolerance to poor soil aeration, pugging, soil and air temperatures, and moisture stress due to either waterlogging or a moisture deficit. Consequently, their nitrogen and sulphur uptake, dry matter production, and survivability also vary markedly. *Phalaris aquatica*, tall fescue, meadow fescue, meadow foxtail, Yorkshire fog, *Poa trivialis*, timothy, creeping bent, sweet grass, pennyroyal, waterpepper, buttercup, duckweed, and dock are tolerant of poor aeration and waterlogging due to pugging or poor drainage. Perennial ryegrass, white clover, cocksfoot, chewing fescue, browntop, *Poa annua*, and crested dogstail are moderately tolerant of poor aeration and waterlogging. Matua prairie grass, sweet vernal, *Poa pratensis*, ratstail, meadow rice grass, and yarrow are sensitive to poor aeration and waterlogging and will die out if conditions persist.

PLATE 21 Visual scoring (VS) of pasture quality

**GOOD CONDITION VS = 2**

Pasture has ≥ 95 percent green leaf herbage with ≥ 60 percent legume cover (≥ 30 percent DM), and < 5 percent dead matter. Brix sugar levels are ≥ 12 .

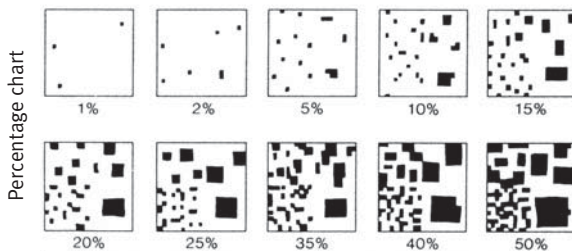
Pasture composition has a good mix of high-producing pasture species (e.g., ryegrass, white clover, cocksfoot, etc.) and species intolerant of poor aeration and waterlogging (see below). Pasture composition reflects the original mix. Forage herbs including chicory, plantain and yarrow also contribute to pasture quality.

**MODERATE CONDITION VS = 1**

Pasture has 75–80 percent green leaf herbage with 20–40 percent legume cover (10–20 percent DM), and 20–25 percent dead matter. Brix sugar levels are 6–9. Pasture composition has a mix of high and low fertility species. Pastures also show a range of tolerances to waterlogging and stock treading (see below). Pasture mix differs somewhat from that originally sown.

**POOR CONDITION VS = 0**

Pasture has < 50 percent green leaf herbage with little or no legume, and ≥ 50 percent dead matter. Brix sugar levels are ≤ 3 . Pastures are dominated by low-producing, low-fertility species and species that are more tolerant of poor aeration and waterlogging due to pugging; species such as ryegrass that are more tolerant of stock treading; and species such as white clover that quickly colonise bare ground created by severe treading (see below). Pasture composition has little relationship to the original seed mix.



Pasture composition will also change according to the degree of treading damage. Ryegrass and *Poa pratensis* resist treading damage better than many other species, and often become more common in pugged pastures. *Poa trivialis*, brown top, white clover, and timothy are moderately tolerant of treading.

Cocksfoot, red clover, Yorkshire fog, and many low fertility pasture species such as sweet vernal and chewing fescue are sensitive to intensive treading and disappear under prolonged pugging. Treading damage and the exposing of bare ground will also allow the invasion by opportunist species such as white clover and *Poa annua*, broadleaf dock and other weeds, and less desirable pasture species. White clover, being stoloniferous, can rapidly colonise bare ground and become dominant in severely pugged pasture.

The importance of pasture quality

While the quantity (intake) of pasture is important in terms of stocking rate and animal performance, maximising pasture quality provides dramatic increases in overall farm profitability and environmental performance. The quality of the pasture has a major effect on conception and survival rates, live-weight gain, animal health, wool and milk production, and food quality. Quality pasture maximises the feed conversion factor into milk solids and meat thereby maximizing the dollar return per kg of dry matter consumed.

White clover contains more crude protein (or total N) and readily fermentable carbohydrates, but lower concentrations of water soluble carbohydrates (sugars), lipids, lignin, cellulose and fibre than perennial ryegrass. With the exception of Italian, tetraploid and hybrid diploid (high sugar) ryegrasses, which have higher soluble carbohydrate levels compared with many perennial ryegrasses, grasses often have similar nutrient levels under similar soil fertility, regardless of species. Legumes and herbs, on the other hand, have a higher nutritive value and feed quality than grasses, especially in summer when temperatures are higher. Legumes such as clover contain more Ca, P, Mg, Zn, Cu, B and Co, but lower concentrations of Na and Se than perennial ryegrass. Yarrow has significantly higher concentrations of P, K, Fe, Mn, Cu, B, Co and I than mixed ryegrass/white clover, and explains why lambs kill-out heavier when grazing paddocks containing yarrow. Chicory is higher in K, Na, Zn and Mo than ryegrass, and plantain is higher in Ca, Na, Fe, B, Co, Se, I and tannins than mixed ryegrass/white clover.

Condensed tannins (CT) in temperate pastures protect plant protein from digestion in the rumen, which results in a greater supply of protein to the small intestine, thus improving protein adsorption and animal performance in terms of live-weight gain, wool production, and reproductive efficiency. CTs also help protect ruminants against bloat, reduce the

level of scouring and dags when grazing protein-rich pastures, reduce methane emissions by 15 percent by decreasing methanogenesis, and have a direct negative effect on internal parasites. Pastures containing birdsfoot trefoil (*Lotus corniculatus*), plantain and dock contain the most desirable forms of CTs, while the CTs in sainfoin, lotus major and sulla seem only to mitigate the impact of parasites. CT levels in pastures are generally low, and raising their concentration would improve pasture quality.

Pastures with a high energy level, nutrient density, and nutritive value have a higher palatability and digestibility and contain more useful energy per unit of dry matter. They also maintain good microbial growth rates and an active bacterial population in the rumen. Animals therefore have a higher feed-conversion efficiency and eat less to attain the number of kilojoules required for body maintenance, growth and lactation. Pasture quality also influences feed intake because while the animal wants to eat more herbage of low nutritive value to correct mineral imbalances, it moves more slowly through the animal's digestive track, physically restricting intake.

Pastures rich in crude protein and nitrate-N and with a low sugar content are difficult for the micro-organisms in an animal's rumen to break down by fermentation because of the lack of energy (sugars) in the pasture. Crude protein/nitrate-rich pastures also produce large amounts of nitrite (NO_2^-) that accumulates in the rumen during the reduction of nitrate (NO_3^-) to ammonia (NH_3). Nitrite reduces the total microbial population and, in particular, three of the four bacteria commonly found in the rumen. As a consequence, digestibility is reduced and livestock are only able to convert about 20 percent of the protein in the herbage into milk, meat and fibre – a low feed-conversion efficiency. Furthermore, because of the low sugar levels and high nitrate concentration, rumen microbes do not have the energy or capacity required to utilize the excess N in the feed and, as a consequence, convert 80 percent of it into ammonia. Some of the ammonia is used by the rumen bacteria for their own growth while most is absorbed into the blood stream. High concentration of ammonia in the blood (a toxic substance) overloads the liver as it attempts to convert it to urea, which is subsequently excreted in urine, milk and breath – this comes at a high energy cost to the animal. The bile ducts can also become blocked, forcing yellow bile out between the forelegs of the animal. The high concentration of N in the urine markedly increases the amount of N leached into the groundwater and waterways (pp. 75 & 76) and the amount of nitrous oxide (N_2O) emitted into the atmosphere (pp. 94–97). Poor rumen function also produces higher amounts of carbon dioxide (CO_2) and methane (CH_4). Moreover, pasture with poor digestibility spends more time in the rumen, thereby producing more fermentation gases, including CH_4 and CO_2 , which further increase the emissions of green house gases into the atmosphere.

Additionally, high crude protein/nitrate-rich pastures cause a number of animal health issues. While rumen bacteria attempt to convert non-protein N into usable protein, the bacteria burn much energy doing so, and as a result the animal draws from its body

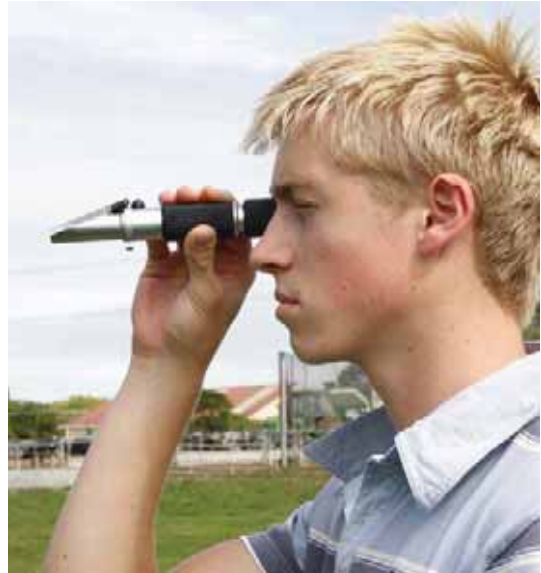
reserves of carbohydrates and stored fats (ketosis), eventually losing body condition and becoming run down and stressed. High concentrations of nitrite produced by the reduction of nitrate-rich pasture to ammonia in the rumen also give rise to nitrite poisoning (toxicosis). Nitrite is absorbed into the blood stream and combines with haemoglobin to form methaemoglobin. As methaemoglobin is unable to carry and transport oxygen it causes death through anoxia. It also suppresses oxygen transfer to the foetus, causing oxygen starvation and the abortion of the foetus. Lack of sufficient oxygen due to nitrate/nitrite toxemia is a common cause of infertility and high empty rates. High nitrate levels also suppress the production of Vitamin E, a key vitamin in protecting oxygen supply to the foetus.

High crude protein/nitrate-rich pastures and the resulting high nitrate/nitrite/ammonia levels in the rumen and subsequently the blood, also raise the blood pH to levels above the 7.3 required for a healthy animal. The overly alkaline gut and elevated blood pH (alkalosis) causes a range of metabolic disorders, including increased susceptibility to pulmonary emphysema, mastitis, laminitis, scouring, severe dags, and, if the pH rises above 7.4, death. Moreover, high pH affects the tenderness, flavour, colour and shelf life of meat.

Pastures can contain cyanogenic glycosides (hydrocyanocides) in new and rapidly growing shoots, and particularly during the spring flush. Growth rates are exacerbated by the addition of soluble, salt-based nitrogenous fertilisers during this period, producing crude protein/nitrate-rich pasture and subsequent alkalosis. Hydrocyanocides break down to hydrocyanic acid (HCN or hydrogen cyanide) under overly alkaline conditions in the rumen, causing cyanide poisoning and death.

High nitrate levels also suppress the production of Vitamin D₃, an important component of the melanin pigment under the skin that protects the animal from the sun's ultra-violet rays. This makes the animal more susceptible to sunburn (spring eczema). In addition to

PLATE 22 Assessing the sugar content



Assessing the sugar content (Brix) of pasture sap with a hand-held refractometer.

creating nitrate/crude protein-rich pastures, the excessive use of N causes luxury uptake of K, which suppresses the absorption of Ca, Mg (and Na) in the animal, causing milk fever (hypocalcaemia) and grass tetany (hypomagnesaemia). While attempts to manage the effects of high K levels often include the use of magchloride ($MgCl_2$) and causmag (MgO), such products would not be necessary if the appropriate fertilisers were used and the uptake of Ca and Mg not suppressed. The use of some forms of chlorides (such as KCl) and caustics should be avoided where possible.

High levels of N in the soil and pasture can promote the pathogenesis of viruses, bacteria and fungal disease (see p. 54), and insect pests. The application of optimum levels of Ca can help counterbalance the effect of N, particularly when added in conjunction with Na, B, carbohydrates, humates, and organic acids.

One of the keys to successful pastoral farming is to grow pasture with a high sugar (energy) content (with Brix levels of 12 or more) and a high nutrient density. This is achieved by ensuring a good mix of pasture species, including a good herb and clover content, and by promoting the photosynthetic pathway through ensuring the presence of key sugar-making elements and the subsequent conversion of the sugars into fats, carbohydrates, starch and mature protein. In addition to N, P, K, and S, this requires Ca, Mg, Na, Fe, Mn, Cu, Zn, Mo, Co, B, Cl, B vitamins, vitamin C, adenosine triphosphate (ATP), and good soil life. An example of pastures developing a higher nutrient density and nutritional value after just one year in biologically grown pasture versus conventionally grown pasture is given in Table 5 and Figure 4. Correcting nutritional imbalances by raising the nutrient density and sugar level will also help to curtail or eliminate insect pests. Moreover, the presence of adequate levels of sugars, carbohydrates and starch in the pasture are vital because they are acidifiers, countering the alkaline effect of nitrates and other nutrients, and so help maintain the pH of the rumen at optimum levels. Soluble carbohydrate concentrations are influenced by sunlight and Brix (sugar) levels are therefore best measured mid-afternoon on sunny days (Plate 22). Overcast conditions will reduce soluble carbohydrate concentrations.

In addition to raising pasture sugars levels, rumen function (and feed-conversion efficiency) is improved by ensuring yttrium and cobalt levels are adequate in the pasture. To enable the bacteria in the rumen to produce the vitamin B_{12} necessary to promote efficient digestion, Co levels in the herbage should be of the order of 0.1–0.15 mg/kg. The animal is better able to store trace elements in its organs and glands and utilise them over a longer term if the nutrients are adsorbed through the digestive system, rather than being administered as generic forms in drenches, bullets or injections.

The age of the pasture since grazing (i.e. the length of the regrowth period) also has a significant bearing on the chemical composition and nutritive value of the pasture. Pasture quality in the spring, summer, and autumn is greatest 25–40 days after grazing. Before that, the fibre, dry matter, and mineral (ash) content is lower and pastures are

rich in nitrate-N and crude protein through insufficient time for the soluble carbohydrates (sugars), organic acids and mature protein to build up. After a period of approximately 4–6 weeks, the quality of the pasture starts to decline with cell age, increased lignification and fibre content, and because nutrients begin to translocate down from the leaf to the root system. Rapidly growing pasture requires approximately 5–6 week to mature, while slow growing grass needs only 3–4 weeks.

White clover (*Trifolium repens* L.) is important for pastoral agriculture, not only because of its ability to fix nitrogen, but also because of its high nutritive and feed value (high protein and high mineral content), its seasonal complementarity with the growth pattern of grasses (perennial ryegrass), and its ability to improve animal feed intake and utilisation rates. While the quality of ryegrass is high in the spring, clover and herbs (such as chicory) are able to maintain their high nutritive value in the summer. White clover and herbs enhance the palatability of the pasture and because of their high digestibility and metabolisable energy, are utilised more efficiently than grasses, thus increasing the energy level, body condition, live-weight gain and reproductive function of the animal. The high digestibility of clover and herbs also gives rise to increased milk production with high protein, lactose and fat yield and a more efficient use of feed nitrogen, reducing the concentration of N in the blood and excreta. Furthermore, the more efficient digestion of clover and herbs enables the animal to better utilise the energy content of the pasture, converting it to meat, milk and fibre instead of methane and carbon dioxide. Animals grazing a ryegrass sward produce twice the amount of CH₄ (24 g/kg dry matter intake) compared with animals grazing white clover (12.9 g/kg dry matter intake). Methane emissions can be reduced by at least 10 percent when grass forage is replaced by a mixed ryegrass/legume sward. In addition, the meat tends to have a higher Omega 3 content, a better flavour, and the animal has a higher kill-out weight due to a higher muscle:fat ratio.

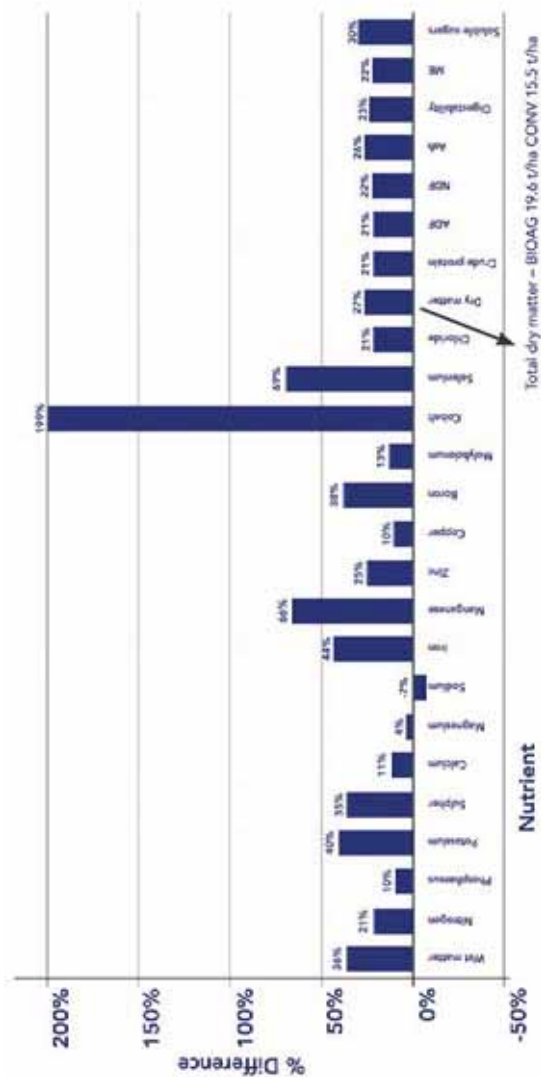
Clover drives the growth rates in lambs and, because of its high feed quality, stock generally gain more live-weight on white clover (growing 90 percent faster) than on perennial ryegrass. Diet selection studies show sheep prefer around 70 percent (dry matter) of their intake to come from white clover and 30 percent from grass. While cows milk better on clover pastures, the clover content of dairy pastures, often around 15–20 percent, is lower than the 50–70 percent needed for maximum milk solid production. A clover content in dairy pastures of at least 30–50 percent DM is also required for maximum pasture growth. Clearly, a greater proportion of white clover in mixed pastures would be beneficial to animal production. This can be achieved by promoting the condition of the soil, a higher level of N fixation through strong clover nodulation and the enhancement of free-living N-fixing bacteria, good grazing management practices, and meeting the nutritional requirements of clover including the appropriate use of specific forms of fertilisers other than nitrogen. The frequent and heavy use of fertiliser-N suppresses N-fixation, clover content, and clover growth, and limits clover recovery once N rates are reduced (see pp. 44–45). Because of this, 30 percent of clover DM in the pasture sward is not achievable and the pasture will therefore not meet the criteria required to be in good condition as defined in Plate 21.

TABLE 5 Nutrient densities¹ of biologically grown pasture versus conventionally grown pasture

Treatment	N	P	K	S	Ca	Mg	Na	Cl	Fe	Mn	Zn	Cu	B	Mo	Co	Se
Biologically grown pasture	3.24	0.39	3.20	0.40	0.62	0.23	0.17	1.04	159	89	178	6.8	5.8	1.43	0.19	0.19
Conventionally grown pasture	3.40	0.42	2.98	0.32	0.59	0.25	0.22	0.93	120	59	150	6.8	5.4	1.66	0.07	0.07

¹ Mean of 5 cuts taken in the autumn and spring. Data from the first year of field trials on a Waikato dairy farm; courtesy of Abron Living Soil Solutions.

FIGURE 4 Nutrient level improvements in pasture



Nutrient level improvements of biologically grown pasture versus conventionally grown pasture on a Waikato dairy farm. Values represent the mean of nine analyses of samples taken over an 11 month period and adjusted for differences in total dry matter production; courtesy of Abron Living Solutions.

Assessment

- ❶ The N-fixing ability of a pasture can be assessed by the density, size, colour and depth of clover nodules.
- ❷ Remove three to four clover plants with a spade, pushing the spade down to a depth of 250 mm. Gently shake the soil free exposing the root system and clover nodules (Plate 23).
- ❸ Assess the number of nodules, their size, the depth at which they occur, and the colour of the leghaemoglobin within the nodule (Plate 24), and colour, compare with the criteria given in Table 6. Clover nodules are best assessed in the spring when leaf growth and N demand is greatest, but can be checked at any time of the year provided the plant isn't under stress through defoliation, drought, or soil and air temperatures being too high or low.
- ❹ Nodules on clover have a short life-cycle of 3–4 weeks. Healthy nodules start as white, then become pink on the surface as red leghaemoglobin develops inside the nodule, at which point it become active, fixing N_2 . The redder the colour, the more active it is. The nodules then decline as the leghaemoglobin decays to a yellow bile pigment (Plate 24) and eventually becomes elongated and white or grey again, appearing like a deflated balloon. Depending on their stage of maturity, nodules will also display a range of sizes varying from very small up to 3–5 mm. Nodules on mature healthy roots will therefore have a range of colours, shapes and sizes. To assess the degree of redness of the leghaemoglobin, select 3 or 4 of the pinkest nodules and split them in half between your fingernails and observe the colour with a magnifying hand lens. Discard any nodules showing yellow bile pigment because they are becoming inactive and nearing the end of their cycle.

Importance

CLOVER NODULES are produced in response to invasion through the root hairs by *Rhizobium*, a bacterium which infects and stimulates the proliferation of root cells to form nodules. Once the nodule is formed, the bacterium multiplies and changes form into a bacteroid that contains a nitrogenase enzyme capable of reducing atmospheric nitrogen gas to ammonia ($N_2 + 8H^+ \rightarrow 2NH_3 + H_2$). The nitrogenase enzymes break the triple bond holding the two N atoms of the N_2 molecule, and adds hydrogen to form ammonia. The reaction requires hydrogen and a considerable amount of energy in the form of adenosine triphosphate (ATP) and carbohydrates from photosynthesis. The enzyme has two components, a molybdenum-iron protein and an iron protein. Molybdenum and iron must therefore be present in adequate amounts to enable the production of the nitrogenase enzyme and therefore the fixation of N_2 . While *Rhizobium* is an aerobe, nitrogenase enzymes cannot function in the presence of oxygen and so oxygen levels are kept low by a diffusion barrier on the outer wall of the nodule, by high bacterial respiration rates within the nodule, and by the presence of leghaemoglobin. The critical function of leghaemoglobin is to absorb O_2 and transport it within the anaerobic zone to the bacterial cells to support their respiration. Leghaemoglobin can only be produced if levels of Fe, Mn, Zn, Co, Se and in particular Cu (the blood elements) are adequate. A pink/red colour

PLATE 23 **Clover nodules**



Clover roots showing strings and clusters of distinct healthy pale pink nodules. Photo taken in the spring: Courtesy of John Brock.

PLATE 24 **Inside a clover nodule**



Clover nodule split open showing brownish red leghaemoglobin (LHb). Note the decay of the LHb to the yellow bile pigment above the red area. Photo: Courtesy of Michael Templer.

inside the nodule indicates the nodule is actively fixing N; the redder the colour, the more active it is. The ability of the *Rhizobium* bacteria to fix N also depends on whether the strains of rhizobia present in the soil have an effective nitrogenase system, and if not, then clover seed needs to be inoculated with effective strains.

The ammonia produced by N-fixation is rapidly converted to ammonium (NH_4^+) and taken up by the plant to produce protein and organic N compounds. The N fixed by clover nodules is only released to other pasture plants such as grasses by a combination of two processes. First, when the clover plant dies and decomposes, the organically bound N compounds are mineralised by a wide range of bacteria and fungi in the soil to release N in the form of plant available ammonium (NH_4^+). Under aerobic conditions, the majority of ammonium is converted to nitrate (NO_3^-), another plant available form of N by nitrosomonas and nitrobacter bacteria (a process known as nitrification). Second, most of the N ingested by grazing animals is returned to the soil as urine, which then hydrolyses to urea. Urea is converted to ammonia by the urease enzyme followed by its hydrolysis to ammonium and then nitrification to nitrate-N. A possible third but minor mechanism could involve the direct excretion of small amounts of N through root leakage from intact growing legumes.

Depending on its relative dominance in a sward, white clover is able to fix up to 300 kg N/ha/year in high-producing sheep farms, and up to 380 kg N/ha/year in dairy farms. Higher levels of N fixation could possibly be achieved if optimal conditions for N fixation were provided. The actual amount of N fixed is very dependent on a number of factors including the performance and condition of the clover nodules. Factors that limit white clover growth often result in much lower N fixation rates of 80–150 kg N/ha/year. Such factors include moisture stress, high temperatures, cultivar choice, competition from grasses and incompatible companion species, pasture establishment, shading, grazing management, endophytic toxins from ryegrass, pest and diseases, soil acidity ($\text{pH} < 5.8$), low soil carbon, low soil fertility (other than N) including low Ca levels, and poor soil aeration. Poorly aerated and compacted soils have less air and consequently less N available for biological fixation. In addition to the elemental requirements for the production of nitrogenase and leghaemoglobin, white clover plants require adequate levels of N, P, K, S, Ca, and B for root development and growth. Aerobic N-fixing micro-organisms also require adequate levels of Ca and Co, and good soil aeration to function at optimum levels.

N-fixation by clover nodules is further governed by the amount of mineral-N in the soil. Clover prefers to take up mineral-N than fix N from the atmosphere because it is a more energy-efficient process and therefore has less energy cost to the plant. Clover will only resort to N-fixation when a deficiency in N occurs within the plant. Thus the frequent and heavy use of water-soluble N in the form of urea, anhydrous ammonia or nitrate will suppress N-fixation, clover content, and clover growth, and limit clover recovery once N rates are reduced.

TABLE 6 Visual scoring (VS) clover nodules

Visual score (VS)	Clover nodules
2 [Good]	Clover roots have strings and clusters of lots of nodules (4–8 per 20 mm) and occur to a depth of 150–200 mm; many are large (> 2 mm). At least 50 percent of the nodules have a distinct pale pink hue on the surface and a bright red or brownish red leghaemoglobin content that bleeds when split open and squeezed.
1 [Moderate]	Clover roots have a moderate number of nodules (1 per 20 mm) to a depth of 75–150 mm. The largest nodules are of medium size (1–2 mm) and have a faint pale pink hue on the surface and a pink to pale reddish brown leghaemoglobin content when split open.
0 [Poor]	Clover roots have few or no nodules and only occur in the upper 75 mm of the soil. Nodules are small (< 1 mm) and are white on the surface with little or no signs of leghaemoglobin when split open.

Nitrogen can also be fixed by free-living N-fixing aerobic *Azotobacter* bacteria and by anaerobic *Clostridium* bacteria. The fixed-N (up to 10–15 kg N/ha/yr) is made available to the plant when the bacteria die and decompose. *Azotobacter* bacteria need good aeration, high levels of available C, and non-acidic soils to function in large numbers. Under favourable, non-acidic, well-aerated soil conditions with optimum levels of trace and major elements including Ca and C, as well as a good earthworm population, free-living N-fixing bacteria could potentially produce substantially more than 10–15 kg N/ha/yr.

Nitrogen fixing bacteria, be they free-living in the rhizosphere, confined to nodules on plant roots, or existing as endophytes in leaves or stems, derive most of their energy from dissolved organic carbon (liquid sugar) fixed during photosynthesis. N-fixation is therefore very dependent on the flow of liquid carbon from the leaf to the roots.

The rate of N-fixation depends on the demand for N, which is governed by the clover growth rate. Because N-fixation is influenced by the amount of mineral-N in the soil, clover growth is not necessarily a direct indicator of N-fixation. In spring, grasses are more active and use most of the soil N, and while clover growth may not be high, N-fixation will be. In summer when clover is more active, grasses are less active and soil N can accumulate and clover N-fixation may be lower.

Assessment

- 1 Assess the number of weeds (using the percentage chart on p. 48) and variety of undesirable weeds in the pasture, and at what level their presence detracts from the value of the pasture. Undesirable weeds include ragwort, barley grass, bristle grass, water pepper, willow weed, wild carrot, mayweed, hedge mustard, buttercup, duckweed, and thistles.

In making your assessment, consider how often a given level of weed infestation occurs in the paddock from season to season, and at what level it is perceived to be a problem. Consider also your grazing management and the need for weed control measures, including the use of herbicides, biological control agents, mowing, steaming, cultivation, pastoral renewal, and other measures taken to deal to weeds before they go to seed. Make your assessment according to the photos and criteria given in Plate 25 on the basis of what the field would look like without any weed control measures except for grazing management.

Importance

WHILE SOME WEEDS are beneficial and contain a number of essential nutrients for stock, others have little nutritional value, are difficult to digest, can be poisonous, and generally reduce the overall value of the feed. Weeds compete with desired pasture species for water, nutrients and growing space, displacing more beneficial, high-producing pasture species, thereby encouraging the use of clover-damaging herbicides. They allow poor pasture quality to develop, reducing pasture utilisation and plant and animal production.

While weeds can occur for a number of reasons, they can be useful indicators of the condition of the soil, including the level of compaction, soil aeration and waterlogging, nutrient fertility, pH, the amount and type of organic matter, and the microbial biomass. It is commonly believed that healthy soils support weeds and desirable pasture species equally well. In the same way that insect infestation indicates unhealthy plants with a nutritional imbalance, a weed infestation indicates something is not right with the soil, which is suppressing the growth of high producing pasture species and providing an environment favouring weeds. Soil structural degradation resulting from stock treading (pugging), wheel traffic, over-cultivation, or soil dispersion due to a low Ca:Mg ratio or high Na levels, reduces soil aeration, soil drainage, available water-holding capacity, nutrient uptake, and the rooting potential of the crop, allowing weeds to establish and compete with the crop. Lighter soils with a coarser textural class can have more weeds than heavier soils with a finer textural class, while acidic soils can have a greater variety of weeds than non-acid soils.

PLATE 25 **Visual scoring (VS) of weeds**



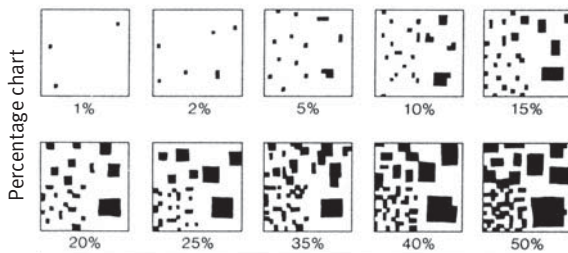
GOOD CONDITION VS = 2
Pasture has few or no weeds.



MODERATE CONDITION VS = 1
Weeds are very common covering 5–10 percent of the ground surface.



POOR CONDITION VS = 0
Weeds are abundant covering ≥ 20 percent of the ground surface. They indicate either significant compaction, poor aeration, waterlogging, low functional organic carbon and Ca, or poor mineral and microbial composition.



Weeds will also develop and thrive in soils that have a poor mineral and microbial balance. Weeds will grow and proliferate where there is a Ca and P deficiency and an excess of K and Zn. They will develop where there is an imbalance of Fe to Mn, a lack of biologically available Ca, a lack of biologically active carbon

including humus and humic acids, and where there are high nitrate levels, and a lack of bacteria or fungi. Pastoral soils need to maintain a fungal to bacteria ratio of 0.75:1 (or 1:1), which is necessary to preserve and promote pastoral plants. An imbalance of this ratio along with poor soil nutrition could explain why pastures may show poor persistence and a tendency to revert to other plant species such as woody weeds.

Thistles, including the nodding, wing, Scotch and Californian thistles, are some of the most annoying and destructive weeds: the smothering and competitive effects of rosettes reduce pasture production, and the prickly leaves discourage even grazing and good pasture utilisation. Thistles can indicate the soil is deficient in Ca and bacteria and high in K and S. An infestation of thistles would suggest soil conditions and fertility are insufficiently adequate to maintain a complete, vigorous pasture cover and the high growth rates required to reduce seed germination and kill young seedlings and developing rosettes.

Broad-leaved weeds such as dock can develop on soils that are moderately acidic with moderately high fungal levels. They like a soil environment that is low in Ca and P and high in N and K, where available K greatly exceeds the available P. High nitrate levels also help to promote seed germination. Dock can further indicate a decline in the C:N ratio. If the available K continues to increase relative to P, a point may be reached where herbicides cannot control the broadleaf weed. While they are poor competitors and germination is inhibited under a dense leaf canopy, dock can establish and take hold in open or disturbed patches of pasture due to overgrazing, compaction, pugging, and the uneven application of slurry or manure. Some would argue that docks in grassland are not weeds because they contribute trace elements and herbage to a grazing animal's diet and hence do not need to be controlled. Broad-leaved dock is relatively high in P and K in the leaves, and is particularly high in Mg. Cattle fed on herbage containing docks help to prevent bloat because tannins in the dock leaves help to protect plant proteins from digestion and degradation and precipitate out soluble proteins in the rumen, thus preventing the formation of a degraded protein-based foam.

Barley grass is found on rough bare ground in summer-dry, seasonally stressed areas, on soils deficient in Na, and on the margins of cultivated fields. Barley grass does not compete well against a vigorous perennial ryegrass/white clover sward on fertile, moist

soils. **Ragwort** is not common in seasonally stressed, summer-dry pastures and is more usually associated with wetter areas, and on soils low in Ca, P, Co and bacteria, and high in K (particularly when using muriate of potash). The ragwort seed is well adapted to areas of local disturbance, as may be found in well-trafficked, compacted areas. Ragwort does not compete well against strong competition from vigorous, rapidly growing perennial ryegrass/white clover pastures on good quality, highly fertile soils. Ragwort is toxic to stock and can induce photosensitization, jaundice, weight loss, and impairment of liver function. **Dandelions** indicate a Ca, P, vitamin A and in some cases an Fe deficiency in the soil. Their occurrence is exacerbated by Mg, Zn and the excessive use of K (muriate of potash), which further suppresses Ca levels. **Buttercup** grows especially well on wet, poorly drained, poorly aerated soil, and soils that are low in Ca, P, humus and bacteria and high in K (particularly if using muriate of potash). It is tolerant of compaction and grazing, and fresh plants can be bitter and toxic to grazing animals.

The condition and properties of the soil have a major bearing on whether the pasture is able to grow in a sufficiently vigorous way to out-compete, and prevent or restrict the establishment and growth of weeds. Competitive suppression by vigorous pasture growth plays a major role in preventing weed establishment. Weed suppression can also occur after a pasture is sown by the production of auxins (or plant growth hormones) when the seed germinates. Auxins limit or stop the germination of other seeds from either pasture or weeds. While this suppression lasts for only 1–2 days in poor quality soils, it can last for 6–8 weeks in biologically active, well-aerated soils, thus providing an effective, natural weed control. The application of liquid calcium incorporating a form of organic carbon such as molasses or humic/fulvic acids (to act as a food supply for soil microbes), along with the addition of an organic form of phosphorus and selected trace elements such as B, Co and Se, can help alter the soil environment in such a way that weeds are suppressed. As the soil chemistry adjusts and nitrogen is converted to an organic form (freely available to mycorrhizal fungi but not to annual weeds), the incidence of weeds, pests and diseases that are stimulated by low levels of microbial diversity and high rates of non bio-friendly, water soluble potassic and nitrogenous fertilizers, will decline.

Changing the soil environment can successfully deal with any weed problem and can provide a more effective solution than the application of straight herbicides, which gives a short-term and often limited response. However, where weeds are an initial problem, the incorporation of herbicides into a solution containing ammonium humate or fulvic/humic acids with a pH modifier, can provide good weed control. Such a mixture enables the amount of herbicide used to be reduced by 25–35 percent, and also helps buffer the effect of the herbicide on soil life. The regular use of herbicides and pesticides have an adverse effect on soil microbes (including mycorrhizal fungi), which are responsible for maintaining the nutrient balance and availability of nutrients in the soil. The quick-kill approach using chemical herbicides only addresses the symptoms and does nothing to rectify the underlying cause.

Assessment

- 1 Assess pasture growth since the last grazing by pasture probe, rising plate, herbage cut measurements, or alternatively by visual estimation (Plate 26), and compare with the criteria given in Table 7. If this information is not available, use visual approximations of dry matter (DM) production levels. For a reliable comparison, make assessments at the same time of year, preferably in mid spring. Consider also the total dry matter production per annum.

Importance

HIGH PASTURE PRODUCTION AND GROWTH RATES depend on good soil structure and aeration, good soil fertility, earthworm and microbial activity, available water, seasonal weather conditions, and the maintenance of good residual levels ($\geq 1\ 800$ kg DM/ha) after grazing. Just as pasture quality has a marked effect on live-weight gain, milk and fibre production, livestock health, and reproductive performance, so does pasture quantity. Intake is influenced in part by the amount of pasture offered to the animal. The more offered, the more can potentially be eaten, up to a maximum where increased DM production has no more influence on intake and live-weight gain. For stock to be in good condition at calving and lambing, an adequate pasture cover of 2 000 kg DM/ha is needed, and pastures need to be capable of rapid regrowth.

Treading damage on compacted moist soils can reduce pasture production by up to 27 percent; on pugged (deformed) wet soils, however, the reduction can be as much as 45 percent. As a consequence, farmers are forced to budget for extra feed (up to 30 percent more) in the winter. Moderately pugged ground with a moderate VSA soil structure score (of 1) can give rise to a loss of 200 kg DM/ha/month or 13 kg milk solids/ha/month. Assuming a payout of \$5.50/kg MS, this would equate to a loss of approximately \$715/ha/yr or \$107,250 in income from a 150-ha dairy farm.

TABLE 7 Visual scoring (VS) pasture growth

Visual score (VS)	Pasture growth	Dry matter production (tonnes/ha/yr)	
		Lowland farms	Upland farms (300 m [1 000 ft] above sea level)
2 [Good]	Good pasture growth	17	13
1 [Moderate]	Moderate pasture growth	13–15	9–11
0 [Poor]	Poor pasture growth	< 11	< 7

PLATE 26 Assessing dry matter production



Assessing dry matter production and pasture growth rates with a rising plate meter.

Treading damage and the loss of dry matter production can be reduced significantly by grazing paddocks when the soil is sufficiently dry to minimise compaction and pugging. To assess whether soil conditions are suitable for grazing, apply the ‘worm test’ (Plate 47, p. 70). Take a piece of soil (half the volume of your index finger) and press firmly with your fingers to form a pencil. For silty soils, if you can roll a worm 10 mm wide by 50 mm long (7 mm wide by 50 mm long for clayey soils) between the palms of your hand without it cracking, the soil is too wet to graze. If the worm cracks when it is 10 mm wide for silty soils (7 mm for clayey soils), the soil is ready to graze. Compacted, pugged pastures and the subsequent reduction in dry matter production can also be ameliorated by artificial soil aeration. To assess whether soil conditions are suitable for aerating, apply the ‘worm test’ (Plate 47, p. 70). Aerating the soil can increase DM production by 33 percent after 6 months and by 52 percent after 8 months. Pasture composition and nutritional value are also significantly improved.



Assessment

- 1 Compare the colour and growth of the pasture between urine patches with the colour and growth of the urine patches, and compare with the three photographs and criteria given in Plate 27. The best time to carry out the assessment is just before the next grazing in the autumn, late winter and late spring, avoiding very cold and wet weather. In making the assessment, consideration must be given to the time of year, the pasture species, stage of growth, soil moisture and temperature conditions, and also the presence of pests and diseases (e.g., nematodes). If the pasture receives more than 30 kg/ha/yr of artificially applied nitrogen, consider what the pasture looks like just before the application of N.



Importance

THE COLOUR AND GROWTH OF THE PASTURE RELATIVE TO THE URINE PATCHES and blemishes on the leaf can provide a good indication of the nutrient status and condition of the soil. Pasture colour depends on a number of factors, including a deficiency or excess of N, P, S, Ca, Mg, Fe, Mn, Cu, B, Co, and Mo. Chlorosis (or yellowing of pasture) due to the loss or inadequate formation of chlorophyll, commonly occurs as a result of low N, S, Mg, Fe, Mn, Cu and Zn levels in the soil, low soil and air temperatures, prolonged cloudy days, and poor soil aeration resulting from compaction and waterlogging.

The difference in pasture growth in and between urine patches can distinguish between pastures that are and are not reliant on fertiliser-N to generate growth. The frequent and excessive application of N (especially during dry conditions) together with certain types of fertilisers, herbicides and pesticides can adversely affect the biological regime and nitrogen cycle of the soil, and can also suppress other elements critical for plant growth. As a result, pastures can become dependent on a 'fix' of nitrogen or fertiliser to stimulate growth. Yellow, stunted grass between darker green urine patches (pastoral chickenpox), can be a further sign that the nitrogen cycle has broken down and the utilisation and supply of N and other nutrients by micro-organisms has been adversely affected. In other words, the engine room of the soil, as discussed on p. 21, has become 'rusty' and no longer has the 'horse power' to produce the dry matter required. The addition of N in such cases will only give a short-term pasture response, and an ongoing dependency on N can result – no applied nitrogen, no grass.

Yellow, stunted grass between urine patches can also occur as a result of a N and S deficiency caused by a reduction of plant-available forms of N and S to plant-unavailable forms in poorly aerated, waterlogged soils (pp. 6, 13 & 28). S and N can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form. Plants can also only utilise N if S is present in oxygenated sulphate form.

PLATE 27 **Visual scoring (VS) pasture colour and growth relative to urine patches****GOOD CONDITION VS = 2**

Pasture colour is uniformly deep green with little difference in growth between urine patches. The odd colour blemish on leaves may be apparent within a broad area.

**MODERATE CONDITION VS = 1**

Moderate difference in pasture colour and growth between urine patches. Pasture is yellowish green or medium green between urine patches. Few colour blemishes on leaves may occur.

**POOR CONDITION VS = 0**

Significant difference in pasture colour and growth between urine patches. Pasture is quite yellow between urine patches. Colour blemishes on leaves may commonly occur.

In addition to a yellowing of the pasture, discolorations or blemishes on the leaf can indicate mineral deficiencies (Plates 28–35). Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of S, Zn and Cu while high S levels can suppress the uptake of P and Mg. Excess N can strip Ca from the soil, block Mn, Zn, B and Cu uptake, and cause the plant to luxury feed on K, which in turn can also tie up Mn and B, and suppress the utilisation of Ca and Mg by the animal.

Moreover, N-rich pastures growing on urine patches are often avoided by cattle; they will only eat it when the feed supply is short, or when its sugar level rises. When nitrates exceed 0.23 percent of the DM, nitrate poisoning (toxicosis) is likely to occur as nitrate is reduced to nitrite (NO_2^-) in the rumen. N-rich growth patches also bring increased risk of mycotoxins and toxic substances produced by fungi, which results in milk production losses, reduced feed intake, feed refusal, unthriftiness, rough hair-coat, ketosis, retained placenta, metritis, fatty livers, reproductive problems and poor body condition.

PLATE 28 Phosphorus deficiency in clover



Photo: T. Wallace (1961)

Phosphorus deficiency in clover: Dull bluish green or yellowish green leaves with small bronze spots over the surface.

PLATE 29 Phosphorus deficiency in grass



Phosphorus deficiency in grass: Leaves show a distinct purple colouring.

PLATE 30 **Magnesium deficiency in clover**

Photo: T. Wallace (1961)



Magnesium deficiency: Interveinal chlorosis and of the leaf margins

PLATE 31 **Calcium deficiency in clover**

Photo: H.B. Sprague (1964)



Calcium deficiency: Leafstalks collapse and wilt; leaves are chlorotic with scorched margins.

PLATE 32 Potassium deficiency in clover



Potassium deficiency: White spots on margins of leaves.

PLATE 33 Sulphur deficiency in clover



Sulphur deficiency: Pink clover leaves.

PLATE 34 **Boron deficiency in clover**

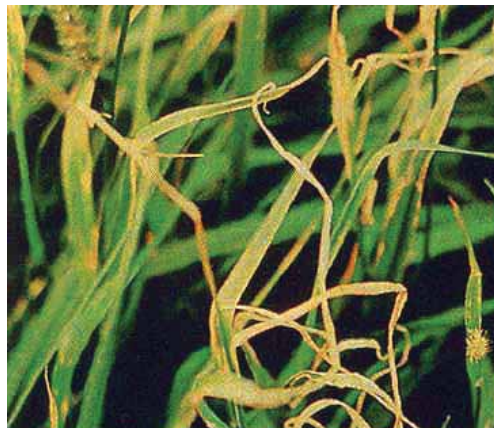
Photo: T. Wallace (1961)



Boron deficiency: Reddish margins of clover leaves; thickened & stiff stems.

PLATE 35 **Copper deficiency in grass**

Photo: W. Bergmann (1993)



Copper deficiency: Chlorosis of the margins and tips of grasses.

Assessment

- 1 Assess pasture utilisation by estimating the proportion of pasture that has been well grazed or poorly grazed, and the proportion not smeared or trampled into the mud by grazing animals, and compare with Plates 36–38 and the criteria in Table 8. In making the assessment, consider the time of year, the pasture species, stage of growth, soil moisture and temperature conditions, radiation levels from the sun, grazing management practices, stocking rate, and the type and amount of fertilisers applied.

Assessments should be made at or as near the end of the grazing period.

Importance

PASTURE UTILISATION provides a good indication of the quality and palatability of the pasture and can be a useful guide to the nutrient status and condition of the soil. Pastures have a high palatability if they are rich in sugars and carbohydrates relative to protein, with a high nutritional value, containing many of the essential elements required and sought after by the animal. As a result, stock graze the whole field with a utilisation of around 80 percent. Conversely, pastures that are protein rich and deficient in sugars and essential elements have poor palatability. Stock graze selectively and roam a lot, and pasture utilisation can be reduced to 40 percent. The nutritional value of the pasture and the degree of utilisation also depend on soil aeration and the vigour and distribution of the root system. Pastures with an extensive root system in well-aerated soils are able to utilise a greater reservoir of water and nutrients. Poorly aerated soils have limited root systems and suppress the availability of elements in a form required by the plant (see pp. 8, 13 & 28). Palatability can further be affected by the pasture being contaminated with fungal toxins.

Utilisation of pasture can also be influenced by treading damage (pugging) when wet. As a result, pastures can experience prolonged surface ponding and are easily trampled into the mud. This makes the pasture both inaccessible and unpalatable to stock. Trampling and surface ponding can reduce pasture utilisation by 20–40 percent.

TABLE 8 **Visual scoring (VS) of pasture utilisation**

Visual score (VS)	Pasture utilisation
2 [Good]	Good pasture utilisation with high palatability and only a little of the pasture being trampled into the mud.
1 [Moderate]	Moderate utilisation of pasture due to moderate palatability or a significant amount of pasture being covered by, and trampled into the mud.
0 [Poor]	Poor utilization of pasture due to poor palatability or a large proportion of pasture being covered by, and trampled into the mud.

PLATE 36 Good utilisation of pasture



Even grazing and good utilisation of pasture due to high palatability.

PLATE 37 Poor utilisation of pasture with low palatability



Poor utilisation of pasture with low palatability. Stock selectively graze and roam a lot.

PLATE 38 Poor utilisation of pasture



Poor utilisation due to severe trampling into the mud.



Assessment

- 1 Remove a piece of soil 200 mm square by approximately 300 mm deep with a spade from the side of the hole where the 200-mm cube was removed for the drop shatter test. With the help of a knife, carefully loosen the soil between the roots and then expose the root system by gently shaking the soil free by tapping the soil sample against the edge of the hole. Compare both the length and the density of the roots with the three photographs and criteria given in Plate 39.

The root length and root density is best assessed in late autumn–early winter when maximum root development occurs, but can also be assessed in late winter–mid-spring when soil moisture and soil temperatures are usually not limiting pasture growth.



Importance

ROOT LENGTH AND ROOT DENSITY provide good indications of the condition of the plant root system. Pastures with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared with pastures with a shallow, thin root system. Dry matter production and tillering is therefore likely to be greater, root pulling less of a possibility, and pastures will have a lower susceptibility to drought stress and recover quicker when the rains come. Pastures with a dense, deep, vigorous root system also raise soil organic matter levels and soil life at depth, thereby sequestering (adding) significant amounts of carbon. The physical action of the roots and soil fauna, and the glues they produce, promote the development of soil structure, soil aeration and drainage. Worm-populated soils also have many tunnels that are coated with mucus and rich in nitrates. Plant roots take advantage of the tunnels as easy-growth channels, extending quickly by taking nutrition from the nitrogen-rich mucus and water as they go. The presence of clover root nodules at depth supplying nitrogen as a result of N fixation further encourages the development of the root system.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Pastures are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up, reducing losses by leaching into the groundwater and waterways.

Root length, root density, plant growth and vigour can be restricted by the mechanical impedance of roots and the lack of soil pores due to soil compaction, a hardpan or rock. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, major and trace element deficiencies, the application of excess nitrogen causing lazy plants, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and poor soil aeration. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, all by-products of chemical and biochemical reduction reactions (see pp. 13 & 28).

PLATE 39 Visual scoring (VS) of root length and root density



GOOD CONDITION VS = 2
Good root length & root density with an evenly distributed root system.



MODERATE CONDITION VS = 1
Moderate root length & density with the root system being somewhat patchy.



POOR CONDITION VS = 0
Poor root length & density with the root system being restricted to limited areas.



Assessment

- 1 Assess the area of bare ground in winter or early spring. Compare the surface of the ground with the three photographs and criteria given in Plate 40. If there is canopy closure due to good growth, part the pasture with your hands and score at ground level. An assessment of an area of bare ground after a long dry period will show how much pasture has died from lack of moisture.



Importance

IN ADDITION TO STOCK CAMPING, DISEASE, INSECT PESTS AND DROUGHT EFFECTS, BARE GROUND is formed by the physical churning up of the soil from treading and pugging. This churning causes leaf and stem crushing, reduced tiller density, the uprooting or burial of plants, and root damage, all of which reduce tiller numbers and pasture density, vigour and growth. Weeds and less desirable pasture species can invade the resulting gaps, further reducing pasture production. Like surface relief, the area of bare ground can be a good indicator of below-ground damage.

Bare ground on fields with a slope can increase their susceptibility to water erosion. Good pasture cover on the other hand, and its below-ground root system, returns organic matter to the soil and promotes soil life including earthworm numbers and activity. The physical action of the roots and soil fauna, and the glues they produce promote the development of soil structure, soil aeration and drainage. As a result, infiltration rates and the movement of water through the soil increases, decreasing runoff, soil erosion, and the risk of flash flooding. Pasture cover on sloping ground also reduces soil erosion by intercepting high impact raindrops, and minimising rain-splash and saltation. Moreover, it acts as a sponge, retaining rainwater longer so that it infiltrates into the soil. The root system of good pasture cover further reduces soil erosion by stabilising the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved, with lower sediment loading and lower nutrient and coliform content. The ground surface needs to have at least 70 percent cover to give good protection; ≤ 30 percent cover provides poor protection.

Good ground cover (with a high leaf-area index) intercepts and absorbs a large amount of carbon dioxide (CO_2) as it escapes from the soil. This increases pasture production as a result of the greater photosynthetic uptake of CO_2 and decreases the amount of CO_2 emitted into the atmosphere, decreasing the level of green house gas emissions.

PLATE 40 Visual scoring (VS) of area of bare ground

75% cover



GOOD CONDITION VS = 2

Pasture covers all or most of the surface area. Surface cover is ≥ 80 percent.

50% cover



MODERATE CONDITION VS = 1

Pasture shows significant areas of bare ground and sporadic growth with the ingress of weeds and white clover caused by treading damage. Surface cover is ≥ 40 percent and < 60 percent.

20% cover



POOR CONDITION VS = 0

Large areas of bare ground (≤ 20 percent cover) occur because of treading damage and the reduction in density and vigour of the pasture. White clover and less desirable pasture species and weeds may have invaded degraded and bare areas

Surface cover photos: courtesy of A. Leys

Assessment

- 1 Assess, from visual evidence and local knowledge, the degree to which pastures are drought stressed during prolonged dry periods by comparing the greenness of the pasture with the three photographs and criteria in Plate 41. Assess also the level of dry matter production, whether drought tolerant species have become dominant in the pasture sward, and how quickly the pasture declines going into a drought and how quickly it recovers following the first rains, according to the criteria given in Plate 41.

Importance

THE DEGREE OF DROUGHT STRESS in dry periods depends on climatic conditions, grazing management, the drought tolerance of the pasture, and the condition of the soil, including the amount of water able to infiltrate into the soil and the water-holding capacity (AWC) of the soil. The latter is governed by soil depth, the length and density of the root system, soil texture, the number and size of soil pores, and amount of soil carbon. One part of soil humus (a relatively stable form of soil carbon) can retain a minimum of four parts of soil water. Pastoral soils with a good structure and soil life, including earthworm populations, have a large number of macropores and coarse and medium-sized micropores, and, subsequently, have a higher water-holding capacity than degraded soils with few pores. Soils with good structure also have high infiltration rates with little or no run-off and are able to capture most of the rainfall. Loamy and silty soils, and in particular soils with silt loam textures and good organic matter levels (of 15–30 percent), are able to store and retain a lot more plant-available water than very fine (clayey) and coarse (sandy) textured soils, particularly if the soil organic matter content is low.

Calcium (in a form such as lime) promotes the biological life, structure and porosity of the soil and therefore the AWC. Lime also converts to water by the following reaction, which increases the soil's resistance to drought: $\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{CO}_2 + \text{H}_2\text{O}$. Optimum levels of Zn and K promote the uptake of water and therefore water-use efficiency by facilitating the movement of water into plant cells. High K levels will suppress the wetting of soils and reduce Ca levels. Although Mg has an affinity for water, increasing plant-available water, too much Mg (and Na) disperses soil clay particles, causing the collapse of the soil structure and pores and consequently the reduction of their water-holding capacity. Ensure the soil has good amounts of Ca relative to Mg, with a Ca/Mg ratio of 7:1 for clayey soils, 5:1 for silty soils and 3:1 for sandy soils.

Mycorrhizal fungi can supply moisture to plants by exploring micropores not accessible to plant roots. They can also improve water flow by their hyphae bridging macropores. This wicking effect along the hyphae can be very significant in dry soils. Mycorrhizal fungi can also increase drought resistance by stimulating an increase in the number and depth of plant roots.

Pastures on good quality soils are slow to decline going into a drought and quick to recover following the first rains. Conversely, pastures on poor quality soils are quick to decline going into a drought and slow to recover following the first rains. This is particularly so for white clover.

PLATE 41 Visual scoring (VS) of drought stress of pastures during prolonged dry periods

**GOOD CONDITION VS = 2**

Pastures are slow to decline going into a drought and remain relatively green, with dry matter production able to hold on, albeit at low levels, further into dry summers. Recover is quick following the first rains. Pasture composition is dominated by ryegrass and white clover during dry periods.

**MODERATE CONDITION VS = 1**

Non-drought tolerant pastures 'brown off' significantly during dry summer months, although thin green patches are still present close to the ground. Dry matter production is very low and pastures become dominated during drought by the more drought-resistant cocksfoot, tall fescue, phalaris, birdsfoot, Lotus trefoil, meadow rice-grass, rats tail and small annual clovers. Deep rooted flat weeds and hawkbit may also be common. Pastures are moderately quick to decline going into a drought and recovery is somewhat delayed following the first rains.

**POOR CONDITION VS = 0**

With the possible exception of drought tolerant grass species and deep rooting herbs such as chicory, pastures brown off completely and pasture growth stops during dry periods. Pastures are quick to decline going into a drought and die off during times of prolonged drought. With the exception of subterranean clover and drought-tolerant species such as phalaris, pastures are slow to recover following the first rains.



Assessment

- 1 Assess the stock-carrying capacity of the paddock in relation to production costs and whether overall production costs have increased in order to maintain stock-carrying capacity.

In making your assessment, consider all production costs including, for example, the use of nitrogen, lime, additional fertilisers, feed supplements, soil aeration of the topsoil (Plates 42–45), subsoiling (deep ripping), artificial drainage, resowing, under-sowing, over-sowing, weed control, drenching, animal health issues, and veterinary costs, etc. Compare with the criteria given in Table 9.



Importance

PRODUCTION COSTS TO MAINTAIN STOCK-CARRYING CAPACITY can provide a good indication of the performance of the soil and pasture. While fertiliser should be seen as an investment rather than a cost, it is one of the major costs associated with farming. The amount, type and therefore cost of applied fertiliser can be significantly influenced by the condition of the soil and the performance of the pasture. The condition of the soil can have a major effect on fertiliser use efficiency, including the N and P conversion factor, i.e. the N and P captured in production going from the farm. For example, poorly aerated and waterlogged soils reduce plant available nitrate-nitrogen (NO_3^- -N) to nitrite (NO_2^-) and N_2 gas, and sulphate-sulphur (SO_4^{2-} -S) to sulphite (SO_3^{2-}) and sulphides, rendering the N and S unavailable to the plant. The N cycle also cannot work if the S cycle is not working, i.e. plants need sulphur in sulphate form to utilize N. It is partly for this reason that farmers commonly apply more N and S than would otherwise be the case in an attempt to overcome the losses incurred by the chemical reduction effect of soils in poor condition.

Poorly aerated and waterlogged soils also decrease the uptake of phosphorus by pastures. Degraded soils with relatively high Olsen P levels (40–50 mg/L) can show a positive pasture production response to applied P. Moreover, plant uptake of Cu and Co is suppressed when the soil is waterlogged and anaerobic. Again, to boost production, farmers will often apply more phosphorus and trace elements than normally would be required in order to mitigate any nutrient deficiencies.

Do you use fertiliser to grow the plant, or do you use fertiliser to feed the soil to grow the plant?

PLATE 42 Farm with low production costs



Farm with on-going low production costs to maintain its current stock-carrying capacity of 3.4 cows per ha.

PLATE 43 Maintenance application of fertiliser

Photo: Courtesy of Robert Tucker



TABLE 9 How to score production costs to maintain stock-carrying capacity

Visual score (VS)	Production costs
2 [Good]	Production costs have not increased. Only maintenance fertiliser applications required to maintain stock-carrying capacity.
1 [Moderate]	Some additional costs required to maintain stocking rates including some additional fertiliser.
0 [Poor]	Significant additional costs required to maintain stocking rates including significant additional fertiliser.

PLATE 44 Use of feed supplements



Feed supplements such as maize silage, wholecrop cereal silage, palm kernel, etc., are often used not only to overcome feed shortages but also to provide an adequate diet of low crude protein and high soluble carbohydrates and starch that are deficient in poor quality pastures.

PLATE 45 Artificial aeration

Photo: Courtesy of James Engineering



Ameliorating poorly aerated, compacted soil by artificial aeration.

In addition to soil fertility issues, soils in poor physical condition can have a significant effect on pasture production. Pasture production can recover almost completely within approximately 6 months if the soils are only moderately compacted by stock treading and wheel traffic. Severe compaction and pugging, and the subsequent increase in root penetration resistance and loss of soil structure, porosity, aeration, root length density,

and water-holding capacity can reduce dry matter production by up to 40–45 percent. The soil can also take years to recover. If feed utilisation ratios are around 0.7, this decline in pasture uptake would reduce potential stock numbers by 10–20 percent. To offset this trend, additional fertiliser is often applied to maintain dry matter production and stock numbers.

The application of fertiliser can be reduced or kept to maintenance levels if the soil is maintained in good condition. Such conditions includes having good soil aeration with good structure, porosity, root length and root density, good levels of soil carbon, and good soil life in terms of the amount, activity and diversity of soil microbes and earthworms. Keeping your soils in good condition can have a significant effect on keeping production costs to a minimum.

Compacted, poorly aerated soils can be ameliorated by artificial aeration. Aerating the soil can increase dry matter production by 33 percent after 6 months and by 52 percent after 8 months. To minimise the effects of root-pruning and maximise root development, compacted soils should be artificially aerated in the autumn just prior to, or during the root development cycle of the pasture, and when transpiration and respiration demands on the plant are lower than in the spring and summer. Soils should also be aerated when they are moist and sufficiently crumbly to give maximum fracturing (Plate 46) and a smooth surface finish behind the aerator (Plate 45). This can be achieved by using the ‘worm test’ (Plate 47). Spending money on diesel instead of fertiliser to aerate compacted soils will often give better pasture production and pasture quality.

PLATE 46 Aerating in the autumn at the optimum water content for maximum results

Photo: Courtesy of James Engineering



Artificial aeration of compacted topsoils must be timed correctly in the autumn to cause maximum fracturing and minimum disturbance of the surface.

PLATE 47 The 'worm test'



For **silty soil**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to aerate. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to aerate.

The amount of feed supplements grown and brought onto the farm not only affects production costs but also provides an indication of the ability of a farm to grow grass and quality pasture. Feed supplements such as maize silage, wholecrop cereal silage, palm kernel, etc., are used not only to overcome feed shortages but also to provide the necessary diet of low crude protein and high soluble carbohydrates and starch. These dietary components are deficient in poor quality pastures but are a feature of high quality pasture. The amount of supplements used could therefore be appreciably reduced by simply improving pasture quality – thereby significantly reducing costs.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 2

Pastures

Visual indicators
of environmental performance
under pastoral grazing

A GUIDE



Pastures

**Visual indicators
of environmental performance
under pastoral grazing**

A GUIDE

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BioAgriNomics.com, New Zealand

Plates, figures, tables and parts of the text are reproduced from Shepherd, T.G. 2009. Visual Soil Assessment, Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country. Second edition. Horizons Regional Council, Palmerston North. 119 p.; under copyright © Horizons Regional Council and BioAgriNomics Ltd 2009.

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List of acronyms

AEC	Adenylate energy charge	MgO	Magnesium oxide
Al	Aluminium	Mn	Manganese
ASC	Anion storage capacity	Mn³⁺	Manganic
ATP	Adenosine triphosphate	Mn²⁺	Manganous
B	Boron	Mo	Molybdenum
C	Carbon	N	Nitrogen
Ca	Calcium	N₂	Nitrogen gas
Ca²⁺	Calcium cation	NO₃⁻	Nitrate
CEC	Cation exchange capacity	NO₃⁻-N	Nitrate-Nitrogen
CH₄	Methane	NO₂⁻	Nitrite
Cl	Chlorine	N₂O	Nitrous oxide
CO₂	Carbon dioxide	Na	Sodium
qCO₂	Metabolic quotient	Na⁺	Sodium cation
Co	Cobalt	NH₄⁺	Ammonium
CT	Condensed tannins	NH₃	Ammonia
Cu	Copper	O₂	Oxygen
DM	Dry matter	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂	Hydrogen gas	SO₄²⁻	Sulphate
H₂S	Hydrogen sulphide	SO₃²⁻	Sulphide
I	Iodine	Se	Selenium
K	Potassium	VS	Visual score
K⁺	Potassium cation	VSA	Visual Soil Assessment
KCl	Potassium chloride	WFP	Water-filled porosity
LHb	Leghaemoglobin	Zn	Zinc
Mg	Magnesium	ZnS	Zinc sulphide
Mg²⁺	Magnesium cation		
MgCl₂	Magnesium chloride		

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER PASTORAL GRAZING

A GUIDE



1. Nutrient loss into the groundwater and waterways



2. Carbon sequestration



3. Greenhouse gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways



Assessment

- ① To assess the susceptibility of soils under pasture to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 79), the visual scores (VS) for the Textural group, Soil structure and the Potential rooting depth from the Soil Scorecard, and the visual scores (VS) for Root length and root density, Pasture quality, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Also add a ranking score for stocking rate and the amount and form of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.



Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals¹, have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is $>7:1$, P is limiting growth. If the N:P $<7:1$, then N will be the limiting factor. Given that most waterways have a N:P >7 , it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

¹ Non-crystalline iron and aluminium hydrous oxides and non-crystalline aluminosilicate clays such as ferrihydrite and allophone.

PLATE 48 Nutrient loss into waterways



- a) Paddock with a moderate potential for nutrient loss into the groundwater and lake. While the soil has a sandy textural group and good soil structure with a rapid permeability, it has a good potential rooting depth, moderately good root length and root density, moderately high carbon levels and CEC in the topsoil, and receives moderate amounts of low water-soluble fertiliser. The paddock has a moderate pasture quality with a moderately low stocking rate.
- b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly estimated from seven of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^- -N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain

more clay and generally more humus as well. Hence their CECs are higher and more able to adsorb and retain positively charged nutrients such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+ , etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic silty clay*, *peaty silt loam*) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P in solution can also leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root length and root density** (p. 60) – Pastures with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with pastures with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root length and root density and the potential rooting depth.

Pasture quality (p. 34) can provide a good indication of the potential for nutrient loss into the groundwater and waterways. Pastures rich in crude protein and nitrate-N with low sugar content are difficult for the micro-organisms in the rumen of the animal to break down by fermentation because of the lack of energy (sugars) in the pasture. As a consequence, livestock are only able to convert about 20 percent of the protein in the herbage into milk, meat and fibre. Furthermore, because of the low sugar levels, the rumen microbes do not have the energy required to utilize the excess N in the feed, converting 80 percent of it into ammonia as a consequence. As a result, the concentration of N in urine patches is markedly increased to 1 000–1 600 kg N/ha, increasing the amount of N lost by surface runoff and leaching into the groundwater and waterways. Leaching from urine patches accounts for about 55 percent of the total N leached from pastures. The amount of N lost can be significantly reduced by simply reducing the concentration of N in the urine by ensuring stock graze sugar-rich, nutrient-dense high quality pasture containing mature proteins, soluble non-structural carbohydrates, cobalt and condensed tannins.

Pasture colour and growth relative to urine patches (p. 52) can also provide a good indication of the potential for nutrient loss versus the retention and utilisation of nutrients in the soil (Plate 49). The greater the colour/growth contrast, the greater the loss potential. Poor growth and yellow pasture relative to urine patches often indicate the nitrogen and/or sulphur cycle has broken down. This is because the amount of humus and the number and activity of soil organisms responsible for nutrient retention, turnover and supply, have been degraded by, for example, the frequent and excessive application of artificial N and certain types of fertilisers, herbicides and pesticides. Without the humus and microbial population, subsequent applications of nutrients, particularly in the form of highly soluble fertilisers and N, will be more readily leached through the soil profile. The presence of

PLATE 49 High potential for nutrient loss



Paddock with a high potential for nutrient loss into the groundwater and waterways due partly to poor pasture quality and associated high concentration of N in the urine as indicated by the tall, dark green grass (nitrogen hills) in the urine patches compared with between urine patches.

tall, dark green grass in the urine patches compared with yellow, poor pasture growth areas between urine patches also indicates a high concentration of N in the urine and its subsequent potential for loss by leaching. In addition, organic acids released from animal manure, and the high pH of liquid manure and sewage sludge, enhance the mobilisation of phosphorus, increasing the amount of P that is leached.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light, well-structured soils, particularly when applied in large amounts. The over-use of highly soluble granulated N products also readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^- . Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching in urine patches. Nitrate and H^+ ions are produced in the urine patch following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes.

The frequent addition of soluble nitrogenous products to boost dry matter production also increases the concentration of N in the herbage and subsequently, the concentration of N in the urine. Moreover, the extra amount of nitrate-rich pasture grown by applying N is consumed by the animal, producing a greater amount of urine. As a consequence, the production of additional amounts of N-rich urine increases the amount of N leached into the groundwater and waterways. In contrast, the application of ‘smart’ fertiliser products that help generate sugar-rich, nutrient-dense, high-quality pastures with a high metabolisable energy and digestibility, result in the animal producing lower concentrations of N in the urine. The energy demand of the animal eating higher quality pasture is also met by it consuming less, thereby producing less urine. In addition, the concentration of N in the urine is reduced by ensuring the animal intake of Co in the herbage is adequate to enable the bacteria in the rumen to produce vitamin B_{12} necessary to promote efficient digestion through good rumen function. To this end, Co levels in the pasture should be of the order of 0.1–0.15 mg/kg. The production of less urine with a lower concentration of N significantly reduces the input of N into the groundwater and waterways. Additionally, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of soluble, salt-based forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate

can strongly inhibit soil life. Soil microbes and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant. Nutrient loss can therefore be reduced by applying fertilisers in a way that promotes soil life.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to pastures to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain carbohydrates and organic C (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and pasture growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^- -N) from urine patches and soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+ -N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. It can further produce phytotoxic effects and yield reductions in white clover and clover N_2 fixation. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Stocking rate (see scorecard – p. 79) can significantly influence nutrient loss into the groundwater and waterways. Animal urine contains a lot of nitrogen and is the principal source of leached N in managed grazing systems (Plate 56, p. 98). The amount of urine produced is roughly proportional to the animal liveweight. A 500-kg dairy cow produces 13–27 litres of urine/day, approximately seven times the amount of a 70-kg ewe, which produces 1.8–3.6 litres of urine/day (Table 10). While urine patches can contain 1 000–

TABLE 10 Average liveweight and the amount of urine produced for different stock classes

Stock class	Average live weight (kg)	Stock unit equivalent ¹	Volume of urine per day (litres)	Volume of urine per year (litres)
Friesian cow	500–550	6.3	13–27	4 740–9 850
Jersey cow	400–450	5.3		
Beef cow	500–600	6.3		
Heffer	250–350	3.4		
Deer	120	2.1		
Goat	60			
Ewe	60–75	1.2	1.8–3.6	650–1 310
Hogget	50	1		
Lamb	35–40	0.7		

¹ Cornforth and Sinclair (1984).

1 600 kg N/ha, N leaching losses from dairy/beef and sheep farms commonly range from 15 to 115 and 10 to 66 kg N ha/yr respectively. The actual amount of N in urine strongly depends on the amount and form of soluble, salt-based nitrogenous fertiliser applied, the amount, quality and type of feed consumed, and the efficiency of rumen function. A high stocking rate on crude protein/nitrate-rich pasture receiving high amounts of soluble salt-based fertiliser N will significantly increase the amount of leached N compared with low stocking rates. All things being equal, 4 cows/ha will add roughly twice as much urinary N as 2 cows/ha.

Animal liveweight per hectare instead of stock units is used to define stocking rates because of the difficulty of accurately reporting stock units for different classes of livestock, and at different times of the year in terms of their size, feed (energy) requirements, animal performance and farming systems. The average liveweight per animal for different stock classes is given in Table 10 and can be quickly used to calculate stocking rate (and feed-use efficiency), regardless of the class of livestock.

Any one of the above indicators provides an estimate of the susceptibility of a soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 28 , certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 28 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching and surface runoff into the environment. Pastures are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth. Farmer involvement is the key to reducing nutrient loss into the groundwater and waterways. The Nutrient Loss Scorecard provides farmers with a simple, quick tool to help them mitigate nutrients emissions into the environment.

FIGURE 5 Scorecard – visual indicators to assess the potential for nutrient loss

Landowner: _____ Land use: _____ Site: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey

Visual indicators of nutrient loss	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	pg. 2	x 3	
Soil structure (Scoring protocol is given below ²)	pg. 4	x 2	
Potential rooting depth (mm)	pg. 22	x 3	
Root length & root density	pg. 60	x 3	
Pasture quality	pg. 34	x 3	
Pasture colour & growth relative to urine patches	pg. 52	x 2	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 3	
Stocking rate (Scoring protocol is given below ⁴)	pg. 77	x 2	
NUTRIENT LOSS INDEX (sum of VS rankings)			

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 15
Moderate potential for nutrient loss	15–28
Low potential for nutrient loss	> 28

1 Textural group (Figure 2b, p. 3):

VS = 2 for Clayey; VS = 1.5 for Fine silty; VS = 1.0 for Fine loamy; VS = 0.5 for Coarse silty; VS = 0 for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 respectively to the VS score. Note VS scores cannot exceed a value of 2.

2 Soil structure – Is the land most susceptible to a) leaching, or b) runoff?

a) Land susceptible to leaching – Flat land with little or no runoff (overland flow)

VS = 2 for Poor soil structure; VS = 1.5 for Moderately poor soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately good soil structure; VS = 0 for Good soil structure.

b) Land susceptible to runoff – Gently undulating to rolling and hilly land

VS = 2 for Good soil structure; VS = 1.5 for Moderately good soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately poor soil structure; VS = 0 for Poor soil structure.

3 Amount and form of fertiliser and N applied

VS = 2 if using liquid foliar sprays, conditioner, or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 30 kg N/ha/yr are applied; VS = 1.0 if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 60–90 kg N/ha/yr using highly soluble, salt-based and nitrogenous fertilisers; VS = 0 if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 120 kg N/ha/yr are applied.

4 Stocking rate – kg liveweight (Lwt) per ha

VS = 2 if the Lwt is ≤ 1 000 kg (≤ 2 cows*)/ha; VS = 1.5 if the Lwt is 1 250 kg (2.5 cows)/ha; VS = 1 if the Lwt is 1 500 kg (3 cows)/ha; VS = 0.5 if the Lwt is 1 750 kg (3.5 cows)/ha; VS = 0 if the Lwt is ≥ 2 000 kg (≥ 4 cows)/ha. [* assuming a cow of 500 kg liveweight]

2. Visual indicators to assess the potential for carbon sequestration



Assessment

- Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 7, p. 89) the visual scores (VS) for the Textural group, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root length and root density, Pasture growth, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Add also a ranking score for the clay mineralogy and the amount and form of fertiliser and nitrogen applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.



Importance

THE AMOUNT OF C in a soil = C inputs – C losses. Carbon inputs and losses are in equilibrium with soil temperature, moisture, mineralogy, drainage status, decomposition rates, leaching, volatilisation, farming systems, and soil and pasture management. With the exception of the last three, most of these governing factors remain fairly constant, providing a potential steady state in the carbon-carrying capacity of the soil. The equilibrium can, however, swing towards increasing soil C by increasing the input of relatively stable forms of carbon through adopting appropriate farm management practices. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition (by oxidation and mineralisation), leaching and volatilization. A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than C losses. Farmers can reduce their ecological and carbon footprint and 'grow' their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture's contribution to CO₂ emissions, providing a cost-effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, three indicators of plant performance, and from the amount and form of fertiliser and nitrogen applied, as described below.

PLATE 50 Carbon positive soil

A carbon positive soil with good soil colour compared with the fenceline, good potential rooting depth, pasture growth, pasture colour and growth compared with urine patches, moderately good earthworm numbers, root length and root density, and carbon-friendly forms of nitrogen applied annually in low amounts.

PLATE 51 Carbon neutral soil

A carbon neutral soil with moderate soil colour compared with the fenceline, moderate earthworm numbers, potential rooting depth, pasture growth, pasture colour and growth compared with urine patches, moderately poor root length and root density, and moderate amounts of granular nitrogenous products applied annually.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of soil C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are $<2\ \mu\text{m}$ and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

Clay mineralogy (see scorecard, p. 89) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Mollic Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and aluminosilicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under pasture contain about 235 t C/ha in the top 1 m, of which 163 t C/ha (69 percent) occur in the upper 300 mm, and 72 t C/ha (31 percent) between 300 and 1000 mm. Compare this with non-allophanic soils below.

Soils with a high proportion of amorphous (poorly crystalline) aluminosilicate clay minerals have a high anion storage capacity (ASC) while soils dominated by crystalline aluminosilicate clays have a low ASC. The ASC can therefore provide a useful indication of the proportion and general type of clay minerals present and can be used to broadly describe the clay mineralogy of the soil. The ASC is also commonly reported on most soil tests, and so farmers will have the information required to score this indicator, as defined in the scoring protocol on p. 89.

Soil colour compared with that under the fenceline (p. 10) can provide a rough indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present (Fig. 6, p. 88). With the exception of poorly aerated and saturated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C.

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. Earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil carbon. Soils are also less well aerated and have fewer microbes at depth and so organic carbon is more protected and able to build up because it is less likely to be oxidised and mineralised.

Potential rooting depth (p. 22) and the **Root length and root density** (p. 60) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 160 tonnes C/ha, of which 117 t C/ha (73 percent) occur in the upper 300 mm, and 43 t C/ha (27 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good rooting depth contain about 173 t C/ha in the top 1 m, of which 103 t C/ha (60 percent) occur in the upper 300 mm, and 70 t C/ha (40 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme.

Pasture growth (p. 50) provides a further indication that soil C is increasing, decreasing or at steady state. The greater the dry matter production, the greater the root and shoot mass, and therefore the greater the C input from the root system and the decomposition of the additional surface litter and animal dung. A farm growing 18 tonnes of dry matter (DM)/ha/yr with a shoot:root ratio of 1:1 adds similar amounts of plant material to the soil, of which 41 percent or 7.4 t/ha/yr is carbon. Approximately 6.2 t C/ha/yr is added to the soil from the roots and 1.2 t C/ha/yr from plant litter, assuming 84 percent pasture utilisation. A further 4.3 t C/ha/yr is added from animal excreta, making a total input of 11.7 t C/ha/yr. Of this, approximately 0.43 t C/ha/yr is incorporated as soil C. A farm growing just 15 t DM/ha/yr adds a total input of 9.8 t C/ha/yr, of which approximately 0.36 t C/ha/yr is incorporated as soil C, 16 percent less than the higher producing farm. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the pasture is not overstocked, has good residual levels, root-length density, and potential rooting depth, and the soil is allophanic with good soil life and doesn't receive high applications of salt-based nitrogenous products. In addition, the

microbial decomposition of roots, plant litter, and dung produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture, and soil and air temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing pasture growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Pasture colour and growth relative to urine patches (p. 52) can provide an additional indication of the potential of the soil to sequester or lose C. First, poor growth and yellow pasture relative to urine patches indicate the N and S cycle has broken down because the amount of humus and the number and activity of soil organisms responsible for nutrient retention, turnover and supply have been degraded. The input of soil C declines as a consequence causing a net loss of C. Second, the strong growth of grass in the urine patches also indicates the dissolution and loss of a significant amount of C by the high concentration of N in the urine patch (see below).

Amount and form of fertiliser and nitrogen applied to pastoral soils (see scorecard, p. 89) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, vermicasts, worm leachates, animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' conditioner fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and pasture management practices, good pasture production, pasture quality and soil C levels can be sustained and increased over the long term.

The plant converts CO₂ in the atmosphere into dissolved organic carbon (DOC, i.e. liquid sugar) by photosynthesis in the leaves of the plant. The dissolved liquid carbon is subsequently transported in the sap through the roots to the soil across a microbial 'bridge' formed by the mycorrhizal fungi. This provides a constant flow of C to the soil and at the same time feeds the microbes (mycorrhizal fungi and bacteria) attached to the roots and in the soil. The microbes in turn provide macro-nutrients (such as P, organic N and

Ca), trace elements (Zn, B, and Cu), and plant growth hormones to the plant in exchange for the sugar, a process known as ‘bidirectional flow’. The supply of nutrients stimulates plant growth, which in turn increases the photosynthetic supply of liquid C to the soil and soil microbes, increasing the population of soil microbes. Mycorrhizal roots can transfer as much as 15 times more carbon to the soil than can non-mycorrhizal roots. The DOC not used directly by the soil microbes is converted through the process of microbial humification to humus, which is a relatively stable form of carbon. Up to 80 percent of DOC can be humified if there is sufficient microbial diversity and the right fungal metabolites (including amino acids) and enzymes are present. Soil microbes, including actinomycetes and mycorrhizal fungi, also play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important stable organic compound that can comprise 30 percent or more of the humus fraction in pastoral soils.

Mycorrhizal fungi and bacteria, include those forming the microbial bridge between the soil and the plant roots are strongly inhibited by excessive soil disturbance and high levels of water-soluble, salt-based forms of N and P. Cultivation and the application of high levels of mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP), superphosphate, urea, and anhydrous ammonia suppress and disrupt the mycorrhizal colonization of plant roots and thus the microbial bridge, reducing the photosynthetic rate by up to 35 percent and, as a result, significantly reducing C flow to the soil and its humification to humus. Conversely, appropriately managed farmland promotes carbon sequestration by allowing the liquid carbon pathway to function.

Moreover, while nitrogen promotes pasture growth, and therefore the input of C into the soil, certain forms of N are more effective at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic C and carbohydrates such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N.

The application of frequent and high rates of soluble granular forms of N and high analysis nitrogenous fertilisers to boost dry matter production:

- i) promotes the vegetative growth of the shoots relative to the roots and creates lazy plants, encouraging a shallow root system. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil because shoots contribute 6 times less C than roots do;
- ii) produces ‘watery’ pasture with a lower dry matter content and a lower concentration of C in the shoots and roots, adding less C to the soil on decomposition;
- iii) leads to the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 20:1 or less;

- iv) causes the N enrichment of urine and the subsequent mineralisation of soil C by stimulating the activity of the microbial biomass through the priming action of dissolved carbon in the urine. As a result, bacteria mineralise 2–3 times the amount of humus they would ordinarily mineralise. High concentrations of N in urine patches may also cause the dissolution (emulsification) of soil humus and its subsequent loss as dissolved organic C in the leachate;
- v) reduces the earthworm and microbial biomass, further reducing C levels in the soil.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to pastures to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (such as ammonium humate, humic/fulvic acids), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent). The utilisation of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root length density, and pasture growth.

The form in which essential elements are applied can also have a significant effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and, as such, increases pasture production and C flow to the soil, partly by providing a soil environment conducive to mycorrhizal activity and the formation of a microbial bridge between the roots and soil. Potassium chloride (muriate of potash), on the other hand, can be harmful to the roots and soil life, and can have adverse effects on animal health.

Moreover, the addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore 'grow' the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 30), certain management practices and specific types of fertiliser and N (if required) need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (>30) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits as well.

Off-setting GHG emissions

The sequestration over a 12 month period of 6.3 and 7.1 tonnes C/ha in the top 1 m of soil (an increase of 3.6 and 5.5 percent respectively from the previous year) on two dairy farms that recently converted from soluble, salt-based high-analysis N:P:K fertilisers to bio-

friendly fertilisers, equates to the sequestration of 23 and 26 tonnes CO₂ equivalents/ha respectively. GHG emissions from dairy farms are typically of the order of 7–9 tonnes CO₂ equivalents/ha/yr, two-thirds less than the 23–26 tonnes CO₂ equivalents/ha sequestered as soil C. The soil clearly has a huge capacity to act as a carbon sink under appropriately managed farmland, off-setting GHG emissions. Soil carbon sequestration by adopting carbon farming strategies, such as developing the root system, increasing earthworm numbers, and applying bio-friendly forms of fertilizer, is consequently a cost-effective strategy to mitigate GHG emissions.

Carbon sequestration of atmospheric CO₂ in the soil, ultimately as stable humus, may well provide a more lasting solution than temporarily sequestering CO₂ in the standing biomass through re- and afforestation. Carbon sequestration will also contribute to higher soil fertility, greater biodiversity, aeration, infiltration and water-holding capacity, less droughtiness and dependence on supplements in protracted dry periods, and sustainable food productivity and quality.

PLATE 52 A carbon negative field



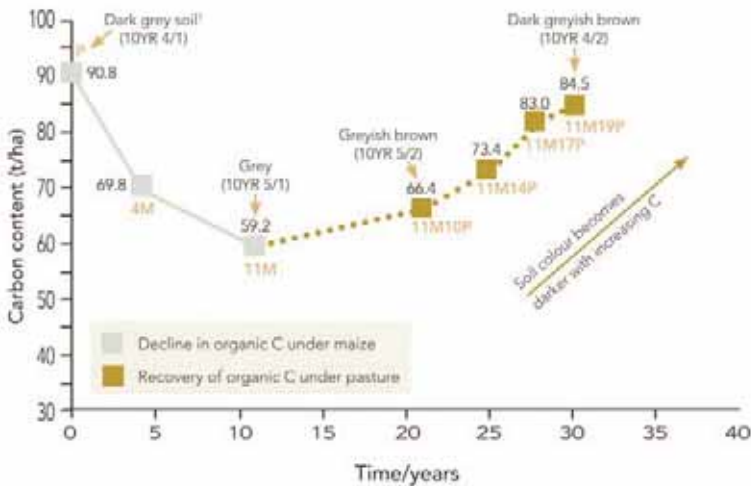
Total organic C declined in the upper 200 mm of soil from 90.8 tonnes/ha under pasture to 59.2 tonnes/ha after 11 years of maize under poor management practices (Figure 6). Photo taken in 1984 after harvesting for the 11th consecutive year of maize (for grain).

PLATE 53 Carbon sequestration under pasture



Carbon sequestration under pasture following 11 yrs of continuous maize cropping. Total organic C recovered from 59.2 tonnes/ha under 11 yrs of maize to 84.5 tonnes/ha in the upper 200 mm of soil after 19 yrs of ryegrass/clover pasture, an average recovery rate of just 1.3 tonnes C/ha/yr (Fig. 6). The rate of C sequestration could have been much greater had pastoral management practices focused better on promoting soil life, the potential rooting depth, root length and root density, pasture production and pasture quality, and applied the appropriate amount and form of fertiliser and N.

FIGURE 6 Rate of recovery of total C under pasture following intensive cropping



Total C in the topsoil (0–200 mm) and associated soil colour after 10, 14, 17 and 19 years of pasture following 11 yrs of maize under conventional cultivation.

FIGURE 7 Scorecard – visual indicators to assess the potential for carbon sequestration

Land owner:	Land use:	Site:	GPS:	
Soil type:	Drainage class:	Topsoil depth:	Date:	
Textural group <input type="checkbox"/> Sandy <input type="checkbox"/> Coarse loamy <input type="checkbox"/> Fine loamy <input type="checkbox"/> Coarse silty <input type="checkbox"/> Fine silty <input type="checkbox"/> Clayey <input type="checkbox"/> Peaty (upper 1 m):				
Visual indicators of soil carbon		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹) pg. 2			x 2	
Clay mineralogy (Scoring protocol is given below ²) pg. 82			x 2	
Soil colour pg. 10			x 1	
Earthworms (Number =) (Av. size =) pg. 14			x 3	
Potential rooting depth (mm) pg. 22			x 3	
Root length and root density pg. 60			x 3	
Pasture growth pg. 50			x 3	
Pasture colour and growth relative to urine patches pg. 52			x 2	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)			x 3	
SOIL CARBON INDEX (sum of VS rankings)				
Soil Carbon Assessment		Soil Carbon Index		
Soil is potentially carbon negative		< 16		
Soil is potentially carbon neutral		16–30		
Soil is potentially carbon positive		> 30		

- 1 Textural group (Fig. 2b, p. 3):** VS = 2 for Clayey; VS = 1.5 for Fine loamy and Fine silty; VS = 1.0 for Coarse silty and Peaty (virgin land); VS = 0.5 for Coarse loamy; VS = 0 for Sandy and Peaty (developed land). Strictly speaking, peaty soils cannot be defined as a textural group; however, they are closely aligned to, and have a huge effect on, soil texture.
- 2 Clay mineralogy:** VS = 2 if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; VS = 1 if the soil has moderate levels of Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an ASC of 60–75 percent; VS = 0 if the soil has little or no Fe & Al hydroxides and amorphous aluminio-silica minerals; ASC is < 45 percent.
- 3 Amount and form of fertiliser and N applied:** VS = 2 if ‘smart’ conditioner fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 30 kg N/ha/yr is applied as urea or in other forms of highly soluble, salt-based nitrogenous fertilisers; VS = 1 if moderate amounts of highly soluble, non-biologically friendly salt-based phosphatic & potassic fertilisers are used, and 60–90 kg N/ha/yr is applied as urea or in other highly soluble, salt-based nitrogenous fertilisers; VS = 0 if high amounts of highly soluble, salt-based phosphatic & potassic fertilisers are used, and > 120 kg N/ha/yr is applied as urea or in other highly soluble, salt-based nitrogenous fertilisers.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions



Assessment

- 1 Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 9, p. 99) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual scores for Pasture quality, Pasture growth, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Also add a ranking score for stocking rate and the amount and form of nitrogen applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.



Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C ; without them the earth's average temperature would be around -18°C . However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Solar radiation



Agriculture can provide a significant source of methane and nitrous oxide and is responsible for 15 percent of greenhouse gas emissions worldwide. In an agriculture-based country like New Zealand, farming practices can produce half the country's GHG emissions, of which 33 percent is breathed out as CH_4 from the digestive system of the animal and from dung emissions, and 17 percent is emitted as N_2O from animal urine, dung and nitrogenous fertilisers. These high emission levels are more to do with farm-management practices than the farming of ruminant animals. Climate-friendly and smart agricultural management can significantly reduce emissions.

GHG emissions result from a number of sources, including the soil, stock, and applied fertiliser N. The level of emissions varies according to a number of factors, including the condition of the soil, the quality of the pasture, and the application of nitrogenous fertilisers, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this

PLATE 54 Field with a low potential for greenhouse gas emission

Field with a low potential to emit GHGs due to good pasture quality and the soil being a well-drained, coarse silty soil with good porosity. The stocking rate is moderately low, urine patches are not readily apparent and little water-soluble, salt-based nitrogenous fertilizer is applied. In addition, good pasture growth and cover removes a large amount of CO₂ from the atmosphere by photosynthesis and intercepts/absorbs a large amount of CO₂ escaping from the soil.

PLATE 55 Field with a high potential for greenhouse gas emission

Field with a high potential to emit GHGs due to poor pasture quality and the soil being an imperfectly drained, fine silty soil with poor porosity. The stocking rate is high, urine patches are strongly expressed, and high application rates of water-soluble, salt-based nitrogenous fertilizer are applied. In addition, poor pasture growth and cover removes only a small amount of CO₂ from the atmosphere by photosynthesis and intercepts/absorbs a small amount of CO₂ escaping from the soil.

by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO₂ to soil C, and by promoting the soil as a CH₄ sink. Apart from improving soil quality, the C credits gained can off-set farmer's GHG emissions.

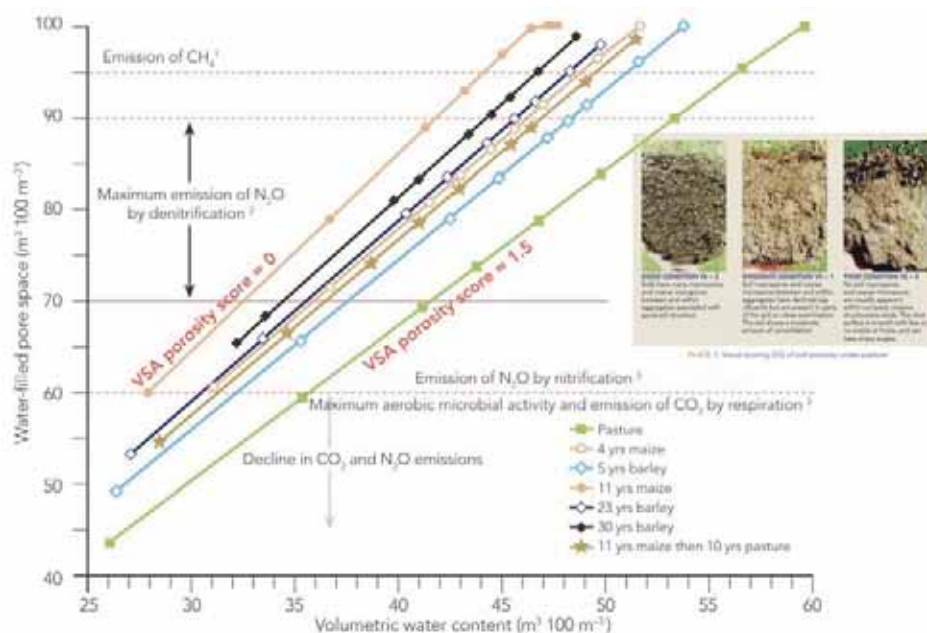
While CO_2 is a major GHG, it is reabsorbed as photosynthate by plants and can therefore be greenhouse neutral. Most atmospheric methane is also removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radical in the atmosphere. In addition, methane is inactivated by oxidation in aerated, biologically active soils (methanotrophy), and represents a globally significant sink. Nitrous oxide emissions, however, are more of an issue because their Global Warming Potential (i.e. a heat-absorbing ability) is 310 times that of CO_2 and, unlike CO_2 and CH_4 , they do not have a natural means of regulating their levels in the atmosphere. While 70 percent of the total global N_2O is produced during denitrification, denitrifying bacteria and denitrification enzymes would have to achieve complete denitrification to emit N_2 instead of N_2O as an end product. Emphasis must therefore be placed on reducing the application of nitrogenous fertilisers and the emission of N from stock, and on promoting the many alternative pathways to supply N through biological processes (pp. 12, 14 & 20–21) and from legumes such as clovers (p. 44–45).

The potential of a site to emit GHGs can be roughly estimated from four indicators of soil quality, three indicators of plant performance, and from the amount and form of nitrogen applied, as described below.

Textural groups (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major ‘driver’ of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs. Finer textured (heavier) soils also tend to be more poorly drained and therefore more likely to emit GHGs, as discussed below. Soils with a peaty ‘textural’ group are high amitters of CO_2 and CH_4 .

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O , and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 8); emissions of N_2O are lowest when the WFPS is <50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils. Soil compaction can cause a seven-fold increase in N_2O emissions.

FIGURE 8 Effect of water-filled pore space and water content on greenhouse gas emissions



¹ After MacDonald *et al.* (1996); ² After Dobbie *et al.* (1999); ³ After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 8) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O . In contrast, a severely compacted soil after 11 years of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 8) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2 . While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is hence an effective means of reducing GHG emissions. The relationship between the WFPS

and the visual assessment of the porosity of the soil, as shown in Fig. 8, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Emissions of N_2O can be 20 percent lower in a well-drained sandy loam soil than in a poorly drained silt loam soil. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink.

Pasture quality (p. 34) can provide an additional indication of the potential for GHG emissions. Poor quality pastures with high nitrate-N and crude protein levels, poor pasture composition, and low sugar (energy) levels are difficult for the microorganisms in the rumen of the animal to break down by fermentation. As a result these pastures have a low feed-conversion efficiency, producing high amounts of CO_2 and CH_4 , which the animal emits through belching and flatulence. High N and low sugar levels in the pasture also markedly increase the concentration of N excreted in the urine and dung because the rumen microbes have insufficient energy to utilize the excess N in the feed, converting 80 percent of it into ammonia instead of into milk, meat and fibre. As a consequence, the high concentration of N in the urine, often equivalent to 1 000–1 600 kg N/ha, markedly increases the amount of N_2O emitted into the atmosphere. High nitrate, crude-protein pastures also cause an overly alkaline gut that results in scouring and the production of 'liquid' dung with high concentrations of N and CH_4 that are subsequently emitted into the atmosphere. In contrast, nutrient-dense, sugar-rich, high-quality pastures containing mature proteins, high levels of soluble non-structural carbohydrates, condensed tannins and cobalt, have a high metabolisable energy and digestibility. As a consequence, they have a high feed-conversion efficiency that produces significantly less CO_2 and CH_4 in the rumen and digestive tract. They also produce less N in the urine and less N and CH_4 in the dung, and therefore emit less GHGs. Condensed tannins can reduce CH_4 emissions by 15 percent, by decreasing methanogenesis. Moreover, high quality pastures shift the production of acetates (CH_3COOH) in the rumen to propionates (volatile fatty acids – $\text{CH}_3\text{CH}_2\text{COOH}$), leading to a reduction in hydrogen and consequently in the production of CH_4 . Plants such as coriander and turmeric could reduce the amount of methane produced by bacteria in an animals stomach by up to 40 percent.

The concentration of N in the urine and GHG emissions is also reduced by ensuring the animal intake of Co in the herbage is adequate to enable the bacteria in the rumen to produce the vitamin B_{12} necessary to promote efficient digestion through good rumen function. To this end, Co levels in the herbage should be of the order of 0.1–0.15 mg/kg. Moreover, good

rumen function and therefore greater feed-conversion efficiency (to build protein) and lower GHG emissions are improved by ensuring yttrium levels are adequate in the rumen.

Pasture quality also influences the volume of feed intake and thus the amount of GHGs emitted. Good quality pastures with high energy levels, nutrient density and nutritive value have a higher palatability and digestibility and contain more useful energy per unit of dry matter than poor quality pastures. Animals therefore need to eat less to attain the number of kilojoules required for body maintenance, growth, and lactation. As a result, the amount of forage digested is less, which reduces the level of GHGs emitted. The animal produces less dung and urine and consequently there are less CH₄ emissions from the dung and N₂O from the urine. Highly digestible forage also spends less time in the rumen thereby producing fewer fermentation gases, including CH₄ and CO₂. Animals grazing a ryegrass sward produce twice the amount of CH₄ (24 g/kg dry matter intake) compared with animals grazing white clover (12.9 g/kg dry matter intake). Methane emissions can be reduced by at least 10 percent when grass forage is replaced by a mixed ryegrass/legume sward.

While forage-fed ruminants can emit significant amounts of GHGs and as a result are often used as global warming scapegoats, in reality much can be done to significantly reduce their emissions. This can be achieved by improving the quality of advice given to farmers, including addressing the factors discussed above.

Pasture growth (p. 50) can provide an indication of the potential to reduce GHG emissions. The greater the pasture growth, the greater the amount of CO₂ removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO₂ emitted by microbial respiration and the conversion of pasture into GHGs by grazing animals. As CO₂ escapes from the soil, most, if not all, is absorbed by the stomata on the leaves, which have an insatiable appetite for CO₂. The greater the pasture cover (leaf area index), the greater the amount of CO₂ removed. Furthermore, if we assume that one kilogram of carbon in the dry matter grown removes 3.67 kg CO₂ from the atmosphere, a farm growing 18 tonnes of dry matter/ha/year (or 7.4 t C/ha/yr) will remove approximately 27 tonnes of atmospheric CO₂/ha/yr. A farm growing just 15 tonnes of dry matter/ha/yr (or 6.2 t C/ha/yr) will remove approximately 23 tonnes of atmospheric CO₂/ha/yr, 15 percent less than the higher producing farm. While CO₂ is the least potent of the GHGs with a Global Warming Potential (i.e. a heat-absorbing ability) that is 21 and 310 times less than CH₄ and N₂O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO₂ into sugars and oxygen, and subsequently into soil carbon, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Pasture colour and growth relative to urine patches (p. 52) can provide a further indication of the potential for GHG emissions. First, poor growth and yellow pasture between urine patches and strong pasture growth in the urine patches indicate poor quality pasture with low sugar levels and the subsequent emission of CH₄ and excretion of N-rich urine. The N gives rise to increased emissions of N₂O by the denitrification of nitrate and nitrification of ammonium present in high concentrations in the urine patches. Second, poor growth

and yellow pasture between urine patches indicates the nitrogen and/or sulphur cycle has broken down, suggesting a decline in the uptake of N by the plant and its subsequent release to the environment.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 99) can provide another indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and in particular by denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 8). In addition to N added in the form of animal excreta, particularly as urine, the nitrification of urea and ammonium-based fertilisers, and the denitrification of high concentrations of nitrates in the soil resulting from the excessive application of other salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Increasing the application rate of urea from 80 to 190 kg N/ha, for example, can increase N_2O emissions from 1.2 to 3.6 t/ha (on a CO_2 -equivalent basis).

The excessive use of nitrogenous products can also reduce the capacity of soils to take up and oxidise atmospheric CH_4 , thereby reducing the ability of the soil to act as a methane sink. Aerobic soils can be net sinks for CH_4 due to the presence of methanotrophic bacteria that take up methane as their sole source of energy. Methanotrophs are however chemically sensitive, and their biomass and activity is reduced by nitrogenous and other soluble, salt-based inorganic fertilisers, the N inhibitor Dicyandiamide (DCD), herbicides, insecticides, acidification and excessive soil disturbance. Farming in ways that enhance rather than inhibit soil biological activity would improve the capacity of agricultural soil to act as a methane sink, helping to mitigate CH_4 emissions.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to pastures to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides microsites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root length and root density, and pasture growth, improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70 percent, they can increase NH_3 emissions and potential NH_4^+ -N leaching losses. The jury is also still out as to their long-term impact on soil biology,

in terms of microbial biomass, diversity and activity. The N inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. It can further produce phytotoxic effects and yield reductions in white clover. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures giving limited grass growth despite the application of N. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available to reduce N loss.

Stocking rate (see scorecard – p. 99) can significantly influence GHG emissions. Nitrogen deposited in the form of animal urine and dung is a principal source of N_2O production in managed grazing systems (Plate 56). More than half New Zealand's N_2O emissions originate directly from excretal N in grazed pastoral soils, while another 30 percent of emissions are from indirect emissions from leached and volatilized excretal-N. Nitrous oxide emissions from soils are caused principally by microbial nitrification and especially denitrification, processes controlled partly by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil. Animal urine contains a lot of nitrogen, with urine patches containing an equivalent of up to 1 000–1 600 kg N/ha. The amount of urine produced is roughly proportional to the animal liveweight. A 500-kg dairy cow produces 13–27 litres of urine/day, approximately seven times the amount of a 70-kg ewe, which produces 1.8–3.6 litres of urine/day (Table 10, p. 78). The actual amount of N in urine depends strongly on the amount and form of soluble, salt-based nitrogenous fertiliser applied, the amount, quality and type of feed consumed, and the efficiency of rumen function. A high stocking rate on crude protein/nitrate-rich pasture receiving high amounts of soluble salt-based fertiliser N will significantly increase N_2O emissions compared with low stocking rates.

About 96 percent of anthropogenic CH_4 (i.e. caused by humans) is emitted from ruminant animals by methanogenic fermentation in the gut. Methane is also produced by anaerobic fermentation of animal manure. Like N_2O , the greater the stocking rate on poor quality, crude protein/nitrate-rich pasture, the greater the emissions of CH_4 . Most of the methane, however, is removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radicals in the atmosphere, and by methanotrophic oxidation in aerated, biologically active soils, producing a globally significant sink.

Animal liveweight per hectare instead of stock units is used to define stocking rates because of the difficulty of accurately reporting stock units for different classes of livestock, and at different times of the year in terms of their size, feed (energy) requirements, animal performance and farming systems. The average liveweight per animal for different stock classes is given in Table 10 (p. 78) and can be quickly used to calculate stocking rate (and feed-use efficiency), regardless of the class of livestock.

PLATE 56 High stocking rate with >2 000 kg liveweight/ha



Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by Emission Trading Schemes. If the GHG Emission Index is ≤ 26 , certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of >26 provides significant environmental benefits because less GHGs would be emitted into the atmosphere. Farmer involvement is the key to reducing agricultural emissions of GHGs. The GHG Emissions Scorecard provides farmers with a simple, quick tool to help them mitigate the production of GHGs.

Off-setting GHG emissions. The sequestration over a 12 month period of 6.3 and 7.1 tonnes C/ha in the top 1 m of soil (an increase of 3.6 and 5.5 percent respectively from the previous year) on two dairy farms that recently converted from soluble, salt-based high-analysis N:P:K fertilisers to bio-friendly fertilisers, equates to the sequestration of 23 and 26 tonnes CO₂ equivalents/ha respectively. GHG emissions from dairy farms are typically of the order of 7–9 tonnes CO₂ equivalents/ha/yr, two-thirds less than the 23–26 tonnes CO₂ equivalents/ha sequestered as soil C. The soil clearly has a huge capacity to act as a C sink, mopping up most of the excess carbon being emitted into the atmosphere. Soil C sequestration can therefore more than off-set GHG emissions under appropriately managed farmland. Soil carbon sequestration by adopting carbon farming strategies, such as developing the root system, increasing earthworm numbers, and applying bio-friendly forms of fertilizer, is consequently a cost-effective strategy to mitigate GHG emissions.

Enhanced feed nutrition and sequestration of atmospheric CO₂ in the soil, ultimately as stable humus, may well provide a more lasting solution than temporarily sequestering CO₂ in the standing biomass through re- and afforestation. Improved feed nutrition and microbially active soils will also help reverse the processes of land degradation and thus contribute to higher soil fertility, greater biodiversity, aeration, infiltration and water-holding capacity, less droughtiness and dependence on supplements in protracted dry periods, and sustainable food productivity and quality.

FIGURE 9 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner: _____ **Land use:** _____ **Site:** _____
Soil type: _____ **Drainage class:** _____ **Date:** _____
Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Peaty

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	. 2	x 2	
Soil porosity	. 6	x 3	
Number and colour of soil mottles	.	x 3	
Soil colour	. 10	x 1	
Pasture quality	. 34	x 2	
Pasture growth	. 50	x 2	
Pasture colour and growth relative to urine patches	. 52	x 2	
Amount and form of N applied (Scoring protocol is given below ²)	. 6	x 2	
Stocking rate (Scoring protocol is given below ³)	. 9	x 2	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 14
Moderate potential GHG emissions	14–26
Low potential for GHG emissions	> 26

1 Textural group (Figure 2b, p. 3):

VS = 2 for Sandy and Coarse loamy; VS = 1.5 for Coarse silty; VS = 1.0 for Fine loamy; VS = 0.5 for Fine silty; VS = 0 for Clayey and Peaty. Strictly speaking, peaty soils cannot be defined as a textural group; however, they are closely aligned to, and have a huge effect on, soil texture.

2 Amount and form of N applied:

VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 30 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 60–90 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 120 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 Stocking rate – kg liveweight (Lwt) per ha

VS = 2 if the Lwt is ≤ 1000 kg (≤ 2 cows*)/ha; VS = 1.5 if the Lwt is 1250 kg (2.5 cows)/ha; VS = 1 if the Lwt is 1500 kg (3 cows)/ha; VS = 0.5 if the Lwt is 1750 kg (3.5 cows)/ha; VS = 0 if the Lwt is ≥ 2000 kg (≥ 4 cows)/ha. [* assuming a cow of 500 kg liveweight]

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for Pasture*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 1

Maize



Maize

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List of acronyms

AEC	Adenylate energy charge	Mn²⁺	Manganous ions
Al	Aluminium	Mo	Molybdenum
ASC	Anion storage capacity	N	Nitrogen
ATP	Adenosine triphosphate	N₂	Nitrogen gas
B	Boron	NO₃⁻	Nitrate
C	Carbon	NO₃⁻-N	Nitrate-nitrogen
Ca	Calcium	NO₂⁻	Nitrite
Ca²⁺	Calcium cation	N₂O	Nitrous oxide
CEC	Cation exchange capacity	Na	Sodium
CH₄	Methane	Na⁺	Sodium cation
CO₂	Carbon dioxide	NH₃	Ammonia
qCO₂	Metabolic quotient	NH₄⁺	Ammonium
Co	Cobalt	O₂	Oxygen
Cu	Copper	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂S	Hydrogen sulphide	SO₄²⁻	Sulphate
K	Potassium	SO₃²⁻	Sulphide
K⁺	Potassium cation	VS	Visual score
Mg	Magnesium	VSA	Visual Soil Assessment
Mg²⁺	Magnesium cation	WFPS	Water-filled pore space
Mn	Manganese	Zn	Zinc
Mn³⁺	Manganic ions	ZnS	Zinc sulphide

Visual Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of maize cropping. A decline in soil quality has a marked impact on yield and quality of maize for grain and silage, production costs, the risk of soil erosion, nutrient loss into the groundwater and waterways, carbon sequestration and green-house gas emissions. It can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Soil physical properties control the movement of water and air into and through the soil, the ease with which roots penetrate the soil, the number, type and activity of soil organisms, and the availability and uptake of soil nutrients. Damage to the soil can change these properties and reduce plant growth, food quality and environmental outcomes, regardless of nutrient status. Safeguarding soil resources for future generations and minimizing the ecological footprint of maize cropping is an important task for land managers.

Often, not enough attention is given to:

- ❖ the basic role of soil quality in efficient and sustained production;
- ❖ the effect of the condition of the soil on the gross profit margin;
- ❖ the long-term planning needed to sustain good soil, crops and food quality;
- ❖ the effect of land management decisions on soil quality, plant performance and environmental outcomes.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance of maize cropping and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for growing crops, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for maize. Scoring is out of 54: the higher the score, the better the condition of the soil and the performance of the plant. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

In addition, the VSA provides a quick, low cost method for estimating the potential for nutrient loss into the groundwater and waterways, C sequestration, and the emission of greenhouse gases.

The VSA method

While the name Visual Soil Assessment implies a focus on the soil, the method is equally about assessing both the soil and the plant. Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a score card. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require

knowledge of the growing history of the crop. This knowledge will facilitate the satisfactory and rapid completion of the plant score card. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. they are capable of changing under different management regimes and land use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the 'soil' and 'plant' scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate, or poor condition.

Placing the soil and plant scores side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- ✦ **A SPADE** (flat-faced) – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- ✦ **A PLASTIC BASIN** (about 450 x 350 x 250 mm) – to contain the soil during the drop shatter test;
- ✦ **A HARD SQUARE BOARD** (about 260 x 260 x 20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- ✦ **A HEAVY-DUTY PLASTIC BAG** (about 750 x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;

PLATE 1 The VSA tool kit



- ❖ **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- ❖ **A WATER BOTTLE** – to assess the field soil textural class;
- ❖ **A TAPE MEASURE** – to measure the sampling depth, topsoil depth, potential rooting depth, crop height, and the length of ears;
- ❖ **A VSA FIELD GUIDE** – to make the photographic comparisons;
- ❖ **A PAD OF SCORECARDS** – to record the visual score (VS) for each indicator.

The procedure

When should it be carried out?

The test should be carried out when the soils are moist and suitable for grazing. If you are not sure, apply the ‘worm test’ (p. 63). For **silty soils**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to test. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to test.

Setting up

Time

Allow 40 minutes per site. For a representative assessment of soil quality, sample four sites over a 5 hectare area.

Reference sample

Take a small sample of soil (about 100 x 50 x 150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. The condition of the soil in maize fields is site specific. Avoid areas that have had heavier traffic than the rest of the field and sample between wheel traffic lanes. VSA can also be used however, to assess the effects of high traffic on soil quality by selecting to sample along wheel traffic lanes. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the scorecard. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicators score card.

Carrying out the test

Initial observation

Dig a small hole about 200 x 200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample

If the topsoil appears uniform, dig out a 200 mm cube with the spade.

You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If, for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two 200 x 200 x 100 mm samples with a spade. If the 100–200 mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two 200 x 200 x 100 mm samples. Note that taking a 200 mm cube immediately below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and crop management.

The drop shatter test

Drop the test sample a maximum of three times onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, depends on the texture of the soil, and the degree to which the soil breaks up, as described on pp. 2–4.

Systematically work through the score card, assigning a visual score (VS) to each indicator by comparing it to the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS ranking in the right-hand column of the scorecard.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

“Despite mankind’s lofty aspirations and many notable achievements, our survival depends on a six-inch layer of topsoil and the fact that it rains”

anonymous

FIGURE 1 Soil scorecard – visual indicators for assessing soil quality in maize

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Topsoil depth:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____ **Date:** _____

Textual group: (upper 1 m) Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other
Moisture condition: Dry Slightly moist Moist Very moist Wet
Seasonal weather conditions: Dry Wet Cold Warm Average

Visual indicators of soil quality	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture pg. 2		x 3	
Soil structure pg. 4		x 3	
Soil porosity pg. 6		x 3	
Number and colour of soil mottles pg. 8		x 2	
Soil colour pg. 10		x 2	
Earthworms (Number =) (Av. size =) pg. 14		x 3	
Soil smell pg. 18		x 2	
Potential rooting depth (m) pg. 22		x 3	
Surface ponding pg. 26		x 3	
Surface cover and surface crusting pg. 30		x 2	
Soil erosion (wind/water) pg. 32		x 1	
SOIL QUALITY INDEX (sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 20
Moderate	20–37
Good	> 37



Assessment

- ❶ Take a sample of soil half the size of your thumb from the topsoil to assess the *soil texture*. Take also a sample/s that is/are representative of the subsoil to assess the overall *textural group* of the soil profile.
- ❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.
- ❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball and then squeezing it between the thumb and forefinger. With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the *textural class* obtained by reference to the textural diagram (Figure 2a). The *textural group* is obtained by comparing the position of the textural class in Figure 2a with Figure 2b (e.g., silt loam = fine silty).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For instance, if the soil has a reasonably high content of organic matter, i.e. is humic with 17–29 percent organic matter, raise the textural score by one (e.g., from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.



Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt, and clay. Sand is that fraction that has a particle size ≥ 0.06 mm; silt varies between 0.06 and 0.002 mm, while the particle size of clay is < 0.002 mm.

Texture influences soil behaviour in several ways, notably through its effect on water retention and availability, soil structure, aeration, drainage, soil workability and trafficability, soil life, and the supply and retention of nutrients. A knowledge of both the textural class and potential rooting depth (p. 22) enables an approximate assessment of the total water holding capacity of the soil, one of the major drivers of crop yield.

FIGURE 2 Soil texture classes and groups

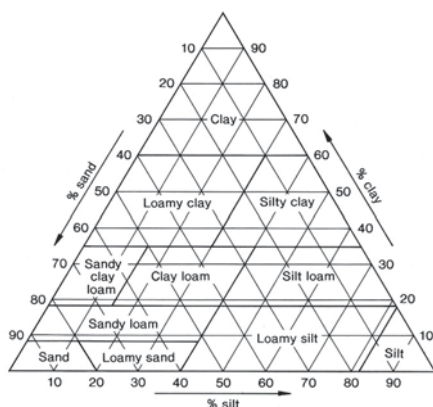


Figure 2a
Textural classes.

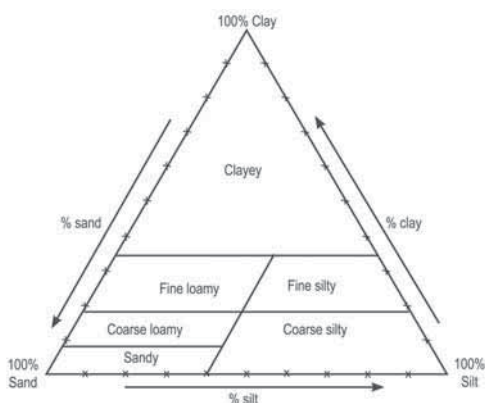


Figure 2b
Textural groups.

TABLE 1 How to score soil texture

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed flat.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
1 [Moderate]	Loamy silt	Smooth feel, non sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
	Sandy loam	Slightly gritty, faint rasping sound. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
0.5 [Moderately poor]	Silty clay & Clay	Very smooth, very sticky, very plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
0 [Poor]	Loamy sand	Gritty and rasping sound. Will almost mould into a ball but disintegrates when squeezed between thumb and forefinger.
	Sand	Gritty and rasping sound. Cannot be moulded into a ball.



Assessment

- ❶ Remove a 200-mm cube of topsoil with a spade (between or along wheel tracks).
 - ❷ Drop the soil sample a maximum of three times from a height of one metre onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Don't drop any piece of soil more than three times. For soils with a sandy loam texture (p. 3), drop the cube of soil once only from a height of 0.5 metres. If the sandy loam is humic (17–29 percent organic matter), drop the soil twice from 1 metre. Transfer the soil onto the large plastic bag.
 - ❸ For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade once from a height of just 50 mm and then roll the spade over spilling the soil onto the plastic bag.
 - ❹ Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures if present. If the clod cannot be easily parted, do not apply further pressure because the cracks and fissures are probably not continuous and therefore unable to readily conduct oxygen, air and water.
 - ❺ Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates on the plastic bag so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs and criteria given in Plate 2.
- The method is valid over a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.



Importance

SOIL STRUCTURE is extremely important for grain maize crops. It regulates:

- ❖ soil aeration and gaseous exchange rates;
- ❖ soil temperature;
- ❖ soil infiltration and erosion;
- ❖ the movement and storage of water;
- ❖ nutrient supply;
- ❖ root penetration and development;
- ❖ soil workability;
- ❖ soil trafficability;
- ❖ the resistance of soils to structural degradation.

Good soil structure reduces the susceptibility to compaction under wheel traffic and increases the window of opportunity for vehicle access and for carrying out no-till, minimum till, controlled traffic or conventional cultivation under optimum soil conditions.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, sub-angular and sub-rounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or sub-angular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 Visual scoring (VS) of soil structure

**GOOD CONDITION VS = 2**

Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally sub-rounded (nutty) and often quite porous.

**MODERATE CONDITION VS = 1**

Soil contains significant proportions (50 percent) of both coarse clods and friable fine aggregates. The coarse clods are firm, sub-angular or angular in shape and have few or no pores.

**POOR CONDITION VS = 0**

Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or sub-angular in shape and have very few or no pores.

Assessment

- ❶ Remove a spade slice of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and break in half.
- ❷ Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs and criteria in Plate 3. Look for the spaces, gaps, holes, cracks, fissures between and within soil aggregates and clods.
- ❸ Examine also the porosity of a number of the large clods from the soil structure test. This provides important additional information as to the porosity of the individual clods (the intra-aggregate porosity).

Importance

SOIL POROSITY is important to assess along with soil structure. Soil porosity, and particularly macroporosity (or large pores), influences the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores or coarse micropores within the large clods, thus restricting their drainage and aeration.

Poor aeration leads to the build up of methane, sulphide gases and alcohol, and reduces the ability of plants to take up water and nutrients, particularly nitrogen, phosphorus, potassium, sulphur, zinc, copper and cobalt. Poorly aerated and compacted soils reduce plant-available N in the form of nitrate-nitrogen (NO_3^- -N) and ammonium (NH_4^+) to nitrite (NO_2^-), nitrogen (N_2) gas and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available sulphate-sulphur (SO_4^{2-} -S) is also reduced to sulphite (SO_3^{2-}) and sulphides, rendering N and S unavailable to the plant. Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form. The number, activity and biodiversity of micro-organisms and earthworms are also greatest in well-aerated soils and are able to decompose and cycle organic matter and nutrients more efficiently.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilise the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, but greatly reduces fertiliser efficiency and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce less greenhouse gases. The greater the porosity the better the drainage and therefore the soil pores will be less likely to be water-filled to the critical levels required to accelerate the production of greenhouse gases (see p. 82–83). Aim to keep the porosity score above 1.

PLATE 3 Visual scoring (VS) of soil porosity

**GOOD CONDITION VS = 2**

Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

**MODERATE CONDITION VS = 1**

Soil macropores and coarse micropores between and within aggregates have declined significantly but are present in parts of the soil on close examination. The soil shows a moderate amount of consolidation.

**POOR CONDITION VS = 0**

No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few cracks or holes, and can have sharp angles.

Assessment

- Assess the number, size and colour of soil mottles by taking a sample of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and comparing it with the three photographs and criteria in Plate 4. The percentage chart below will help you determine the percentage of the soil occupied by mottles.

Mottles are patches of different colour interspersed within the dominant (background) soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also early warnings of a decline in soil structure as a result of compaction under wheel traffic and over-cultivation. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces iron (Fe) and manganese (Mn) from their *brown/orange* oxidised ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey due to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey mottles predominate. The abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicate the soil is moderately well drained, and no mottles indicate good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S, Zn, Cu and Co (p. 6). While Olsen P levels of 22 mg/L are generally adequate for optimum crop production on most soils in good condition, degraded, poorly aerated soils with relatively high Olsen P levels (40–50 mg/L) can show a positive crop response to applied P. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, which are toxic to plant roots. In addition, decay and die-back of roots can occur as a result of fungal diseases such as *Rhizoctonia*, *Pythium* and *Fusarium* root rot,

foot rot, and crown rot in soils that are strongly mottled and poorly aerated. Fungal diseases and reduced nutrient and water uptake give rise to poor plant vigour and ill-thrift. If your visual score for the number and colour of soil mottles is one or less, you need to aerate the soil.

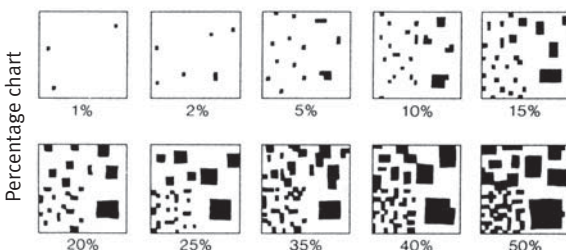


PLATE 4 Visual scoring (VS) of the number and colour of soil mottles



GOOD CONDITION VS = 2
Mottles are generally absent.



MODERATE CONDITION VS = 1
Soil has many (10–20 percent) fine and medium orange and grey mottles.



POOR CONDITION VS = 0
Soil has profuse (> 50 percent) medium and coarse orange and particularly grey mottles.

Assessment

- 1 Compare the moist colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area (Plate 5). If the soil is dry, pour water over the surface of the sample.
- 2 Using the three photographs and criteria given in Plate 6, compare the *relative change* in soil colour that has occurred. As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.

Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not so easily and accurately assessed; in general, the darker the colour, the greater the amount of organic matter and humus in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, collectively determining soil health. It promotes infiltration, the movement and retention of water, helps develop and stabilise soil structure, cushions the impact of wheel traffic and cultivators, reduces the potential for wind and water erosion, and indicates whether

PLATE 5 Soil colour under the fenceline



Soil colour under the fenceline on the left compared with that in the field on the right. The comparative difference in soil structure and porosity is also a useful observation to make.

PLATE 6 Visual scoring (VS) of soil colour



GOOD CONDITION VS = 2

Dark coloured topsoil that is similar to, or darker than that under the fenceline.



MODERATE CONDITION VS = 1

The colour of the topsoil is somewhat paler than under the fenceline, but not markedly so.



POOR CONDITION VS = 0

Soil colour has become significantly paler compared with under the fenceline.

the soil is functioning as a carbon 'sink' or as a source of greenhouse gases. Organic matter acts as a major reservoir of organic carbon in the soil, carbon that is sequestered by microorganisms and from CO₂ in the atmosphere by plants. Organic matter also provides an important food resource for soil organisms and is an important source and major reservoir of plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; nitrogen, phosphorus, potassium and sulphur requirements of crops increase markedly, and other major and minor elements are more readily leached. The result is an increased dependency on fertiliser input to maintain nutrient status.

Soil colour (compared with that under the fenceline) can be a useful indicator of whether soils on a farm or in a field are becoming darker due to gaining (sequestering) carbon. If the soil is paler, it could possibly be losing carbon, i.e. becoming C negative. If there is no colour difference, the soil carbon regime may be in a steady (C neutral) state, i.e. neither losing nor gaining carbon. Soil colour, along with soil texture, clay mineralogy, earthworm numbers, root development, potential rooting depth, the amount and form of fertiliser applied, and the method of cultivation can collectively provide a good indication as to whether a particular management practice or landuse is carbon positive, neutral or negative. A farm that has similar or darker coloured topsoils in the field relative to the fenceline, with fine silty or clayey textures, good earthworm numbers, root development, potential rooting depth, crop yields, and is applying no-till technology and carbon-friendly forms of fertiliser and nitrogen will sequester significant amounts of carbon (see carbon sequestration, pp. 72–79). Farms will therefore be C positive and in a position to potentially gain 'Carbon Credits' rather than possibly pay a carbon tax.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is markedly influenced by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidised form of ferric (Fe³⁺) and manganic (Mn³⁺) oxides. Grey or grey-blue colours can indicate the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that reduce Fe and Mn to ferrous (Fe²⁺) and manganous (Mn²⁺) oxides. Ferrous and manganous oxides are more soluble than their oxidised forms and are therefore more readily taken up by the plant. High levels of soluble Fe and Mn in the soil can however suppress the availability and uptake of other elements.

In addition to the production of toxic levels of Fe²⁺ and Mn²⁺ ions, poor aeration and waterlogging, gives rise to a further series of chemical and biochemical reduction reactions that produce toxins such as hydrogen sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde that damage the root system. This, and the effect of waterlogging, reduces the ability of plants to take up water and nutrients (particularly

N, P, K, S, Zn, Cu and Co), causing poor crop growth and vigour. Decay and die-back of roots can also occur as a result of pests and diseases including *Rhizoctonia*, *Pythium* and *Fusarium* root rot in soils prone to waterlogging. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, crops typically struggle to take up nutrients such as Na that are necessary to make carbohydrates, and K required for complete kernel filling.

What is more, soil colour can indicate the potential of a soil to convert plant-available forms of nutrients into unavailable forms. Soils that are distinctly grey in colour due to being anaerobic and waterlogged reduce plant-available N in the form of nitrate (NO_3^-) and ammonium (NH_4^+) to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available S in the form of sulphate-sulphur (SO_4^{2-} -S) is reduced to plant unavailable sulphite (SO_3^{2-}) and sulphides. Sulphur and nitrogen can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Plants also need S in the sulphate form to utilise N.

Dark coloured soils further suggest that the microbial biomass is predominantly aerobic enabling the efficient decomposition of organic matter to humus and the retention, immobilisation and release of soil nutrients.

Assessment

- Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 2, p. 5 & Plate 7). Note also the number of species present (Plates 8–10) and compare with the criteria given in Table 2. Earthworms vary in size and number depending on the species, maturity, and the season. For year-to-year comparisons, therefore, earthworm counts must be made at the same time of year (preferably late winter to early spring), and when soil moisture and temperature levels are good; avoid dry conditions. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. As a 200-mm cube sample is equivalent to 1/25 square metre, the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.

Importance

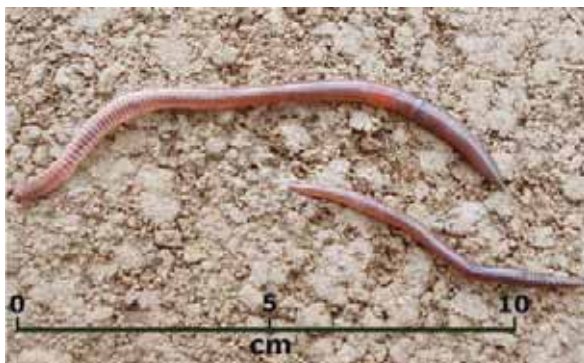
EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digesting, and casting, earthworms have a major effect on the chemical, physical, and biological properties of the soil; they shred and decompose plant residue converting it to organic matter and releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg. They can also contain more Ca and plant-available Mo,

and have a higher pH, organic matter, and water content. In addition, dead earthworms can contribute significant amounts of N to the soil, being 60–70 percent protein (dry weight) with a N content of 12 percent. Thirty-five earthworms per 200-mm cube of soil (875/m²) are roughly equivalent to a biomass of 3 tonnes of earthworm/ha, and could release 32–38 kg N/ha upon their death. Earthworms also act as biological aerators and physical conditioners of the soil, improving soil porosity, aeration, soil structure, soil aggregate stability, water retention, water infiltration, and drainage, and reducing surface runoff and erosion.

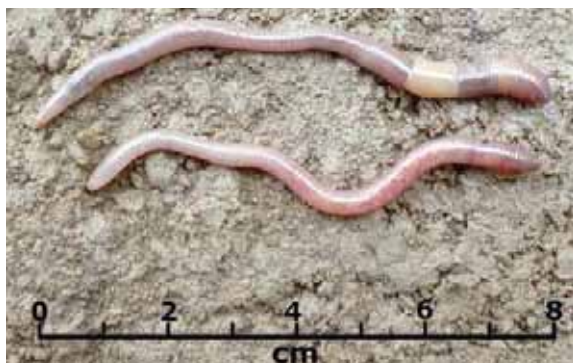
PLATE 7 Sample for assessing earthworms



Photo shows earthworms present in a 200-mm cube sample of soil.

PLATE 8 *Lumbricus rubellus*

A very active surface litter and dung feeding earthworm; commonly red-brown or red-purple in colour with a paler underside; has a distinctly flattened tail; commonly 25–220 mm long.

PLATE 9 *Aporectodea caliginosa*

A medium-sized (40–90 mm) topsoil dwelling earthworm; commonly grey-pink on both the dorsal and ventral surfaces; does not have a flattened tail.

PLATE 10 *Aporectodea longa*

A long (90–180 mm) deep burrowing earthworm; commonly dark grey-brown with a black head; tail end is paler and slightly flattened. Underside is paler than the dorsal surface.

TABLE 2 Visual scores (VS) for earthworms

Visual score (VS)	Earthworm numbers (per 200 mm cube of soil)
2 [Good]	35 (with preferably 3 or more species)
1.5 [Moderately good]	29–35
1 [Moderate]	22–28 (with preferably 2 or more species)
0.5 [Moderately poor]	15–21
0 [Poor]	< 15 (with predominantly 1 species)

They promote plant growth by secreting plant-growth hormones and increasing root development and root density through the rapid growth of roots down nutrient enriched worm channels. While earthworms can deposit around 25–30 tonnes of casts/ha/yr on the surface (Plate 11), 70 percent of their casts are deposited below the surface of the soil. Earthworms therefore play an important role in arable cropping and can increase growth rates, crop yields and protein levels significantly.

Earthworms also increase the population, activity and diversity of soil microbes. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus. Soil microbes such as mycorrhizal fungi play a further role in the supply of nutrients, digesting soil and fertiliser and unlocking nutrients such as P that are fixed by the soil. Microbes also retain significant amounts of nutrients in their biomass, releasing them when they die. Moreover, soil microbes produce plant growth hormones and compounds that stimulate root growth, and promote the structure, aeration, infiltration, and water-holding capacity of the soil. Microorganisms further encourage a lower incidence of pests and diseases, and promote a more rapid breakdown of organic herbicides. The collective benefits of microbes can increase crop production markedly while at the same time reducing fertiliser requirements.

Earthworms can increase the depth of topsoil and the carbon content of both topsoil and subsoil by their burrowing, digesting, reworking, and mixing of soil and plant residues (bioturbation), and by the deposition of worm casts. High numbers of earthworms ingest considerable amounts of soil and plant material, building up soil C levels by converting C to more stable organic compounds bonded to clay particles. Organic matter gradually works down to the subsoil and so increases the depth of topsoil. The burrowing, casting, and

incorporation of organic matter into the soil contributes to increasing topsoil depth by decreasing soil density and increasing the porosity, and therefore the volume of soil. Given that 30 percent of worm casts are deposited on the surface and 70 percent below ground, the potential for earthworms to increase soil carbon levels and topsoil depth is substantial.

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by the crops grown, the amount and quality of surface residues, the use of cover crops and the method of tillage. Earthworm populations can be up to three times higher under no-tillage than conventional cultivation. Earthworm numbers are also governed by soil moisture, temperature, texture, soil aeration, pH, soil nutrients (including levels of Ca), and the type and amount of fertiliser and nitrogen used. The over-use of acidifying salt-based fertilisers, anhydrous ammonia, and ammonia-based products, and some insecticides and fungicides can further reduce earthworm numbers.

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown and decompose plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest, and mix the top 200–300 mm of soil; and (iii) deep burrowing species that pull down and mix plant litter and organic matter at depth. Earthworm species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 12) can indicate adverse soil conditions.

PLATE 11 Earthworm casts under crop residue



PLATE 12 Yellow-tail earthworm (*Octolasion cyaneum*)



Assessment

- 1 Remove a spade slice of soil (approximately 100 mm wide × 100 mm long × 100 mm deep) and break in half. Place the exposed face of the soil close to your nose, take three deep sniffs, and compare with the criteria given in Table 3. Soil smell can be assessed on the same sample used to assess soil porosity. The test is best carried out when the soil is moist, including during or immediately after the wet months of the year.

Importance

SOIL SMELL, while very dependent on the water content and aeration status of the soil, is also a good indicator of the amount and the activity of soil life and therefore soil health. Soil smell is determined principally by the gases given off by the aerobic or anaerobic respiration of soil microbes, and by the type and amount of organic matter and humus present in the soil. Aerobic respiration by soil fungi, bacteria, yeast, protozoa (i.e. single cell animals), nematodes, arthropods (mites, beetles, millipedes, etc.), and earthworms produce distinctive odours. The degree and nature of the odours are determined by the composition and activity of the soil biology which in turn is governed in part by the available food supply in the form of organic matter and humus. Soils rich in fungi, for example, produce aromatic compounds and organic acids that give an earthy, rich, sweet, fresh or sometimes musty smell (Plate 14). These are often the characteristic smells of forest soils, which are generally rich in fungi. The presence of similar fungal smells in a cropping soil suggests it is not only well aerated but also has a good, active microbial biomass with a fungal to bacteria ratio of 3:1. Such a ratio is necessary to preserve and promote a good biological environment for crops. Intensively cropped and fertilised soils have a greater abundance of bacteria relative to fungi than soils that are less intensively cropped and fertilised. As a consequence, they are more sensitive to plant stress, are less efficient in terms of uptake, cycling and retention of nutrients including N, and are more susceptible to N leaching. An imbalance of the ratio of fungi to bacteria, along with poor soil nutrition could explain why crops may show consistently poor growth and vigour.

TABLE 3 **How to assess soil smell**

Visual score (VS)	Soil smell
2 [Good]	Soil has a distinct rich, earthy, sweet, wholesome or fresh smell.
1 [Moderate]	Soil has a slight earthy, sweet odour or a “mineral” smell.
0 [Poor]	Soil has a putrid, sour, chemical or unpleasant smell.

Biological regimes are very sensitive to intensive conventional cultivation practices with the result that well aerated soils can have very little or no soil smell. Anaerobic respiration of micro-organisms (including anaerobic bacteria and yeast) in saturated, poorly aerated soils produce methane and nitrous oxide (greenhouse gases), alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, and putrid sulphide gases including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS), all of which inhibit root growth when accumulated in the soil (Plate 15). Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root /shoot growth.

PLATE 13 Sample to assess soil smell



While soils should have good microbial biomass with levels preferably in excess of 1 600 mg/kg, to be beneficial, soil microbes also need to be active. The level of activity and therefore functionality of the microbial biomass is something that must always be kept in mind when assessing the status of the soil biological community. The activity and energy status of soil microbes can be assessed by measuring the level of their respiration relative to their biomass (i.e. the respiration to biomass ratio or the metabolic quotient qCO_2), and their AEC, which should be 0.8. Microbial viability is maintained at AEC values between 0.8 and 0.5 – the cells die at values below 0.5.

Soil microbes, including actinomycetes and mycorrhizal fungi, play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important organic compound that comprises up to 30 percent of the humus fraction in soils. Soil organisms also play a key role in the promotion and maintenance of soil fertility through nutrient and carbon cycling, and their role in the N and S cycle. Microbes immobilise and retain significant amounts of nutrients in the humus they produce and in their biomass, releasing them when they die. Moreover, soil microbes, including mycorrhizal fungi, play a major role in the supply of plant-available nutrients, digesting soil and fertiliser, and unlocking nutrients such as phosphorus that are fixed by the soil.

Where legumes are cropped, soil microbes and particularly bacteria also play a major role in the fixation and supply of nitrogen. *Rhizobium* bacteria in clover nodules fix N directly from the atmosphere. The ammonia produced by N-fixation is taken up by the plant to produce protein and organic N compounds that are then mineralised by a further range of bacteria and fungi, releasing N in the form of plant available ammonium (NH_4^+) when the plant dies. Under aerobic conditions, the ammonium is converted by nitrosomonas and nitrobacter bacteria to nitrate (NO_3^-), another plant available form of N (a process known as nitrification). Free-living aerobic *Azotobacter* bacteria and anaerobic (*Clostridium*) bacteria in the soil further promote the fixation and supply of plant available N.

In addition, bacterial- and fungal-feeding protozoa and nematodes release large amounts of N when feeding on their selected prey and are responsible for a large amount of plant-available N. The predator-prey interaction of protozoa on bacteria releases 5 units of plant-available N in the form of ammonium for every six bacteria consumed. The feeding of nematodes on bacteria releases 19 units of N for every 20 bacteria consumed. Given that bacterial numbers should be greater than one million per gram for all agricultural soils, and nearer 100 million per gram for productive soils, the potential storage and release of N from bacteria is considerable. Between 40 and 80 percent of the N in plants can come from the predator-prey interaction of protozoa with bacteria.

In addition to adding organic matter to the soil, soil organisms play a key role in soil formation by developing and promoting the structure, aggregate stability, porosity, aeration, infiltration and water-holding capacity of the soil, and reduce waterlogging and runoff from the topsoil. Soil microbes also play an important role in purifying water and filter, buffer, degrade, immobilise, and detoxify organic and inorganic pollutants. Moreover,

PLATE 14 Sample of a moderately good soil smell



Soil has a moderately rich, earthy, sweet smell with a smell score of 1.5.

PLATE 15 Sample of a poor soil smell



Soil has a putrid, unpleasant smell of hydrogen sulphide with a smell score of 0.

they suppress pests and diseases, producing compounds that inhibit the growth of, or are toxic to pathogens, reducing the invasion of the plant by a pathogen. Soil microbes further produce plant growth hormones and compounds that stimulate root growth and produce B group vitamins including vitamin B₁₂.

The collective benefits of microbes reduce fertiliser requirements and can give significant increases in crop yield. They can also significantly improve the nutrient density and health of the plant. Soil life can therefore be effectively described as the 'engine room' of the farm. The trick to smart and sustainable cropping is to ensure the engine remains well-oiled.



Assessment

- Assess the potential rooting depth by digging a hole to identify the depth to a limiting (restricting) layer if present (Plate 16), and compare with the class limits in the Table 4. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks, and fissures down which roots can extend. Note also whether there is an overthickening of roots (a result of a high penetration resistance), and whether the roots are forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed due to prolonged waterlogging, and whether there is a hard pan present such as a strongly developed human-induced tillage or plough pan (pp. 24–25), or a strongly developed natural pan such as an iron, silica or calcitic pan. An abrupt transition from a fine textured material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.



Importance

POTENTIAL ROOTING DEPTH is the depth of soil plant roots can potentially exploit before reaching a barrier to root growth, and indicates the ability of the soil to provide a suitable rooting medium for plants. The greater the rooting depth, the greater is the available water-holding capacity of the soil. In drought periods, deep roots can access larger water reserves, thereby alleviating water stress and promoting the survival of non-irrigated crops. The exploration of a large volume of soil by deep roots means that they can also access more macronutrients and micronutrients, thereby accelerating the growth and enhancing the yield and quality of the crop. Conversely, soils with a restricted rooting depth caused by, for example, a layer with a high penetration resistance such as a compacted layer or a hardpan, restrict vertical root growth and development, causing roots to grow sideways. This limits plant uptake of water and nutrients, reduces fertiliser efficiency, increases leaching, and decreases yield. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hard pans impede the movement of air, oxygen and water through the soil profile, the latter increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- ✦ an abrupt textural change;
- ✦ pH;
- ✦ aluminium (Al) toxicity;
- ✦ nutrient deficiencies;
- ✦ salinity;
- ✦ sodicity;
- ✦ a high or fluctuating water table;
- ✦ low oxygen levels.

Anaerobic (anoxic) conditions caused by deoxygenation and prolonged waterlogging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions.

Crops with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth. The physical action of the roots and soil fauna and the glues they produce, promotes soil structure, porosity, water storage, soil aeration, and drainage at depth. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be taken up, so reducing losses by leaching into the environment.

PLATE 16 Potential rooting depth



Hole dug to assess the potential rooting depth. The potential rooting depth extends to the base of the arrow at 350 mm below which the soil is extremely firm and very tight with no roots or old root channels, no worm channels, and no cracks and fissures down which roots can extend. Note the root mat at the bottom of the arrow. Compare the potential rooting depth of this soil with that in Plate 53, p.91

TABLE 4 Visual scoring (VS) of potential rooting depth

VSA score (VS)	Potential rooting depth (mm)
2.0 [Good]	800
1.5 [Moderately good]	600–800
1.0 [Moderate]	400–600
0.5 [Moderately poor]	200–400
0 [Poor]	< 200

Identifying the presence of a hardpan

Assessment

- 1 Examine for the presence of a hard pan such as a strongly developed tillage or plough pan by rapidly jabbing the side of the soil profile (dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically to the bottom of the hole (Plate 17). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (see photos below).
- 2 Having identified the possible presence of a tillage or plough pan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the pan is. A strongly developed pan is very tight and extremely firm and has a high penetration resistance to the knife. Confirm also its presence or absence by removing a large, hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (by referring back to pp. 4, 6 and 8). In addition, look for the presence or absence of roots. Compare with the photos and criteria given in Plate 18. Only a strongly developed hardpan will restrict all root development and its presence will determine the potential rooting depth.

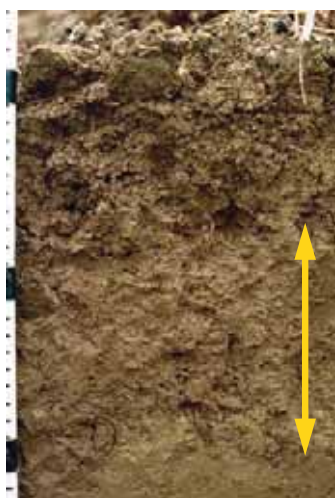
PLATE 17 Identifying the presence or absence of a hardpan with a knife



PLATE 18 Visual assessment of a hard pan

**NO HARDPAN**

The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5 .

**MODERATELY DEVELOPED HARDPAN**

The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

**STRONGLY DEVELOPED HARDPAN**

The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).

Assessment

- 1 Assess the degree of surface ponding based on your observation or general recollection of the time ponded water takes to disappear after a wet period, particularly during early growth, and compare with the photographs and criteria given in Plate 19.

Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the infiltration rate into and through the soil, a high water table, and the time the soil remains saturated. Roots need oxygen for respiration, and prolonged waterlogging depletes oxygen in the soil causing anaerobic (anoxic) conditions that induce root stress and restrict root respiration and growth. Roots are most vulnerable to surface ponding and saturated soil conditions in the spring when respiration and transpiration rates rise markedly, oxygen demands are high, and plant roots and shoots are actively growing. Such waterlogging causes the death of the fine roots responsible for nutrient and water uptake. Roots are also susceptible to ponding in the summer when transpiration rates are highest – reduced water uptake while the crop is actively transpiring causes leaf desiccation and the wilting of plants.

Prolonged waterlogging increases the likelihood of pests and diseases, including *Rhizoctonia*, *Pythium* and *Fusarium* root rot, and reduces the ability of roots to overcome the harmful effects of topsoil-resident pathogens. Plant stress induced by poor aeration and prolonged soil saturation can render crops less resistant to attack from such insect pests as aphids, armyworm, cutworm, and wireworm. Crops decline in vigour, have restricted spring growth (RSG) as evidenced by poor shoot and stunted growth, become discoloured, and die.

Waterlogging and deoxygenation also result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are either toxic to roots or are in a form that is unable to be taken up by the plant, e.g.:

- ✦ iron is reduced to soluble ferrous (Fe^{2+}) ions and Mn to manganous (Mn^{2+}) ions;
- ✦ plant-available nitrate-nitrogen (NO_3^- -N) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas;
- ✦ plant-available sulphate-sulphur (SO_4^{2-} -S) is reduced to unavailable sulphite (SO_3^{2-}) and sulphides, including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS).

Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form.

PLATE 19 Visual scoring (VS) of surface ponding

**GOOD CONDITION VS = 2**

No surface ponding of water evident after 1 day following heavy rainfall on soils that were at or near saturation¹.

**MODERATE CONDITION VS = 1**

Moderate surface ponding occurs for 2 days after heavy rainfall on soils that were at or near saturation.

**POOR CONDITION VS = 0**

Significant surface ponding occurs for 4 or more days after heavy rainfall on soils that were at or near saturation.

¹ Assuming little or no air is trapped in the soil at the time of ponding.

PLATE 20 Sample of prolonged waterlogging



Prolonged waterlogging can severely damage a crop in the early stages of growth.

In addition to N and S, waterlogging and poor aeration reduces the availability and uptake of P, K, Zn, Cu, and Co. This is partly because prolonged ponding of water kills off mycorrhizal fungi, soil organisms that facilitate the efficient uptake and utilisation of soil nutrients. While Olsen P levels of 22 mg/L are generally adequate for optimum crop production on most soils in good condition, degraded, poorly aerated soils with relatively high Olsen P levels (40–50 mg/L) can show a positive crop response to applied P. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots.

Anaerobic respiration of micro-organisms in waterlogged and poorly aerated soils produces methane (greenhouse gases), hydrogen gas, alcohol (ethanol and ethylene), acetaldehyde, and formaldehyde, all of which inhibit root growth when accumulated in the soil. As a result, crops often show poor vigour and ill-thrift. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The by-products of anaerobic respiration and the lack of oxygen in poorly aerated and waterlogged soils also prevent the decay of organic material in the soil. As the soil becomes progressively degraded, the amount of CO₂ increases relative to O₂ and reaches a point where plant residues and kernels cannot decay; instead they begin to ferment, producing alcohol, formaldehydes and methane, which make proper decay and the turnover of organic matter impossible.

Prolonged surface ponding makes the soil more susceptible to damage under wheel traffic, which reduces trafficability and vehicle access. Waterlogging can expose soils to severe wheel rutting and soil structural damage during pre-plant and side-dressing of fertiliser. It can also cause structural damage at sowing and harvesting, and result in significant delays to the timing of these activities. In addition, surface ponding reduces the workability of the soil, decreasing the number of spring-field work-days when the soil is suitable for cultivation. As a consequence, waterlogging can delay ground preparation. Sowing can be further delayed because the seedbed is below the crop-specific critical temperature. Increases in the temperature of saturated soils can be delayed as long as water is evaporating.

Waterlogged topsoils on sloping ground are also prone to erosion by sheetwash and rilling. Soils susceptible to surface ponding therefore need to be carefully managed to minimise the effects of such ponding on soil, crop yield and quality, and the environment.

The tolerance of the root system to surface ponding and waterlogging depends on a number of factors, including the time of year and the cultivar. Tolerance of waterlogging also depends on soil and air temperatures, soil type and condition, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and oxygen consumption rate.



Assessment

- 1 Observe the degree of surface cover and surface crusting and compare with the photographs and criteria given in Plate 21. Surface crusting is best assessed after wet spells followed by a period of drying, and before cultivation.



Importance

SURFACE CRUSTING reduces infiltration of water and water storage in the soil and increases runoff. It also reduces aeration, causing anaerobic conditions by creating a barrier to gas exchange. Crusting cuts off oxygen to soil organisms and prevents the release of CO₂ from the soil to the plant canopy, thus reducing the uptake of photosynthetic CO₂ by the stomata on the crop leaf. The reduced availability of both water and CO₂ significantly limits crop yield. Crusting also prolongs water retention near the surface, which can hamper access by machinery for months. In addition, crusting can inhibit or deform cotyledon emergence. Crusting is most pronounced in fine-textured, poorly structured soils with low organic matter, low aggregate stability, high levels of Na and/or Mg and a dispersive clay mineralogy.

SURFACE COVER after harvesting and before canopy closure of the next crop helps prevent crusting by minimising the dispersion of the soil surface by rain or irrigation. It also helps reduce crusting by intercepting the large rain droplets before they strike and compact the soil surface. In addition, vegetative cover and its root system, together with surface residue, return organic matter to the soil and promote soil life. Earthworm and microbial biomass are strongly correlated to the amount of surface residue present: the greater the surface residue, the greater the biomass of earthworms and soil microbes. Earthworm biomass can be 80 percent of the weight of surface residue. The physical action of the roots and soil fauna, and the glues they produce, promote the development of soil structure, aeration and drainage, and help break up surface crusting. As a result, infiltration rates and the movement of water through the soil increase, which decrease runoff, soil erosion and the risk of flash flooding. The root system also reduces soil erosion by stabilising the soil surface, holding the soil in place during heavy rainfall events. Surface cover reduces soil erosion by intercepting high impact raindrops, thus minimising rain-splash and saltation, and serves as a sponge, retaining rainwater long enough for it to infiltrate the soil. Water storage for plant use thus increases, and water quality downstream is improved through lower sediment loading, and nutrient and coliform content.

The adoption of conservation tillage practices with good surface cover can reduce soil erosion by up to 90 percent and water runoff by up to 40 percent. The surface needs to have at least 70 percent cover to give good protection while \leq 30 percent cover provides poor protection. In addition, surface cover markedly reduces the risk of wind erosion by protecting the soil surface. The practice of 'pasture cropping' where annual crops are direct-drilled into perennial pastures was developed in part to utilise the benefits of maintaining a good surface cover.

PLATE 21 Visual scoring (VS) of surface cover and surface crusting



GOOD CONDITION VS = 2
 Surface cover is ≥ 70 percent with little or no surface crusting.

MODERATE CONDITION VS = 1
 Surface cover is ≥ 30 percent and < 70 percent.
 Surface crusting is 2–3 mm thick and is broken by significant cracking.

POOR CONDITION VS = 0
 Surface cover is ≤ 30 percent.
 Surface crusting is ≥ 5 mm thick and is virtually continuous with little cracking.

Surface cover photos: courtesy of A. Leys



Assessment

- 1 Assess the degree of soil erosion based on current visual evidence and on your knowledge of what the site looked like in the past relative to the three photographs and criteria given Plate 22.



Importance

SOIL EROSION reduces the productive potential of soils through nutrient losses, loss of organic matter, reduced potential rooting depth, and lower available-water-holding capacity. Soil erosion can also have significant off-site effects, including reduced water quality through increased sediment, nutrient and coliform loading in streams and rivers.

Over-cultivation can cause considerable soil degradation associated with the loss of soil organic matter and soil structure. It can also develop surface crusting, tillage pans, and decrease infiltration and permeability of water through the soil profile (causing increased surface runoff). If the soil surface is left unprotected on sloping ground, large quantities of soil can be water eroded by gullying, rilling and sheet wash. The cost of restoration, often requiring heavy machinery, can be prohibitively expensive.

The water erodibility of soil on sloping ground is governed by a number of factors including:

- ✦ the percentage of vegetative cover on the soil surface;
- ✦ the amount and intensity of rainfall;
- ✦ the soil infiltration rate and permeability of water through the soil;
- ✦ the slope and the nature of the underlying subsoil strata and bedrock.

The loss of organic matter and soil structure as a result of over-cultivation can also give rise to significant soil loss by wind erosion of exposed ground.

PLATE 22 Visual scoring (VS) of soil erosion

**GOOD CONDITION VS = 2**

Little or no *water erosion*. Topsoil depths in the footslope areas are < 150 mm deeper than on crest.

Wind erosion is not a concern; only small dust plumes emanate from the cultivator on a windy day. Most wind-eroded material is contained in the field.

**MODERATE CONDITION VS = 1**

Water erosion is a moderate concern with a significant amount of rilling and sheet erosion. Topsoil depths in the footslope areas are 150–300 mm greater than on crests, and sediment input into drains/streams may be significant.

Wind erosion is of moderate concern where significant dust plumes can emanate from the cultivator on windy days. A considerable amount of material is blown off the field but is contained within the farm.

**POOR CONDITION VS = 0**

Water erosion is a major concern with severe gully, rilling and sheet erosion occurring. Topsoils in footslope areas are more than 300 mm deeper than on the crests, and sediment input into drains/streams may be high.

Wind erosion is a major concern. Large dust clouds can occur when cultivating on windy days. A substantial amount of topsoil can be lost from the field and deposited elsewhere in the district.

FIGURE 3 Plant scorecard – visual indicators to assess plant performance in maize

Visual indicators of plant performance	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Crop establishment pg. 36		x 3	
Crop height at maturity pg. 38		x 3	
Leaf colour pg. 40		x 3	
Variability of crop performance along the row pg. 44		x 3	
Root development pg. 46		x 3	
Root diseases pg. 48		x 2	
Weeds pg. 50		x 2	
Ear size pg. 54		x 3	
Crop yield pg. 58		x 3	
Production costs pg. 60		x 1	
PLANT QUALITY INDEX (sum of VS rankings)			

Plant Quality Assessment	Plant Quality Index
Poor	< 20
Moderate	20–37
Good	> 37

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:



Assessment

- 1 Assess the degree and uniformity of crop establishment within a month of sowing by comparing the number and height of established plants with the three photographs and criteria in Plate 23. In making the assessment, consideration must be given to the possible influence of disease, insect attack, poor seed viability, residual herbicides, surface scouring by water erosion, and grazing by ducks, hares, rabbits, etc.



Importance

GOOD SEED GERMINATION, PLANT EMERGENCE AND CROP ESTABLISHMENT depend on factors that include the quality of soil tilth at the time of sowing and during the weeks immediately following. Soils that have poor structure through compaction and over-cultivation can resettle and consolidate rapidly after the seed bed has been prepared. Impeded water and air movement through the soil can give rise to small areas low in oxygen (anaerobic zones). These produce chemical and biochemical reduction reactions, the by-products of which are toxic to plants. These anaerobic zones and poor soil aeration reduce seed germination and plant emergence. As a result, bare patches and poor and uneven early growth are commonly observed throughout paddocks that have poor soil structure. Young plants can also show discolouration of leaves and moisture stress.

The loss of soil structure can reduce crop establishment of barley from 315 to 130 plants/m² and grain yields from 6.7 to 3.9 tonnes per hectare. Seedling mortality of winter cereals can be high if the soil is waterlogged for more than 3–4 days between germination and emergence. Corn germination also slows, and plant populations decrease. Maize plants can decrease from approximately 100 000/ha to 60 000–80 000/ha.

PLATE 23 Visual scoring (VS) of crop establishment

**GOOD CONDITION VS = 2**

Good crop establishment, with few gaps along the row. Crop showing a good, even height.

**MODERATE CONDITION VS = 1**

Moderate crop establishment, with a significant number of gaps along the row and a significant variation in seedling height. Emergence may also be moderately slow but recovers somewhat.

**POOR CONDITION VS = 0**

Poor crop establishment, with a large number of gaps along the row and a large variation in seedling height. Emergence may also be slow with limited recovery.



Assessment

- 1 Measure crop height when the crop has reached maturity and compare with the three photographs and criteria in Plate 24. Your observations of crop growth and vigour during the growing season may also provide a useful indication of seedbed condition. In a good season, under non-limiting conditions, a cultivar should grow to a particular height, with about a 10–15 percent variation. Allowances should be made for exceptionally good seasons and for poor seasons.



Importance

CROP HEIGHT AT MATURITY, while dependent on climatic factors, the cultivar, soil fertility and time of sowing, can be a useful visual indicator of soil quality and plant performance. Crop height is particularly useful if agronomic factors have not limited crop emergence and development during the growing season. The growth and vigour of crops depend in part on the ability of the seedbed to maintain an adequate soil tilth throughout the growing season. Poor soil aeration and resistance to root penetration as a result of structural degradation reduce plant growth and vigour, and delay maturity.

PLATE 24 Visual scoring (VS) of crop height at maturity

**GOOD CONDITION VS = 2**

Crops are at or near maximum height at crop maturity. Maize crops, for example, are generally between 2.3 and 2.7 m at maturity.

**MODERATE CONDITION VS = 1**

Crop heights are significantly below maximum at crop maturity. Crop height for maize, for example, is generally between 1.8 and 2.2 m at maturity.

**POOR CONDITION VS = 0**

Crop heights are well below maximum height at crop maturity. Crop height for maize, for example, is generally between 1.2 and 1.7 m at maturity (chest height).

Assessment

- Note the leaf colour of the crop when all other factors favour rapid growth, and compare with the three photographs and criteria in Plate 25. In making the assessment, consideration must be given to the cultivar, the stage of growth, the soil moisture and temperature conditions, and the presence of pests and diseases (e.g., nematodes). The best time to carry out the assessment is 4–6 weeks after plant emergence, avoiding very cold and wet weather.

Importance

LEAF COLOUR can provide a good indication of the nutrient status and condition of the soil and the crop. The colour of the foliar and blemishes on the leaf are dependent on a number of factors including a deficiency or excess of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B). Chlorosis (or yellowing of crops) due to the loss or inadequate formation of chlorophyll, commonly occurs as a result of low N, S, Mg, Fe, Mn, Cu and Zn levels in the soil, low soil and air temperatures, prolonged cloudy days and poor soil aeration due to compaction and waterlogging.

A deficiency in N and S is a common cause of the yellowing of leaves. Sulphur and N can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form. If the soil is, or becomes poorly aerated and waterlogged, plant-available forms of N and S reduce to plant unavailable forms as discussed on pp. 6, 13 and 26. Soils therefore need to be adequately aerated to enable N and S to remain in a plant available form thereby enabling maximum uptake and utilisation of the N and S present. Plants can also only utilize N if S is present in the oxygenated sulphate form. Put simply, poorly aerated and waterlogging soils reduce the amount of plant-available N and S (and Zn).

The frequent and excessive application of N (especially during dry conditions) and certain types of fertilisers and pesticides to crops can adversely affect the biological regime and nitrogen cycle of the soil, and also suppress the supply and utilisation of other elements. As a result, crops can become dependent on an additional 'fix' of nitrogen or fertiliser to stimulate the colour of the crop and growth. In other words, the engine room of the soil, as discussed on p. 21, has become rusty and no longer has the 'horse power' to produce the yield required without the significant addition of N and fertiliser.

In addition to a yellowing of the crop, discolorations or blemishes on the leaf can also indicate mineral deficiencies (Plates 26–31). Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of S, Zn and Cu, while high S levels can suppress the uptake of P and Mg. Excess N can strip Ca from the soil, block Mn, Zn, B and Cu uptake, and cause the plant to luxury feed on K, which in turn can also tie up Mn and B, and suppress the utilisation of Ca and Mg by the animal.

PLATE 25 Visual scoring (VS) of leaf colour

**GOOD CONDITION VS = 2**

Leaf colour is uniformly deep green. The odd colour blemish on leaves may be apparent within a broad area.

**MODERATE CONDITION VS = 1**

Leaf colour is yellowish green; i.e. has a distinct yellowish tinge. Few colour blemishes on leaves may occur within a wide area.

**POOR CONDITION VS = 0**

Leaf colour is quite yellow over a wide area. Colour blemishes on leaves may commonly occur.

PLATE 26–28 Common symptoms of leaf discolouration due to nutrient deficiencies in maize



26. Phosphorus deficiency – purpling of leaves.



27. Nitrogen deficiency on left.



28. Potassium deficiency.

PLATE 29-31 Common symptoms of leaf discolouration due to nutrient deficiencies in maize



29. Sulphur deficiency on the right.



30. Magnesium deficiency.
Red and purple tints on leaves with
interveinal chlorosis and necrosis.



31. Zinc deficiency.

Assessment

- 1 Cast your eye along the row at crop maturity and observe any variability in crop performance in terms of crop height, stem numbers, stem thickness, leaf colour, leaf density etc. (Plates 32–35), and compare with the class limits in Table 5. In making the assessment, consideration must also be given to other factors that may affect the performance of a crop, such as pest and disease attacks that are not related to the condition of the soil.

Importance

VARIABILITY OF CROP PERFORMANCE ALONG THE ROW can be a good visual indicator of the condition of the soil. In particular, the linear variability in crop performance can be strongly related to the availability of water and nutrients, and the texture of the soil (e.g., whether clayey, silty, loamy or sandy). Also, soils in good condition with good structure and porosity, and a deep, well-aerated root zone enable the unrestricted movement of air and water into and through the soil, the development and proliferation of superficial (feeder) roots, and unrestricted respiration and transpiration. Furthermore, soils with good organic matter levels and soil life show an active biological and chemical process, favouring the release and uptake of water and nutrients and consequently the growth and vigour of the crop.

The spatial variability of crop performance along the row is also a useful indicator because it highlights those areas of the field that are under-performing, thus enabling a specific investigation as to why and what remedial action may be taken.

PLATE 32 Variable crop performance due to differences in rooting depth to an iron pan



Variable crop performance due to differences in rooting depth to an iron pan.

PLATE 33 Variable crop performance due to soil compaction



Variable crop performance due to soil compaction.

PLATE 34 Variable crop performance due to differences in soil aeration and soil wetness



Variable crop performance due to differences in soil aeration and soil wetness.

PLATE 35 Variable crop performance due to differences in the degree of water repellency



Variable crop performance due to differences in the degree of water repellency (i.e. hydrophobicity).

TABLE 5 Visual scoring (VS) of variability of crop performance along the row

Visual score (VS)	Variability of crop performance along the row
2 [Good]	Crop performance is good and even along the rows
1 [Moderate]	Crop performance is moderately variable along the rows
0 [Poor]	Crop performance is extremely variable along the rows



Assessment

- 1 Determine the size and development of the root system by carefully prising the plant out of the soil with a spade and gently shaking it or tapping the sample against the edge of the hole to remove adhering soil from the roots. Use the point of a knife to help loosen the soil if required. Assess both the length and the density of the roots and compare against the three photographs and criteria in Plate 36. Root length and root density is best assessed at or just before crop maturity.



Importance

ROOT LENGTH AND ROOT DENSITY provide a good indications of the development of the plant root system. Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared to crops with a shallow, thin root system. Shoot and leaf growth, kernel development and grain filling is therefore likely to be greater, crops are less likely to suffer windthrow, and they will be less susceptible to drought stress. Crops with a dense, deep, vigorous root system will also add (sequester) greater amounts of organic matter to the soil and increase the level of soil life. The physical action of the roots and soil fauna, and the glues they produce, further promote the development of soil structure, soil aeration and drainage.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Crops are less reliant on high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up reducing losses by leaching into the groundwater and waterways.

Root length, root density, plant growth and vigour can be restricted by the mechanical impediment of roots and the reduction of soil pores as a result of soil compaction or a hardpan. High mechanical resistance to roots limits plant uptake of water and nutrients, restricts the production of several plant hormones in roots necessary for growth, and increases the susceptibility of the crop to windthrow. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, nutrient deficiencies, the application of excess nitrogen causing lazy plants, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and poor soil aeration. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions (p. 8, 12 and 26).

PLATE 36 Visual scoring (VS) of root development



GOOD CONDITION VS = 2

Unrestricted root development with the main large root bulb up to 250 mm wide and 200–250 mm deep.



MODERATE CONDITION VS = 1

Vertical and lateral root development is moderately restricted with right-angle syndrome not uncommon. The main root bulb is commonly 150 mm wide and 150–180 mm deep.



POOR CONDITION VS = 0

Vertical and lateral root development is severely restricted with root systems showing either stunted growth, right-angle syndrome, over-thickening, or growth down coulter channels.



Assessment

- 1 Assess the presence of root diseases by pulling a number of stems out of the soil and carefully examining the root system for evidence of root diseases at, or any time before, crop maturity (Plates 37–38).
- 2 Consider also how commonly root diseases occur in the field from season to season and make your assessment based on the class limits in Table 6.



Importance

POOR SOIL AERATION, soil saturation and high mechanical resistance to root development due to soil structural degradation can increase root rot and soil-borne pathogens. They can also reduce the ability of the root system to overcome the harmful effects of pathogens resident in the topsoil. Root diseases that commonly occur as a result of the loss of soil quality include take-all (*G. graminis* var. *tritici*), Rhizoctonia crown and brace root rot (*Rhizoctonia solani*), and Pythium root rot (*Pythium* spp.). *Fusarium* spp. root rot can also occur when the plant is stressed because of poor aeration and the inadequate allocation of photosynthate to the roots. The presence of root diseases can cause severe yield loss and reduction in grain quality. Symptoms include pre- and post-emergence plant death in seedlings resulting in crop thinning, stunting and reduced tillering/leaf growth, discolouration of and blemishes (lesions) on stems, tillers and leaves, bleached heads, and premature death. Plants may also lean or lodge because the root system is anchored poorly in the soil. Infected plants have sparse root development and characteristically a brown-black rot can be seen at the crown and extending to the base.

The conservation of soil moisture, amelioration of soil compaction, the build up of organic matter and the promotion of good soil life (in terms of microbial biomass, diversity and activity) are factors that contribute to the development of healthy plants and the suppression of soil-borne diseases. They also help enable the plant to better resist the pressure of disease and insect attack. Soil biota, and especially those micro-organisms that enhance cellulytic breakdown and decomposition of maize/straw residues, further limit pathogen survival.

TABLE 6 **Visual scoring (VS) of root diseases**

Visual score (VS)	Occurrence of root diseases due to soil conditions
2 [Good]	Root diseases are rare
1 [Moderate]	Root diseases are common
0 [Poor]	Root diseases are very common

PLATE 37 **Pythium root rot**



Pythium root rot where the rotted cortex has pulled away from the stele. (White DG, 1999. Compendium of Corn Diseases).

PLATE 38 **Rhizoctonia root rot**



Root rot resulting from rhizoctonia fungal infestation on compacted, poorly aerated soils on the left. Healthy root development on uncompacted, well aerated soils on the right.

 **Assessment**

- 1 Assess the degree of weed infestation by visually estimating the number of weeds between rows before canopy closure. Consider also how often a given level of weed infestation occurs in the paddock from season to season, and at what level it is perceived to be a problem. Make your assessment according to the photos and criteria given in Plate 39 on the basis of what the field would look like without significant weed control measures.

In making the assessment, consider those factors that can contribute to weed infestation including, for example, the introduction of seeds from cultivation and harvesting machinery. The timing of sowing, whether early or late, may also play a significant role. Weeds are often less of a problem if the crop is sown early enough and a good, early canopy cover is established. Warmer climate weeds such as those of summer crops respond directly to temperature and light so they germinate and grow faster in warmer conditions with more light. On the other hand, the growth of cooler climate weeds of both winter and summer cereal crops is independent of temperature and the weeds usually grow best when soil moisture is high. Consider also the use and timing of weed control measures, including shallow inter-row cultivation and pre- and post-emergent herbicide sprays. Weed control measures should be implemented at an early stage when the young weeds are easy to control, i.e. before they get to the seedling stage. In addition, consider whether weeds have become more resistant to a herbicide, and whether the persistence of herbicides is reduced, for example, by their strong absorbance by clayey, allophanic, humic or peaty soils. Soils with a high microbial activity can also give rise to a faster than normal dissipation of herbicides. Herbicides can also degrade quicker if applied at higher temperatures, which renders them less effective. They are also less effective when applied to cloddy than to a fine soil tilth.

 **Importance**

A HIGH WEED population uses a lot of the water and nutrients that would otherwise be available to the crop. Actively growing weeds can also grow over and smother the crop, intercepting light and shading the crop, resulting in suppressed growth and poor crop quality with small, stressed kernels and ears (Plate 40). The rampant growth of tall woody and grass weeds (such as broomcorn millet) interfere with harvesting by contaminating the grain with seed heads and berries (Plate 41). In addition, the extra growth is difficult to pass through the knife rolls, overloading the harvester and damaging the nose cones.

While weeds can occur for a number of reasons, they can be useful indicators of the condition of the soil, including level of compaction, soil aeration and waterlogging, nutrient fertility, pH, the amount and type of organic matter, and the microbial biomass. It is commonly believed healthy soils support weeds and crops equally well. In the same way that insect infestation indicates unhealthy plants with a nutritional imbalance, a weed infestation indicates something is not right with the soil, which is suppressing the growth of crops and providing an environment favouring weeds. Soil structural degradation resulting from over-cultivation, wheel traffic, or soil dispersion due to a low Ca:Mg ratio

PLATE 39 Visual scoring (VS) of weeds

**GOOD CONDITION VS = 2**

Weeds are not common in most seasons and are not considered to be a problem. Inter-rows may be protected by a mulch or short grass.

**MODERATE CONDITION VS = 1**

Weeds are common in most seasons and are a moderate problem.

Photo: Courtesy of Trevor James

**POOR CONDITION VS = 0**

Weeds are extremely common in most seasons and are a serious problem.

Photo: Courtesy of Trevor James

or high Na levels, reduces soil aeration, soil drainage, available water-holding capacity, nutrient uptake, and the rooting potential of the crop, allowing weeds to establish and compete with the crop. Warmer climate weeds also use water more efficiently than the crop itself, and so are very competitive when there is reduced moisture. Lighter soils with a coarser textural class can have more weeds than heavier soils with a finer textural class, while acidic soils can have a greater variety of weeds than non-acid soils.

Weeds will also develop and thrive in soils that have a poor mineral and microbial balance. Weeds will grow and proliferate where there is a Ca and P deficiency and an excess of K and Zn. They will develop where there is an imbalance of Fe to Mn, a lack of biologically available Ca, a lack of biologically active carbon including humus and humic acids, and where there are high nitrate levels, and a lack of bacteria or fungi. Cropping soils need to maintain a good, active microbial biomass with a fungal to bacteria ratio of approximately 3:1 for maize, and 2:1–3:1 for wheat and barley. Such ratios are necessary to preserve and promote a good biological environment for crops. An imbalance of these ratios along with poor soil nutrition could explain why crops may show poor growth and a tendency to be infested with weeds.

Bristle-grass may become prominent in compacted soils and where soils are deficient in Ca, P, Se, vitamin C, and have excess Mg with a narrow Ca:Mg ratio. Their occurrence is exacerbated by Mg, Zn, and the excessive use of K (muriate of potash), which also further suppresses Ca levels. Excess Zn along the maize plant row can cause the proliferation of Shepherds purse. Barnyard grass, goosegrass (crowfoot grass), summer grass and broomcorn millet like a soil environment that is low in Ca, P, humus and soil microbes, and high in K. Witch grass likes heavier, sticky soils with very low Ca levels and possibly high Al.

The condition and properties of the soil have a major bearing on whether the crop is able to grow in a sufficiently vigorous way to out-compete, and prevent or restrict the establishment and growth of weeds. Competitive suppression by vigorous crop growth plays a major role in preventing weed establishment. Weed suppression can also occur after a crop is sown by the production of auxins (or plant growth hormones) when the seed germinates. Auxins limit or stop the germination of seeds from other weeds. While this suppression lasts for only 1–2 days in poor quality soils, it can last for 6–8 weeks in biologically active, well-aerated soils, thus providing an effective, natural weed control. The application of liquid calcium incorporating a form of organic carbon such as molasses, or humic/fulvic acids (to act as a food supply for soil microbes), along with the addition of an organic form of phosphorus and selected trace elements such as B, Co and Se, can help alter the soil environment in such a way that weeds do not want to grow. Changing the soil environment can successfully deal with any weed problem and can provide a more effective solution than the application of straight herbicides, which gives a short-term and often limited response. However, where weeds are an initial problem, the incorporation of herbicides into a solution containing ammonium humate or fulvic/humic acids with a pH modifier, can provide good weed control. Such a mixture enables the amount of herbicide used to be reduced by 25–35 percent, and also helps buffer the effect of the herbicide on soil life. The regular use of herbicides and pesticides have an adverse effect on soil microbes

(including mycorrhizal fungi), which are responsible for maintaining the nutrient balance and availability of nutrients in the soil. The quick-kill approach using chemical herbicides only addresses the symptoms and does nothing to rectify the underlying cause.

PLATE 40 Severe weed infestation



Severe weed infestation of Rough bristle-grass suppressing maize growth.

PLATE 41 Severe weed infestation



Severe weed infestation of Broomcorn millet reducing crop yield and preventing harvesting.



Assessment

- 1 Assess the size of the ears just before harvesting and compare them with the photographs and criteria in Plate 42.

While there is a strong association between kernel number and yield, ear size and dry weight are also strong determinants of the final yield. In making the assessment, consideration must be given to the hybrid and crop agronomy including plant population, soil fertility, weather conditions and in particular the rainfall, temperature, and sunlight hours. High plant populations will reduce the size of the ears, and dry conditions and prolonged cloudy weather will reduce photosynthesis and the subsequent formation of carbohydrates and starch required for grain filling.



Importance

EAR SIZE is governed by a number of factors, including the availability of water, nitrogen and other nutrients, and the production of carbohydrate, starch and protein (Plate 43). It is essential that these be maintained during the crop cycle, particularly avoiding any shortage especially during the grain filling period. Small ears are often a sign of poor soil quality, including low fertility. They may also be due to asynchrony between pollen shed and silking caused by high rainfall, low temperatures, drought, or earworm damage. Soils in good condition with good structure, porosity, organic matter levels, soil life, soil fertility, and rooting depth help ensure the supply and availability of water and nutrients, and the duration of photosynthate producing green leaves. The grain-filling period is prolonged as a result and an increase in ear size is achieved.

Ear size is a useful determinant of grain quality in terms of grain size and shape distribution, grain hardness, grain weight, broken (or damaged) corn, moisture content, and the number of grains affected by disease.

PLATE 42 Visual scoring (VS) ear size



GOOD CONDITION VS = 2

Ears are large, varying in length between 180–220 mm. Ears show good grain filling of kernels and tips, and few stress features are apparent



MODERATE CONDITION VS = 1

Ears are of medium size, varying in length between 150–180 mm. Ears often show incomplete filling of kernels and tips, and stress features are often apparent.



POOR CONDITION VS = 0

Ears are small, varying in length from 100–150 mm. Kernels are often undeveloped and poorly filled at the tips. Stress features are very common.

PLATE 43 Small ears due to nutrient and water deficiency



Ears with poorly filled tips and loose chaffy kernels due to potassium deficiency.



Small ears with twisted and undeveloped kernels due to phosphate deficiency interfering with pollination and kernel fill.

PLATE 43 **Small ears due to nutrient and water deficiency** (*continued*)



Small ears with a low protein content and kernels at the tip not filling because of a nitrogen deficiency at critical times. Nitrogen is essential throughout the growing season.



Dry weather slows silking behind tasseling; kernels are not pollinated.

Assessment

- 1 Assess crop yield based on the criteria given in the Table 7. Crop yields are best assessed by noting the harvested dry weight (Plate 44). Maize yields can also be estimated by counting the number and size of ears per square metre and the degree of grain filling. The yield of cereal crops can also be estimated by noting the number and size of ears (spikes) per square metre, the number of kernels (grains) per ear, and the degree of grain filling. In making the assessment, consideration must be given to the variety of the crop, the number of plants per square metre, the soil moisture, air temperature and sunshine hours during the growing season, and pests and diseases not associated with the condition of the soil.

Importance

WITH A DECLINE IN SOIL QUALITY, crops can come under stress as a result of poor soil aeration, water-logging, moisture stress (due to either soil saturation or a reduced available water-holding capacity), a lack of available nutrients, and adverse temperatures. Toxic chemicals can also build up and root growth be impeded owing to chemical reduction reactions (pp. 8 & 26) and a high penetration resistance to root development. This results in poor germination and emergence, poor plant growth and vigour, the need for re-drilling, delays in drilling, root diseases, pest attack, and consequently lower crop yields. Plant stress induced by structural degradation can further affect the quality of grain by changing the amount and type of protein and starch formed, and the enzymic potential. These affect the amount of fermentable carbohydrate, the baking quality of wheat, and the malting potential of barley. Under good soil conditions with adequate water and nutrients, the ripening period is prolonged and the starch accumulation inside the kernel is delayed and more gradual. This increases yield with a higher starch and protein percentage and quality.

Compacted, poorly aerated soils can be partially ameliorated by artificial aeration (Plates 46 & 47, p. 63). Aerating the soil can increase crop production by 10–20 percent on moderately compacted ground, and by up to 40 percent on severely compacted ground. Spending money on diesel to aerate compacted soils instead of additional fertiliser will often give better crop yields.

For good crop yields, the plant requires the following nutrients in adequate amounts:

- ❖ N, S, Mg, Fe, Mn, Zn, and Cu for chlorophyll production
- ❖ N, P, K, Fe, Mn, Cu for photosynthesis
- ❖ N, P, K, Zn, Cu and B to aid the production and use of carbohydrates and starch
- ❖ N, K, S, Fe, Cu – to form amino acids, essential for protein synthesis
- ❖ N, P, K, S, Mg, Fe, Mn, Zn, Cu and Mo, constituents of several enzyme systems involved in building and converting amino acids to proteins.
- ❖ N and P to supply the source of energy, energy storage and transfer in the plant
- ❖ N, P, Ca, Fe and B for cell division and enlargement, vital for plant growth
- ❖ Ca and Co for growth of shoots and shoot tips
- ❖ Ca, P and B for root formation and growth

PLATE 44 Harvesting maize for silage and grain



Harvesting a 20 t/ha maize silage crop (top) and a good maize grain crop with a yield of 15.2 tonnes/ha (bottom).

TABLE 7 Visual scoring (VS) crop yield

Visual score (VS)	Crop yield
2 [Good]	Crops have 40 ears per square metre. The ears are large (180–220 mm in length) and show complete grain filling and few signs of stress, pests or diseases. Harvested yield is 14 tonnes/ha for maize grain and 25 tonnes/ha for maize silage.
1 [Moderate]	Crops have 20–30 ears per square metre. The ears are of medium size (150–150 mm in length), with moderate grain filling, but are often poor at the tips. Stress, pest, and disease evidence is moderately common. Harvested yield is 10–12 tonnes/ha for maize grain and 19–22 tonnes/ha for maize silage.
0 [Poor]	Crops have < 20 ears per square metre. The ears are generally small (100–180 mm in length) and show uneven and poor grain filling, particularly at the tips. Stress, pest and disease features are very common. Harvested yield is < 8 tonnes/ha for maize grain and < 16 tonnes/ha for maize silage.

Assessment

- 1 Assess whether production costs have increased because of increased tillage, fertiliser, herbicide and fungicide requirements over the years (Figure 4) and refer to the class limits given in Table 8. This assessment can be based on perceptions but reference to annual balance sheets will give a more precise answer.

Importance

FERTILISER, GROUND PREPARATION, HERBICIDE AND PESTICIDE INPUTS account for some of the highest costs in any cropping operation, and can increase significantly with increasing soil degradation. While fertiliser is one of the major costs associated with cropping, the amount, type and therefore cost of applied fertiliser can be significantly influenced by the condition of the soil. Soil condition can have a major effect on fertiliser use efficiency, including the up-take of N and S. For example, poorly aerated and waterlogged soils reduce plant available nitrate-nitrogen (NO_3^- -N) to nitrite (NO_2^-) and N_2 gas, and sulphate-sulphur (SO_4^{2-} -S) to sulphite (SO_3^{2-}) and sulphides, rendering the N and S unavailable to the plant. The N cycle also cannot work if the S cycle is not working, i.e. plants need sulphur in sulphate form to utilize N. It is partly for this reason that farmers commonly apply more N and S than would otherwise be the case in an attempt to overcome the losses incurred by the chemical reduction effect of soils in poor condition.

Poorly aerated and waterlogged soils also decrease the uptake of phosphorus. Degraded soils with relatively high Olsen P levels (40–50 mg/L) can show a positive yield response to applied P. Again, to boost production, farmers will often apply more phosphorus than normally would be required.

In addition, continuous cropping using conventional cultivation techniques can give rise to a significant loss of organic matter (see Figs 6 & 7, p. 77) and, as a result, can substantially reduce soil fertility and the ability of the soil to supply nutrients. Higher amounts of fertiliser are needed to compensate for the loss of these nutrients. Moreover, the loss of organic carbon could incur a possible carbon tax, further increasing costs.

Reductions in crop yield are often not recognised as the result of the degradation of soil structure, the loss of organic matter, and a reduction in the number and activity of soil microbes. Rather, growers assume that soil fertility is at fault and increase their production costs by applying extra fertiliser.

Do you use fertiliser to grow the plant, or do you use fertiliser to feed the soil to grow the plant?

FIGURE 4 Assessment of production costs

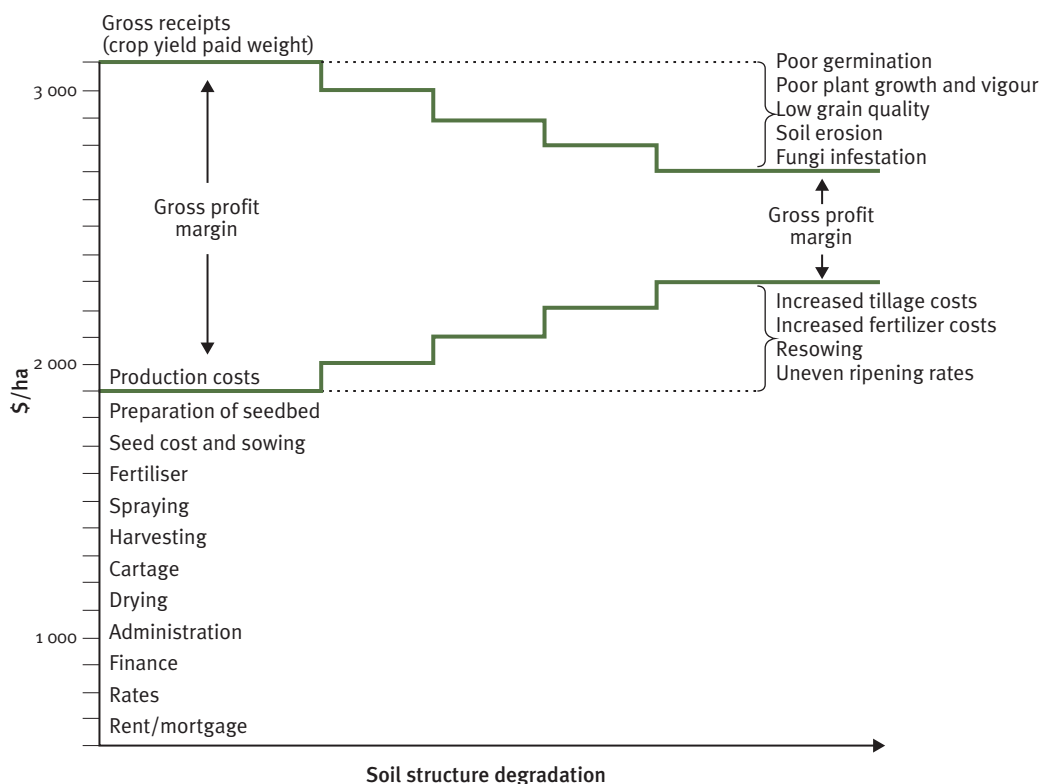


TABLE 8 How to score production costs

Visual score (VS)	Production costs
[Good]	Production costs including fertiliser, ground preparation, herbicide and pesticide requirements have not increased.
1 [Moderate]	Production costs including fertiliser, ground preparation, herbicide and pesticide requirements have increased moderately.
0 [Poor]	Production costs including fertiliser, ground preparation, herbicide and pesticide requirements have increased greatly.

In addition to soil fertility issues, soils in poor physical condition can have a significant effect on the cost of preparing a seedbed. As degradation increases, the density and strength of the soil increases and, as a result, the soil becomes more resistant to tillage forces, effectively creating ‘Sunday Soils’ – too wet to cultivate on Saturday and too dry on Monday. Plough resistance increases so that larger (more costly) tractors are required to avoid excessive wheel slip and to operate at lower ground speeds in a lower gear. The size, density, and strength of soil clods also increase with increasing loss of soil structure, and careful timing and additional energy are needed to break them down to a seedbed. This energy is generally applied by using more intensive methods of cultivation and by making a greater number of passes (often referred to as ‘recreational tillage’). As a result, tillage costs can increase by over 300 percent using conventional cultivation. No-till technology can reduce overall costs by 40–50 percent.

Production costs can be reduced if soils are well aerated and the seedbed is prepared with a minimum number of passes. Cultivating at the optimum water content for maximum breakdown of soil clods to form a seedbed not only reduces the number of passes required, but helps preserve the structure of the soil (Plate 45). Compacted soils should also be artificially aerated when they are sufficiently moist and crumbly to give maximum fracturing (Plate 46). Cultivating and aerating the soil at the optimum water content to give the best results can be achieved by applying the ‘worm test’ (Plate 47).

PLATE 45 Cultivating the soil at the right water content



Cultivating at the optimum water content to achieve maximum breakdown of soil clods to form a seedbed in one pass.

PLATE 46 Artificial aeration

Photo: Courtesy of James Engineering



Artificial aeration of a compacted topsoil at the optimum water content to achieve maximum fracturing of the soil profile.

PLATE 47 The worm test



a



b

- a) Roll a soil worm between the palms of your hands.
- b) For **silty soil**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to aerate. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to aerate.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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part 2

Maize

Visual indicators
of environmental performance
under cropping

A GUIDE



Maize

Visual indicators
of environmental performance
under cropping

A GUIDE

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List of acronyms

AEC	Adenylate energy charge	Mn²⁺	Manganous ions
Al	Aluminium	Mo	Molybdenum
ASC	Anion storage capacity	N	Nitrogen
ATP	Adenosine triphosphate	N₂	Nitrogen gas
B	Boron	NO₃⁻	Nitrate
C	Carbon	NO₃⁻-N	Nitrate-nitrogen
Ca	Calcium	NO₂⁻	Nitrite
Ca²⁺	Calcium cation	N₂O	Nitrous oxide
CEC	Cation exchange capacity	Na	Sodium
CH₄	Methane	Na⁺	Sodium cation
CO₂	Carbon dioxide	NH₃	Ammonia
qCO₂	Metabolic quotient	NH₄⁺	Ammonium
Co	Cobalt	O₂	Oxygen
Cu	Copper	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂S	Hydrogen sulphide	SO₄²⁻	Sulphate
K	Potassium	SO₃²⁻	Sulphide
K⁺	Potassium cation	VS	Visual score
Mg	Magnesium	VSA	Visual Soil Assessment
Mg²⁺	Magnesium cation	WFPS	Water-filled pore space
Mn	Manganese	Zn	Zinc
Mn³⁺	Manganic ions	ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER CROPPING

A GUIDE

Courtesy of Pioneer® brand products



1. Potential for nutrient loss into the groundwater and waterways



2. Carbon sequestration



3. Green house gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways



Assessment

- ① To assess the susceptibility of soils under crops to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 71), the visual scores (VS) for Textural group, Soil colour, Soil smell, and Potential rooting depth from the Soil Scorecard, and the visual score (VS) for Root development from the Plant Scorecard. Also add a ranking score for the amount and solubility of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.



Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals¹, have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is greater than 7:1, P is limiting growth. If the N:P is less than 7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

¹ Non-crystalline iron and aluminium hydroxide oxides and amorphous aluminosilicate clay minerals such as ferrihydrite and allophane.

PLATE 48 Nutrient loss into waterways



- a) A field with a moderate potential for nutrient loss into the groundwater and lake. While it has a coarse loamy textural group and moderately good structure with a moderately rapid permeability, it has moderately high carbon levels and CEC in the topsoil, good potential rooting depth, good root development, and received moderate amounts of water-soluble fertiliser and nitrogen.
- b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly assessed from five of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^- -N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain more clay and generally more humus as well. Hence their CECs are higher and more able

to adsorb and retain positively charged nutrients such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+ , etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic silty clay*, *peaty silt loam*) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P can also readily leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root development** (p. 46) – Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with crops with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root development and the potential rooting depth.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light,

well-structured soils, particularly when applied in large amounts. High rates of fertiliser are also applied to crops in an attempt to overcome sparse root systems and maximise yield. The over-use of highly soluble granulated N products readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^- . Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching. Nitrate and H^+ ions are produced following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should always be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes. In contrast to urea and other highly soluble fertiliser products, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of high analysis, highly soluble forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can have a negative affect on soil life. The microbial biomass and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–65 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^- -N) from soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+ -N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the

soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reduction in white clover. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical cropping practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Any one of the above indicators provides an estimate of the susceptibility of the soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 20 , certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 20 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching into the environment. Crops are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth.

FIGURE 5 Scorecard – visual indicators to assess the potential for nutrient loss

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of nutrient loss	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹) pg. 2		x 3	
Soil structure (Scoring protocol is given below ²) pg. 4		x 2	
Potential rooting depth (mm) pg. 22		x 3	
Root development pg. 46		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 3	
NUTRIENT LOSS INDEX (sum of VS rankings)			

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 11
Moderate potential for nutrient loss	11–20
Low potential for nutrient loss	> 20

1 Textural group (Figure 2b, p. 3):

VS = 2 for Clayey; VS = 1.5 for Fine silty; VS = 1.0 for Fine loamy; VS = 0.5 for Coarse silty; VS = 0 for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 respectively to the VS score. Note VS scores cannot exceed a value of 2.

2 Soil structure – Is the land most susceptible to a) leaching, or b) runoff?

a) *Land susceptible to leaching – Flat land with little or no runoff (overland flow)*

VS = 2 for Poor soil structure; VS = 1.5 for Moderately poor soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately good soil structure; VS = 0 for Good soil structure.

b) *Land susceptible to runoff – Gently undulating to rolling land*

VS = 2 for good soil structure; VS = 1.5 for Moderately good soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately poor soil structure; VS = 0 for Poor soil structure

3 Amount and form of fertiliser and N applied

VS = 2 if using liquid foliar sprays or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 80 kg N/ha/yr are applied; VS = 1.0 if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 160–240 kg N/ha/yr, using highly soluble, salt-based and nitrogenous fertilisers; VS = 0 if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 320 kg N/ha/yr are applied.

2. Visual indicators to assess the potential for carbon sequestration



Assessment

- Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 8, p. 79) the visual scores (VS) for Soil texture, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root development and Crop yield from the Plant Scorecard. Add also a ranking score for the clay mineralogy, the amount and form of fertiliser and nitrogen applied per annum, and for the method of cultivation (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.



Importance

THE AMOUNT OF C in a soil = C inputs – decomposition rates. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition, leaching and volatilization (Plate 49). A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than the decomposition rates (Plate 50). Farmers can reduce their ecological and carbon footprint and ‘grow’ their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture’s contribution to greenhouse gas emissions, providing a cost-effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, two indicators of plant performance, and from the method of cultivation and the amount and form of fertilisers and nitrogen used, as described below. Crops such as maize silage where most of the plant is removed are C negative.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of organic C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are < 2 µm and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

PLATE 49 A carbon positive field

Photo: Courtesy of Baker No-Tillage Ltd



A carbon positive field using no-till technology to sow directly into maize residue left on the surface. The field has good soil colour compared with the fenceline, good root development, potential rooting depth, and crop yields, moderate earthworm numbers, and 80 kg N/ha/yr are applied in a carbon-friendly form.

PLATE 50 A carbon negative field



A carbon negative field under continuous conventional cultivation. The field has moderately poor soil colour compared with the fenceline, poor earthworm numbers, moderate potential rooting depth, root development, and crop yields, and 200 kg N/ha/yr are applied in a non-carbon friendly form. Total organic C in the upper 200 mm of soil declined from 90.8 tonnes/ha under permanent pasture to 41.2 tonnes/ha after 35 yrs of continuous conventional cultivation (Figure 6, p. 77).

Clay mineralogy (see scorecard, p. 79) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and aluminosilicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle-size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under 20 yrs continuous barley contain about 229 t C/ha in the top 1m, of which 159 t C/ha (69 percent) occurs in the upper 300 mm, and 70 t C/ha (31

percent) between 300 and 1000 mm. Compare this with non-allophanic soils below. The amount of C in the upper 300 mm of allophanic soils under cropping is only 4 t/ha less than under permanent pasture, illustrating its relative stability despite continuous, long-term conventional cultivation.

Soil colour compared with that under the fenceline (p. 10) can provide a good indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present. With the exception of poorly aerated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C (Fig. 10, p. 86).

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. The number and activity of soil microbes at depth is much less than in the topsoil and so the carbon is more protected and able to build up because it is less likely to be mineralised. Deep burrowing earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil C.

Potential rooting depth (p. 22) and the **Root development** (p. 46) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 128 tonnes C/ha after 23 yrs cereal and maize cropping: 85 t C/ha (67 percent) occur in the upper 300 mm, and 42 t C/ha (33 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good potential rooting depth of 1 m contain about 134 t C/ha after 22 yrs maize cropping, of which 64 t C/ha (48 percent)

occur in the upper 300 mm, and 70 t C/ha (52 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme. Note the significantly lower C levels of these soils under conventional cultivation compared with pasture (Fig. 6, p. 77).

Crop yield (p. 58) can provide a further indication whether soil C is increasing, decreasing or at steady state. The greater the crop yield, the greater the root and shoot mass, and therefore the greater the input of C from the root system and the decomposition of the additional surface litter and surface residue. A 14-tonne/ha crop of maize for grain would produce an above-ground C input from the surface litter and residue of approximately 7 t C /ha, and a below-ground C input of 2 t/ha from the roots, a total of 9 t C/ha. An 11- tonne/ha crop of maize adds a total of approximately 7.1 t C/ha to the soil, or 21 percent less than the higher producing crop. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the crop has good root development and potential rooting depth, and the soil is allophanic with a good earthworm population, and doesn't receive high applications of soluble, salt-based nitrogenous products. The application of high rates of granular N to boost yield, promotes the vegetative growth of the shoots relative to the roots. The over-use of N also creates lazy plants, encouraging a shallow root system and therefore less C input. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil. In addition, the microbial decomposition of roots, plant litter and husks produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil. The input of C in the soil from maize for silage is considerably less than maize for grain because much of the above ground vegetative matter is removed at harvest. Maize silage can therefore have a C negative effect.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture and temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing crop growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Amount and form of fertiliser and nitrogen applied to cropping soils (see scorecard, p. 79) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, compost teas,

animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and crop management, good crop yields and C levels can be sustained and increased over the long term. The form in which essential elements are applied can also have an effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and is the preferred form for improving crop quality, and if the seedlings or crop are sensitive to chlorine.

Similarly, while nitrogen promotes crop growth and therefore the input of C into the soil, certain forms of N are more effective than others at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic carbon and carbohydrate such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N. The excessive use of soluble granular forms of N and high analysis nitrogenous fertilisers also cause the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 10:1–100:1. The oversupply of N stimulates bacteria to mineralise 2–3 times the amount of humus they would ordinarily mineralise. Moreover, the high use of granular forms of N such as urea, reduce the earthworm and microbial biomass, further reducing C levels in the soil.

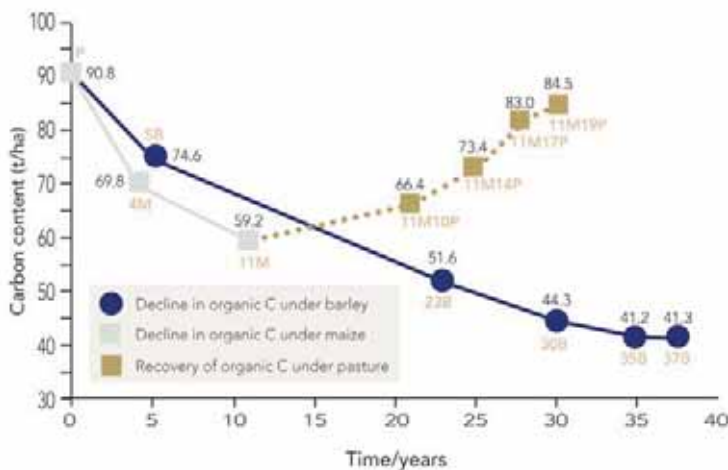
The plant converts CO₂ in the atmosphere into sugar (carbon) by photosynthesis in the leaves of the plant. The sugar dissolves as liquid glucose in the sap of the plant and is subsequently transferred to the soil through the roots to feed the soil microbes. The microbes in turn bring trace elements to the plant in exchange for the sugar. This process of C transfer from the plant to the soil, and the rate of photosynthesis, is disrupted by the over-use of high analysis, highly soluble forms of N and P. These include urea and anhydrous ammonia, and di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (e.g., humates), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70 percent). The utilization of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root development, and crop yield.

The addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

The **method of cultivation** (see scorecard, p. 79) can have a significant effect on soil C levels. Soil organic C can decline markedly under continuous conventional cultivation because the high level of soil disturbance aerates the soil, increasing the rate of mineralisation of soil organic C by microbial respiration and its oxidation to CO₂. The rate of C loss is particularly rapid in the first 4–5 years of cropping, followed by a slower rate of decline, eventually reaching an equilibrium where only the more stable and physically protected carbon remains in the soil (Fig. 6). Total soil C is seen in Fig. 6 to decline by 31.6 t/ha in the upper 200 mm of soil after 11 yrs continuous maize, and by 49.6 t/ha after 35 yrs continuous barley; an average loss of 2.9 and 1.7 t/ha/yr respectively. Note the initial slow rate of recovery of total C after 10 years of pasture following 11 yrs of maize. After 19 yrs of ryegrass/clover pasture, the total C had not recovered to pre-cropping pasture levels of 90.8 t/ha. The significant loss of C under both maize and barley, and the slow rate of C recovery under pasture are due in part to the poor management practices that prevailed. The slow rate of recovery of C under pasture was also due to the extremely compacted, poorly aerated state of the soil.

FIGURE 6 Total C in the topsoil under pasture and continuous cropping



Total C in the topsoil (0–200 mm) after 11 yrs and 37 yrs of continuous maize and barley respectively under conventional cultivation.

Note the rate of recovery of total C after 10, 14, 17 and 19 years of pasture following 11 yrs of maize.

FIGURE 7 Total C in the topsoil under pasture, no-till and conventional cultivation



In comparison, the loss of soil C under no-tillage is significantly less than under conventional cultivation (Fig. 7). In some instances, C levels have increased in the upper 150 mm of soil under no-tillage compared with pasture. The greatest increases in soil C can occur at a depth of 300–600 mm under ‘pasture cropping’ practices where no herbicides or insecticides have been applied. The substantial loss of C under conventional cultivation and the slow rate of C recovery under pasture are due to the non-adoption of carbon capture and storage (CCS) management practices.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore ‘grow’ the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 32), certain management practices and specific types of fertiliser need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 32) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits.

FIGURE 8 Scorecard – visual indicators to assess the potential for carbon sequestration

Landowner: _____ **Land use:** _____
Site location: _____ **GPS ref:** _____
Sample depth: _____ **Topsoil depth:** _____
Soil type: _____ **Soil classification:** _____
Drainage class: _____ **Date:** _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of soil carbon	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g. 2	x 2	
Clay mineralogy (Scoring protocol is given below ²)		x 2	
Soil colour	g. 10	x 2	
Earthworms (Number =) (Av. size =)	g. 14	x 3	
Potential rooting depth (mm)	g. 22	x 3	
Root development	g. 46	x 3	
Crop yield	g. 58	x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 2	
Method of cultivation (Scoring protocol is given below ⁴)		x 3	
SOIL CARBON INDEX (sum of VS rankings)			

Soil Carbon Assessment	Soil Carbon Index
Potentially poor carbon levels	< 17
Potentially moderate carbon levels	17–32
Potentially good carbon levels	> 32

- 1 **Textural group:** VS = 2 for Clayey; VS = 1.5 for Fine loamy and Fine silty; VS = 1.0 for Coarse silty; VS = 0.5 for Coarse loamy; VS = 0 for Sandy.
- 2 **Clay mineralogy:** VS = 2 if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; VS = 1 if the soil has moderate levels of Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an ASC of 60–75 percent; VS = 0 if the soil has little or no Fe & Al hydroxides and amorphous aluminio-silica minerals; ASC is < 45 percent.
- 3 **Amount and form of fertiliser and N applied:** VS = 2 if “smart” fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based N fertilisers.
- 4 **Method of cultivation:** VS = 2 if using ‘pasture cropping’ and no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous mouldboard ploughing with intensive secondary cultivation.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions

Assessment

- 1 Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 12, p. 89) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual score for Crop yield from the Plant Scorecard. Also add a ranking score for the method of cultivation used and the amount and form of N applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.

Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C; without them the earth's average temperature would be around -18°C. However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Solar radiation



Agriculture can provide a significant source of CH₄ and N₂O and is responsible for 15 percent of worldwide greenhouse gas emissions. CO₂ is emitted under arable cropping, however it is reabsorbed as photosynthate by the crop and is therefore greenhouse neutral. While high emission levels of GHGs are more to do with the way we farm, climate friendly and smart agricultural management can significantly reduce emissions.

GHG emissions from cropping result from a number of sources, including the soil, the burning of fossil fuels by farm machinery, and the production and application of nitrogenous fertilisers. The level of emissions varies according to a number of factors, including the condition of the soil, the method of cultivation, and the amount and form of fertiliser N applied, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO₂ to soil C, and by promoting the soil as a CH₄ sink. The C credits gained can help off-set their GHG emissions.

PLATE 51 Field with a low potential for greenhouse gas emission

Field with a low potential to emit GHGs due to the soil being a well-drained, coarse loamy soil with good porosity under a no-tillage regime. In addition, good crop growth and yield remove a large amount of CO₂ from the atmosphere and CO₂ escaping from the soil by photosynthesis.

PLATE 52 Field with a high potential for greenhouse gas emission

Field with a high potential to emit GHGs due to the soil being an imperfectly to poorly drained, clayey soil with poor porosity under continuous conventional cultivation. In addition, poor crop growth and yield remove only small amounts of CO₂ from the atmosphere and CO₂ escaping from the soil by photosynthesis.

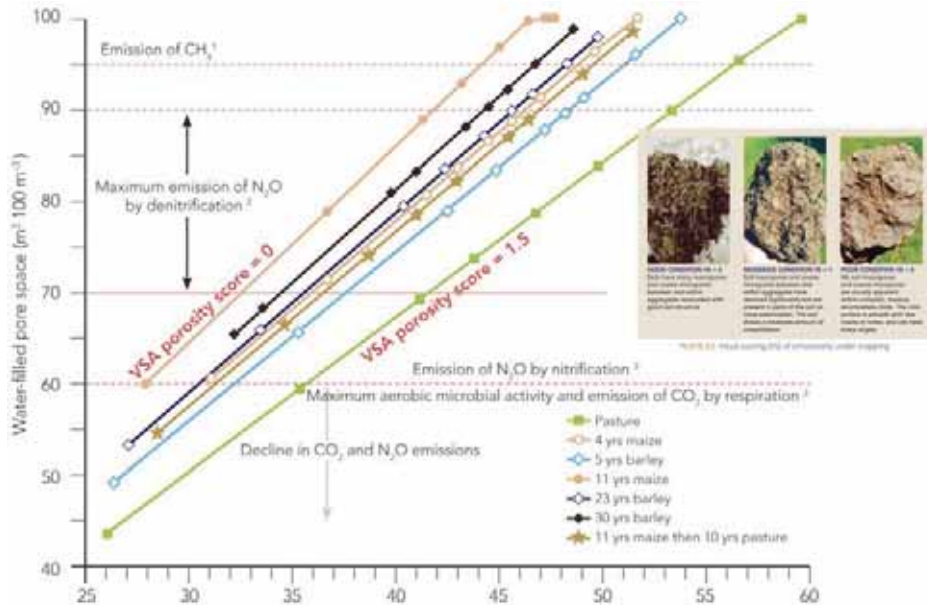
The potential of a site to emit GHGs can be roughly assessed from four indicators of soil quality, one indicator of plant performance, the amount and form of nitrogen applied, and the method of cultivation, as described below.

Soil textures (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major ‘driver’ of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs.

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O , and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 9); emissions of N_2O are lowest when the WFPS is < 50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 9) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O . In contrast, a severely compacted soil after 11 yrs of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 9) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2 . While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is

FIGURE 9 Affect of water-filled pore space and water content on greenhouse gas emissions

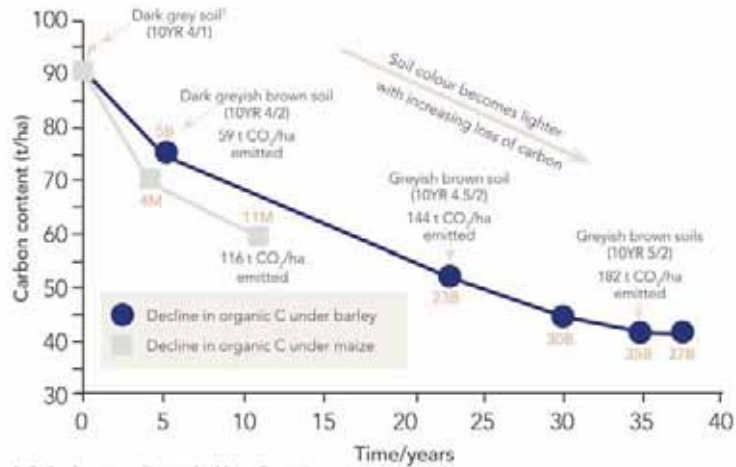


¹ After MacDonald *et al.* (1996); ² After Dobbie *et al.* (1999); ³ After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

hence an effective means of reducing GHG emissions. The relationship between the WFPS and the visual assessment of the porosity of the soil, as shown in Fig. 9, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink. A lighter soil colour compared with soil under the fenceline can also indicate the loss of soil C and the emission of significant amounts of CO_2 into the atmosphere (Figure 10).

FIGURE 10 Soil C loss and associated CO₂ emissions under continuous cropping

Soil C loss, associated soil colour, and CO₂ emissions under continuous maize and barley cropping using conventional cultivation.

Crop yields (p. 58) can provide an indication of the potential to reduce GHG emissions. The greater the crop yield, the greater the amount of CO₂ removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO₂ emitted by microbial respiration, the emission of GHGs from the consumption of the crop by stock, the burning of fossil fuels by farm machinery, and the application of nitrogenous fertilisers. As CO₂ escapes from the soil, most, if not or all, is absorbed by the stomata on the crop leaves, which have an insatiable appetite for CO₂. The greater the canopy cover (leaf area index) and the quicker the canopy closure, the greater the amount of CO₂ removed. Furthermore, if we assume that one kilogram of carbon in a maize crop removes 3.67 kg CO₂ from the atmosphere, a field growing 25 tonnes of maize silage/ha (or 10.3 t C/ha) will remove approximately 38 tonnes of atmospheric CO₂/ha. A field growing just 20 tonnes of maize silage/ha (or 8.2 t C/ha) will remove 30 tonnes of atmospheric CO₂/ha, 22 percent less than the higher producing field. While CO₂ is the least potent of the GHGs with a Global Warming Potential that is 21 and 310 times less than CH₄ and N₂O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO₂ into sugars and oxygen, and subsequently into soil C, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Poor crop yield and the associated reduced crop cover would also reduce insulation from the sun, thereby increasing soil temperatures and reducing the uptake of available N and plant-available water, stimulating N₂O emissions by microbial nitrification and denitrification.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 89) can provide a further indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 9). The nitrification of urea and ammonium-based fertilisers, and particularly the denitrification of nitrates in the soil resulting from the excessive application of salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Fertiliser N applications stimulate emissions in the spring, while crop residues and their incorporation into the soil stimulate emissions in autumn and winter. The highest emissions occur following each fertiliser application, particularly when associated with major rainfall events. Seventy-five to eighty percent of the N_2O emitted can occur within 4 weeks of N application. While N_2O emissions can often account for up to 3 percent of the N applied as fertiliser in small-grain cereal crops and up to 8 percent in maize crops, compact, wet soils can increase N_2O emissions by denitrification 3–4-fold, resulting in a loss of up to 20 percent of fertiliser N, and also decreasing wheat yields by 25 percent. Yield reductions can be attributed in part to N deficiency by high denitrification activity and low mineralization. In addition, the excessive use of nitrogenous products can reduce the capacity of soils to take up and oxidise atmospheric CH_4 , thereby reducing the ability of the soil to act as a CH_4 sink.

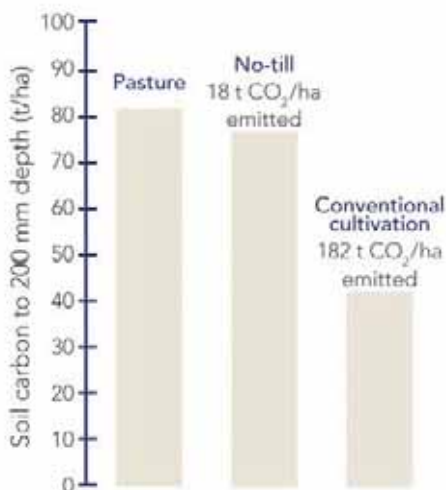
Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied to crops could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic and fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70%) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides microsites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root development, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70%, they can increase NH_3 emissions and potential NH_4^+ -N leaching losses. The jury is also still out as to their long-term impact on soil biology, in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be

applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reductions in white clover. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

The **method of cultivation** (see scorecard, p. 89) can have a marked effect on the level of GHG emissions. Carbon dioxide emissions are significantly greater under conventional cultivation than other forms of ground preparation because of the greater loss of soil C (Figs 10 & 11). The high level of soil disturbance under conventional cultivation aerates the soil, increasing the mineralisation and oxidation of organic C to CO_2 by microbial respiration which subsequently volatilises into the atmosphere. If we assume that one tonne of organic C oxidises to 3.67 tonnes of CO_2 , the loss of 31.6 t C/ha after 11 yrs of conventionally cultivated maize gives rise to the emission of approximately 116 t CO_2 /ha (Fig. 10). The loss of 49.6 t C/ha after 35 yrs of continuous barley produces 182 t CO_2 /ha. These figures do not, however, take into account the C added to the soil from the plant over the 11- and 35-year cropping period, C that would also have oxidised and potentially contributed to CO_2 emissions. However, as mentioned above, after CO_2 escapes from the

FIGURE 11 Soil C loss and associated CO_2 emissions under no-till and conventional cultivation



Soil C loss and associated CO_2 emissions under 20 yrs of double cropping using no-tillage and 35 yrs conventional cultivation.

soil, almost all of it is absorbed by the stomata on the crop leaves and is therefore recycled back into the soil. In addition to the major period of CO₂ emissions when the soil is tilled using conventional cultivation, a certain amount of CO₂ would be emitted after the harvest or senescence of one crop, and canopy closure of the next crop.

In comparison, the loss of soil organic C under no-tillage is significantly less than under conventional cultivation, producing as a result, less emissions of CO₂ (Fig. 11). Adopting carbon capture and storage (CCS) management practices including those cultivation practices that minimise C loss or even promoting C sequestration, is an effective means of reducing the emissions of CO₂ into the atmosphere.

Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by the Emissions Trading Schemes. If the GHG Emission Index is ≤ 22 , certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of > 22 provides significant environmental benefits because less GHGs would be emitted into the atmosphere.

FIGURE 12 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g.2	x 2	
Soil porosity	g.6	x 3	
Number and colour of soil mottles	g.8	x 3	
Soil colour	g.10	x 2	
Crop yield	g.58	x 2	
Amount and form of N applied (Scoring protocol is given below ²)		x 1	
Method of cultivation (Scoring protocol is given below ³)		x 3	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 12
Moderate potential GHG emissions	12–22
Low potential for GHG emissions	> 22

1 Textural group (Figure 2b, p. 3):

VS = 2 for Sandy and Coarse loamy; VS = 1.5 for Coarse silty; VS = 1.0 for Fine loamy; VS = 0.5 for Fine silty; VS = 0 for Clayey.

2 Amount and form of N applied:

VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 Method of cultivation:

VS = 2 if using no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous conventional (mouldboard plough) cultivation with intensive secondary cultivation.

Soil management of maize crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, include ‘pasture cropping’ where annual crops are direct-drilled into perennial pastures, and no-tillage and minimum tillage practices that incorporate the establishment of temporary cover crops and crop residues on the surface. They provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage can also maintain soil life and biological activity (including earthworm numbers), and can increase micro-organism biodiversity above levels commonly found under conventional cultivation. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO₂) and enables the soil to operate as a sink for CO₂. Soil organic matter levels can build up as a result and create the potential to gain ‘carbon credits’, thereby providing an offset to greenhouse gas emissions. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

Where possible, put in place management strategies that don’t require the use of herbicides. Avoid a monochemical herbicide strategy and manage the use of herbicides in association with crop rotations, including the use of livestock, to avoid the development of herbicide tolerance and residual effects. Ensure the soil has adequate levels of available Ca because herbicides are generally more effective when Ca levels in the plant are good. Also ensure that P levels aren’t too high; the higher the P level, the harder it is to deal to snails and slugs. The inappropriate and over-use of various herbicides can significantly change nutrient availability and the efficient uptake of nutrients by binding up micronutrients (chelation immobilization), and through toxic effects on soil organisms important for nutrient turnover and supply.

Continuous conventional cultivation can impact negatively on the environment with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO₂), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades

PLATE 53 A good maize crop



Photo: Courtesy of Kenneth G. Cassman

A good maize crop producing a grain yield in excess of 20 t/ha due in part to the adoption of good management practices that promote a good root system. Note the good potential rooting depth and root development to > 2m. Compare with Plate 16, p. 23

soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. Conventional cultivation should be practiced on a rotational basis with 2 years of cropping followed by 5–7 years pasture.

The fundamental difference between continuous conventional cultivation and conservation tillage is their relative environmental and economic sustainability. The long-term affects of continuous conventional cultivation can be cumulatively negative whereas the long-term affects of conservation tillage can be cumulatively positive. This is provided that good residue management practices are applied and the herbicides used are 100% biodegradable and have no adverse effects on soil or human health.

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Maize

Visual indicators
of environmental performance
under cropping

A GUIDE

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List of acronyms

AEC	Adenylate energy charge	Mn²⁺	Manganous ions
Al	Aluminium	Mo	Molybdenum
ASC	Anion storage capacity	N	Nitrogen
ATP	Adenosine triphosphate	N₂	Nitrogen gas
B	Boron	NO₃⁻	Nitrate
C	Carbon	NO₃⁻-N	Nitrate-nitrogen
Ca	Calcium	NO₂⁻	Nitrite
Ca²⁺	Calcium cation	N₂O	Nitrous oxide
CEC	Cation exchange capacity	Na	Sodium
CH₄	Methane	Na⁺	Sodium cation
CO₂	Carbon dioxide	NH₃	Ammonia
qCO₂	Metabolic quotient	NH₄⁺	Ammonium
Co	Cobalt	O₂	Oxygen
Cu	Copper	P	Phosphorus
Fe	Iron	PO₄³⁻	Phosphate
FeS	Ferrous sulphide	pH	Concentration of H ⁺ ions (Soil acidity/alkalinity)
Fe³⁺	Ferric iron	RSG	Restricted spring growth
Fe²⁺	Ferrous iron	S	Sulphur
GHG	Greenhouse Gas	SO₄²⁻-S	Sulphate-sulphur
H₂S	Hydrogen sulphide	SO₄²⁻	Sulphate
K	Potassium	SO₃²⁻	Sulphide
K⁺	Potassium cation	VS	Visual score
Mg	Magnesium	VSA	Visual Soil Assessment
Mg²⁺	Magnesium cation	WFPS	Water-filled pore space
Mn	Manganese	Zn	Zinc
Mn³⁺	Manganic ions	ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER CROPPING

A GUIDE

Courtesy of Pioneer® brand products



1. Potential for nutrient loss into the groundwater and waterways



2. Carbon sequestration



3. Green house gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways



Assessment

- ① To assess the susceptibility of soils under crops to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 71), the visual scores (VS) for Textural group, Soil colour, Soil smell, and Potential rooting depth from the Soil Scorecard, and the visual score (VS) for Root development from the Plant Scorecard. Also add a ranking score for the amount and solubility of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.



Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals¹, have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is greater than 7:1, P is limiting growth. If the N:P is less than 7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

¹ Non-crystalline iron and aluminium hydroxide oxides and amorphous aluminosilicate clay minerals such as ferrihydrite and allophane.

PLATE 48 Nutrient loss into waterways



- a) A field with a moderate potential for nutrient loss into the groundwater and lake. While it has a coarse loamy textural group and moderately good structure with a moderately rapid permeability, it has moderately high carbon levels and CEC in the topsoil, good potential rooting depth, good root development, and received moderate amounts of water-soluble fertiliser and nitrogen.
- b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly assessed from five of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^- -N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain more clay and generally more humus as well. Hence their CECs are higher and more able

to adsorb and retain positively charged nutrients such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+ , etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic silty clay*, *peaty silt loam*) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P can also readily leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root development** (p. 46) – Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with crops with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root development and the potential rooting depth.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light,

well-structured soils, particularly when applied in large amounts. High rates of fertiliser are also applied to crops in an attempt to overcome sparse root systems and maximise yield. The over-use of highly soluble granulated N products readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^- . Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching. Nitrate and H^+ ions are produced following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should always be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes. In contrast to urea and other highly soluble fertiliser products, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of high analysis, highly soluble forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can have a negative affect on soil life. The microbial biomass and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–65 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^- -N) from soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+ -N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the

soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reduction in white clover. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical cropping practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Any one of the above indicators provides an estimate of the susceptibility of the soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 20 , certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 20 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching into the environment. Crops are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth.

FIGURE 5 Scorecard – visual indicators to assess the potential for nutrient loss

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of nutrient loss	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹) pg. 2		x 3	
Soil structure (Scoring protocol is given below ²) pg. 4		x 2	
Potential rooting depth (mm) pg. 22		x 3	
Root development pg. 46		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 3	
NUTRIENT LOSS INDEX (sum of VS rankings)			

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 11
Moderate potential for nutrient loss	11–20
Low potential for nutrient loss	> 20

1 Textural group (Figure 2b, p. 3):

VS = 2 for Clayey; VS = 1.5 for Fine silty; VS = 1.0 for Fine loamy; VS = 0.5 for Coarse silty; VS = 0 for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 respectively to the VS score. Note VS scores cannot exceed a value of 2.

2 Soil structure – Is the land most susceptible to a) leaching, or b) runoff?

a) *Land susceptible to leaching – Flat land with little or no runoff (overland flow)*

VS = 2 for Poor soil structure; VS = 1.5 for Moderately poor soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately good soil structure; VS = 0 for Good soil structure.

b) *Land susceptible to runoff – Gently undulating to rolling land*

VS = 2 for good soil structure; VS = 1.5 for Moderately good soil structure; VS = 1.0 for Moderate soil structure; VS = 0.5 for Moderately poor soil structure; VS = 0 for Poor soil structure

3 Amount and form of fertiliser and N applied

VS = 2 if using liquid foliar sprays or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 80 kg N/ha/yr are applied; VS = 1.0 if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 160–240 kg N/ha/yr, using highly soluble, salt-based and nitrogenous fertilisers; VS = 0 if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 320 kg N/ha/yr are applied.

2. Visual indicators to assess the potential for carbon sequestration



Assessment

- 1 Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 8, p. 79) the visual scores (VS) for Soil texture, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root development and Crop yield from the Plant Scorecard. Add also a ranking score for the clay mineralogy, the amount and form of fertiliser and nitrogen applied per annum, and for the method of cultivation (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.



Importance

THE AMOUNT OF C in a soil = C inputs – decomposition rates. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition, leaching and volatilization (Plate 49). A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than the decomposition rates (Plate 50). Farmers can reduce their ecological and carbon footprint and ‘grow’ their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture’s contribution to greenhouse gas emissions, providing a cost-effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, two indicators of plant performance, and from the method of cultivation and the amount and form of fertilisers and nitrogen used, as described below. Crops such as maize silage where most of the plant is removed are C negative.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of organic C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are < 2 µm and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

PLATE 49 A carbon positive field

Photo: Courtesy of Baker No-Tillage Ltd



A carbon positive field using no-till technology to sow directly into maize residue left on the surface. The field has good soil colour compared with the fenceline, good root development, potential rooting depth, and crop yields, moderate earthworm numbers, and 80 kg N/ha/yr are applied in a carbon-friendly form.

PLATE 50 A carbon negative field



A carbon negative field under continuous conventional cultivation. The field has moderately poor soil colour compared with the fenceline, poor earthworm numbers, moderate potential rooting depth, root development, and crop yields, and 200 kg N/ha/yr are applied in a non-carbon friendly form. Total organic C in the upper 200 mm of soil declined from 90.8 tonnes/ha under permanent pasture to 41.2 tonnes/ha after 35 yrs of continuous conventional cultivation (Figure 6, p. 77).

Clay mineralogy (see scorecard, p. 79) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and aluminosilicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle-size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under 20 yrs continuous barley contain about 229 t C/ha in the top 1m, of which 159 t C/ha (69 percent) occurs in the upper 300 mm, and 70 t C/ha (31

percent) between 300 and 1000 mm. Compare this with non-allophanic soils below. The amount of C in the upper 300 mm of allophanic soils under cropping is only 4 t/ha less than under permanent pasture, illustrating its relative stability despite continuous, long-term conventional cultivation.

Soil colour compared with that under the fenceline (p. 10) can provide a good indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present. With the exception of poorly aerated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C (Fig. 10, p. 86).

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. The number and activity of soil microbes at depth is much less than in the topsoil and so the carbon is more protected and able to build up because it is less likely to be mineralised. Deep burrowing earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil C.

Potential rooting depth (p. 22) and the **Root development** (p. 46) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 128 tonnes C/ha after 23 yrs cereal and maize cropping: 85 t C/ha (67 percent) occur in the upper 300 mm, and 42 t C/ha (33 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good potential rooting depth of 1 m contain about 134 t C/ha after 22 yrs maize cropping, of which 64 t C/ha (48 percent)

occur in the upper 300 mm, and 70 t C/ha (52 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme. Note the significantly lower C levels of these soils under conventional cultivation compared with pasture (Fig. 6, p. 77).

Crop yield (p. 58) can provide a further indication whether soil C is increasing, decreasing or at steady state. The greater the crop yield, the greater the root and shoot mass, and therefore the greater the input of C from the root system and the decomposition of the additional surface litter and surface residue. A 14-tonne/ha crop of maize for grain would produce an above-ground C input from the surface litter and residue of approximately 7 t C /ha, and a below-ground C input of 2 t/ha from the roots, a total of 9 t C/ha. An 11- tonne/ha crop of maize adds a total of approximately 7.1 t C/ha to the soil, or 21 percent less than the higher producing crop. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the crop has good root development and potential rooting depth, and the soil is allophanic with a good earthworm population, and doesn't receive high applications of soluble, salt-based nitrogenous products. The application of high rates of granular N to boost yield, promotes the vegetative growth of the shoots relative to the roots. The over-use of N also creates lazy plants, encouraging a shallow root system and therefore less C input. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil. In addition, the microbial decomposition of roots, plant litter and husks produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil. The input of C in the soil from maize for silage is considerably less than maize for grain because much of the above ground vegetative matter is removed at harvest. Maize silage can therefore have a C negative effect.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture and temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing crop growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Amount and form of fertiliser and nitrogen applied to cropping soils (see scorecard, p. 79) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, compost teas,

animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and crop management, good crop yields and C levels can be sustained and increased over the long term. The form in which essential elements are applied can also have an effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and is the preferred form for improving crop quality, and if the seedlings or crop are sensitive to chlorine.

Similarly, while nitrogen promotes crop growth and therefore the input of C into the soil, certain forms of N are more effective than others at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic carbon and carbohydrate such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N. The excessive use of soluble granular forms of N and high analysis nitrogenous fertilisers also cause the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 10:1–100:1. The oversupply of N stimulates bacteria to mineralise 2–3 times the amount of humus they would ordinarily mineralise. Moreover, the high use of granular forms of N such as urea, reduce the earthworm and microbial biomass, further reducing C levels in the soil.

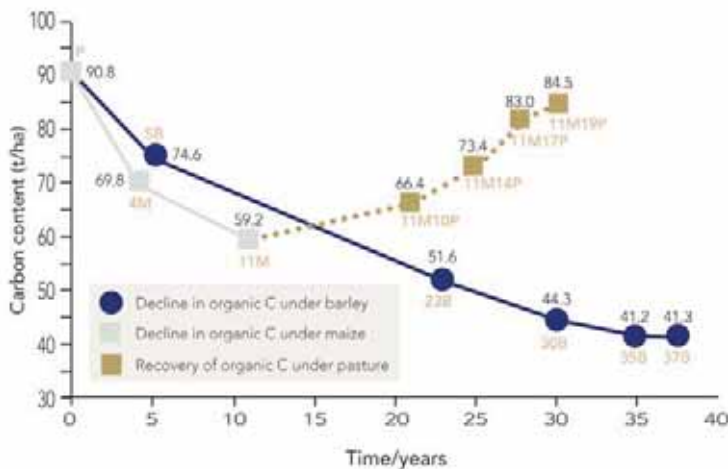
The plant converts CO₂ in the atmosphere into sugar (carbon) by photosynthesis in the leaves of the plant. The sugar dissolves as liquid glucose in the sap of the plant and is subsequently transferred to the soil through the roots to feed the soil microbes. The microbes in turn bring trace elements to the plant in exchange for the sugar. This process of C transfer from the plant to the soil, and the rate of photosynthesis, is disrupted by the over-use of high analysis, highly soluble forms of N and P. These include urea and anhydrous ammonia, and di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (e.g., humates), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70 percent). The utilization of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root development, and crop yield.

The addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

The **method of cultivation** (see scorecard, p. 79) can have a significant effect on soil C levels. Soil organic C can decline markedly under continuous conventional cultivation because the high level of soil disturbance aerates the soil, increasing the rate of mineralisation of soil organic C by microbial respiration and its oxidation to CO₂. The rate of C loss is particularly rapid in the first 4–5 years of cropping, followed by a slower rate of decline, eventually reaching an equilibrium where only the more stable and physically protected carbon remains in the soil (Fig. 6). Total soil C is seen in Fig. 6 to decline by 31.6 t/ha in the upper 200 mm of soil after 11 yrs continuous maize, and by 49.6 t/ha after 35 yrs continuous barley; an average loss of 2.9 and 1.7 t/ha/yr respectively. Note the initial slow rate of recovery of total C after 10 years of pasture following 11 yrs of maize. After 19 yrs of ryegrass/clover pasture, the total C had not recovered to pre-cropping pasture levels of 90.8 t/ha. The significant loss of C under both maize and barley, and the slow rate of C recovery under pasture are due in part to the poor management practices that prevailed. The slow rate of recovery of C under pasture was also due to the extremely compacted, poorly aerated state of the soil.

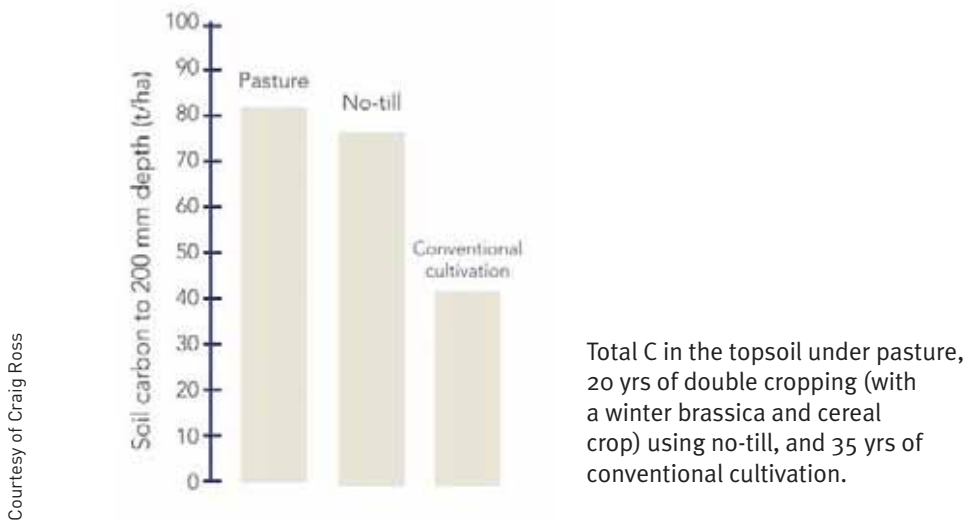
FIGURE 6 Total C in the topsoil under pasture and continuous cropping



Total C in the topsoil (0–200 mm) after 11 yrs and 37 yrs of continuous maize and barley respectively under conventional cultivation.

Note the rate of recovery of total C after 10, 14, 17 and 19 years of pasture following 11 yrs of maize.

FIGURE 7 Total C in the topsoil under pasture, no-till and conventional cultivation



In comparison, the loss of soil C under no-tillage is significantly less than under conventional cultivation (Fig. 7). In some instances, C levels have increased in the upper 150 mm of soil under no-tillage compared with pasture. The greatest increases in soil C can occur at a depth of 300–600 mm under ‘pasture cropping’ practices where no herbicides or insecticides have been applied. The substantial loss of C under conventional cultivation and the slow rate of C recovery under pasture are due to the non-adoption of carbon capture and storage (CCS) management practices.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore ‘grow’ the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 32), certain management practices and specific types of fertiliser need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 32) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits.

FIGURE 8 Scorecard – visual indicators to assess the potential for carbon sequestration

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of soil carbon	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g. 2	x 2	
Clay mineralogy (Scoring protocol is given below ²)		x 2	
Soil colour	g. 10	x 2	
Earthworms (Number =) (Av. size =)	g. 14	x 3	
Potential rooting depth (mm)	g. 22	x 3	
Root development	g. 46	x 3	
Crop yield	g. 58	x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below ³)		x 2	
Method of cultivation (Scoring protocol is given below ⁴)		x 3	
SOIL CARBON INDEX (sum of VS rankings)			

Soil Carbon Assessment	Soil Carbon Index
Potentially poor carbon levels	< 17
Potentially moderate carbon levels	17–32
Potentially good carbon levels	> 32

- 1 **Textural group:** VS = 2 for Clayey; VS = 1.5 for Fine loamy and Fine silty; VS = 1.0 for Coarse silty; VS = 0.5 for Coarse loamy; VS = 0 for Sandy.
- 2 **Clay mineralogy:** VS = 2 if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; VS = 1 if the soil has moderate levels of Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an ASC of 60–75 percent; VS = 0 if the soil has little or no Fe & Al hydroxides and amorphous aluminio-silica minerals; ASC is < 45 percent.
- 3 **Amount and form of fertiliser and N applied:** VS = 2 if “smart” fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based N fertilisers.
- 4 **Method of cultivation:** VS = 2 if using ‘pasture cropping’ and no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous mouldboard ploughing with intensive secondary cultivation.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions

Assessment

- 1 Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 12, p. 89) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual score for Crop yield from the Plant Scorecard. Also add a ranking score for the method of cultivation used and the amount and form of N applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.

Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C; without them the earth's average temperature would be around -18°C. However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Solar radiation



Agriculture can provide a significant source of CH₄ and N₂O and is responsible for 15 percent of worldwide greenhouse gas emissions. CO₂ is emitted under arable cropping, however it is reabsorbed as photosynthate by the crop and is therefore greenhouse neutral. While high emission levels of GHGs are more to do with the way we farm, climate friendly and smart agricultural management can significantly reduce emissions.

GHG emissions from cropping result from a number of sources, including the soil, the burning of fossil fuels by farm machinery, and the production and application of nitrogenous fertilisers. The level of emissions varies according to a number of factors, including the condition of the soil, the method of cultivation, and the amount and form of fertiliser N applied, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO₂ to soil C, and by promoting the soil as a CH₄ sink. The C credits gained can help off-set their GHG emissions.

PLATE 51 Field with a low potential for greenhouse gas emission

Field with a low potential to emit GHGs due to the soil being a well-drained, coarse loamy soil with good porosity under a no-tillage regime. In addition, good crop growth and yield remove a large amount of CO₂ from the atmosphere and CO₂ escaping from the soil by photosynthesis.

PLATE 52 Field with a high potential for greenhouse gas emission

Field with a high potential to emit GHGs due to the soil being an imperfectly to poorly drained, clayey soil with poor porosity under continuous conventional cultivation. In addition, poor crop growth and yield remove only small amounts of CO₂ from the atmosphere and CO₂ escaping from the soil by photosynthesis.

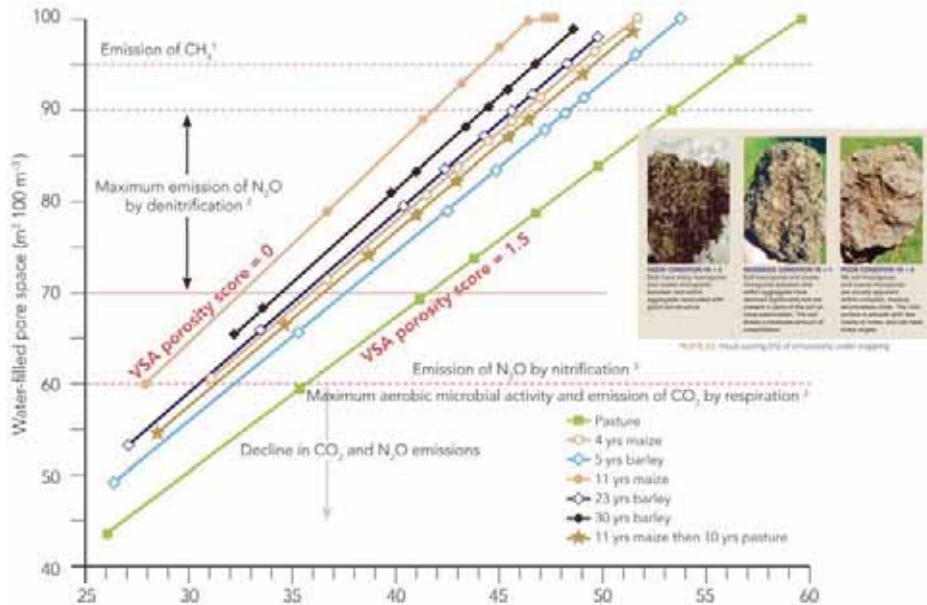
The potential of a site to emit GHGs can be roughly assessed from four indicators of soil quality, one indicator of plant performance, the amount and form of nitrogen applied, and the method of cultivation, as described below.

Soil textures (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major ‘driver’ of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs.

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O , and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 9); emissions of N_2O are lowest when the WFPS is < 50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 9) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O . In contrast, a severely compacted soil after 11 yrs of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 9) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2 . While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is

FIGURE 9 Affect of water-filled pore space and water content on greenhouse gas emissions

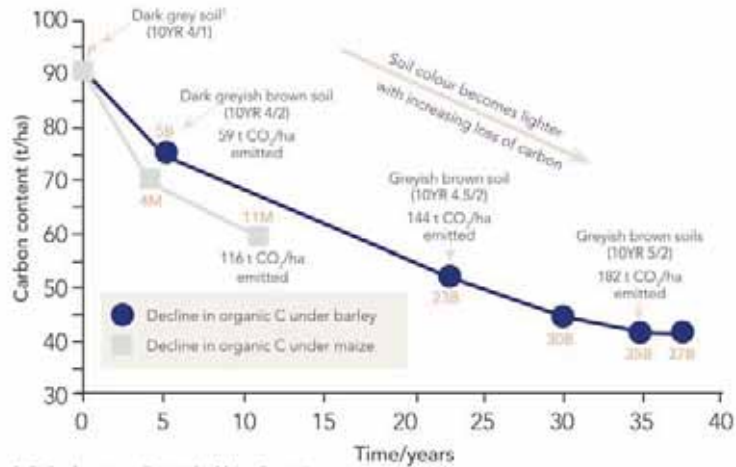


¹ After MacDonald *et al.* (1996); ² After Dobbie *et al.* (1999); ³ After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

hence an effective means of reducing GHG emissions. The relationship between the WFPS and the visual assessment of the porosity of the soil, as shown in Fig. 9, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink. A lighter soil colour compared with soil under the fenceline can also indicate the loss of soil C and the emission of significant amounts of CO_2 into the atmosphere (Figure 10).

FIGURE 10 Soil C loss and associated CO₂ emissions under continuous cropping

Soil C loss, associated soil colour, and CO₂ emissions under continuous maize and barley cropping using conventional cultivation.

Crop yields (p. 58) can provide an indication of the potential to reduce GHG emissions. The greater the crop yield, the greater the amount of CO₂ removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO₂ emitted by microbial respiration, the emission of GHGs from the consumption of the crop by stock, the burning of fossil fuels by farm machinery, and the application of nitrogenous fertilisers. As CO₂ escapes from the soil, most, if not or all, is absorbed by the stomata on the crop leaves, which have an insatiable appetite for CO₂. The greater the canopy cover (leaf area index) and the quicker the canopy closure, the greater the amount of CO₂ removed. Furthermore, if we assume that one kilogram of carbon in a maize crop removes 3.67 kg CO₂ from the atmosphere, a field growing 25 tonnes of maize silage/ha (or 10.3 t C/ha) will remove approximately 38 tonnes of atmospheric CO₂/ha. A field growing just 20 tonnes of maize silage/ha (or 8.2 t C/ha) will remove 30 tonnes of atmospheric CO₂/ha, 22 percent less than the higher producing field. While CO₂ is the least potent of the GHGs with a Global Warming Potential that is 21 and 310 times less than CH₄ and N₂O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO₂ into sugars and oxygen, and subsequently into soil C, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Poor crop yield and the associated reduced crop cover would also reduce insulation from the sun, thereby increasing soil temperatures and reducing the uptake of available N and plant-available water, stimulating N₂O emissions by microbial nitrification and denitrification.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 89) can provide a further indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 9). The nitrification of urea and ammonium-based fertilisers, and particularly the denitrification of nitrates in the soil resulting from the excessive application of salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Fertiliser N applications stimulate emissions in the spring, while crop residues and their incorporation into the soil stimulate emissions in autumn and winter. The highest emissions occur following each fertiliser application, particularly when associated with major rainfall events. Seventy-five to eighty percent of the N_2O emitted can occur within 4 weeks of N application. While N_2O emissions can often account for up to 3 percent of the N applied as fertiliser in small-grain cereal crops and up to 8 percent in maize crops, compact, wet soils can increase N_2O emissions by denitrification 3–4-fold, resulting in a loss of up to 20 percent of fertiliser N, and also decreasing wheat yields by 25 percent. Yield reductions can be attributed in part to N deficiency by high denitrification activity and low mineralization. In addition, the excessive use of nitrogenous products can reduce the capacity of soils to take up and oxidise atmospheric CH_4 , thereby reducing the ability of the soil to act as a CH_4 sink.

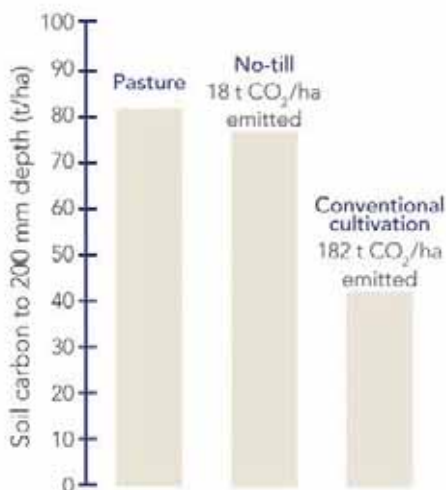
Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied to crops could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic and fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70%) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides microsites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root development, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70%, they can increase NH_3 emissions and potential NH_4^+ -N leaching losses. The jury is also still out as to their long-term impact on soil biology, in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be

applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reductions in white clover. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

The **method of cultivation** (see scorecard, p. 89) can have a marked effect on the level of GHG emissions. Carbon dioxide emissions are significantly greater under conventional cultivation than other forms of ground preparation because of the greater loss of soil C (Figs 10 & 11). The high level of soil disturbance under conventional cultivation aerates the soil, increasing the mineralisation and oxidation of organic C to CO_2 by microbial respiration which subsequently volatilises into the atmosphere. If we assume that one tonne of organic C oxidises to 3.67 tonnes of CO_2 , the loss of 31.6 t C/ha after 11 yrs of conventionally cultivated maize gives rise to the emission of approximately 116 t CO_2 /ha (Fig. 10). The loss of 49.6 t C/ha after 35 yrs of continuous barley produces 182 t CO_2 /ha. These figures do not, however, take into account the C added to the soil from the plant over the 11- and 35-year cropping period, C that would also have oxidised and potentially contributed to CO_2 emissions. However, as mentioned above, after CO_2 escapes from the

FIGURE 11 Soil C loss and associated CO_2 emissions under no-till and conventional cultivation



Soil C loss and associated CO_2 emissions under 20 yrs of double cropping using no-tillage and 35 yrs conventional cultivation.

soil, almost all of it is absorbed by the stomata on the crop leaves and is therefore recycled back into the soil. In addition to the major period of CO₂ emissions when the soil is tilled using conventional cultivation, a certain amount of CO₂ would be emitted after the harvest or senescence of one crop, and canopy closure of the next crop.

In comparison, the loss of soil organic C under no-tillage is significantly less than under conventional cultivation, producing as a result, less emissions of CO₂ (Fig. 11). Adopting carbon capture and storage (CCS) management practices including those cultivation practices that minimise C loss or even promoting C sequestration, is an effective means of reducing the emissions of CO₂ into the atmosphere.

Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by the Emissions Trading Schemes. If the GHG Emission Index is ≤ 22 , certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of > 22 provides significant environmental benefits because less GHGs would be emitted into the atmosphere.

FIGURE 12 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner: _____ Land use: _____
 Site location: _____ GPS ref: _____
 Sample depth: _____ Topsoil depth: _____
 Soil type: _____ Soil classification: _____
 Drainage class: _____ Date: _____

Textural group (upper 1 m): Sandy Coarse loamy Fine loamy Coarse silty Fine silty Clayey Other

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below ¹)	g.2	x 2	
Soil porosity	g.6	x 3	
Number and colour of soil mottles	g.8	x 3	
Soil colour	g.10	x 2	
Crop yield	g.58	x 2	
Amount and form of N applied (Scoring protocol is given below ²)		x 1	
Method of cultivation (Scoring protocol is given below ³)		x 3	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 12
Moderate potential GHG emissions	12–22
Low potential for GHG emissions	> 22

1 Textural group (Figure 2b, p. 3):

VS = 2 for Sandy and Coarse loamy; VS = 1.5 for Coarse silty; VS = 1.0 for Fine loamy; VS = 0.5 for Fine silty; VS = 0 for Clayey.

2 Amount and form of N applied:

VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 1 if 120–160 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; VS = 0 if ≥ 200 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 Method of cultivation:

VS = 2 if using no-till practices; VS = 1.5 if using strip tillage; VS = 1 if using minimum tillage; VS = 0.5 if using a mouldboard plough with limited secondary cultivation; VS = 0 if using continuous conventional (mouldboard plough) cultivation with intensive secondary cultivation.

Soil management of maize crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, include ‘pasture cropping’ where annual crops are direct-drilled into perennial pastures, and no-tillage and minimum tillage practices that incorporate the establishment of temporary cover crops and crop residues on the surface. They provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage can also maintain soil life and biological activity (including earthworm numbers), and can increase micro-organism biodiversity above levels commonly found under conventional cultivation. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO₂) and enables the soil to operate as a sink for CO₂. Soil organic matter levels can build up as a result and create the potential to gain ‘carbon credits’, thereby providing an offset to greenhouse gas emissions. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

Where possible, put in place management strategies that don’t require the use of herbicides. Avoid a monochemical herbicide strategy and manage the use of herbicides in association with crop rotations, including the use of livestock, to avoid the development of herbicide tolerance and residual effects. Ensure the soil has adequate levels of available Ca because herbicides are generally more effective when Ca levels in the plant are good. Also ensure that P levels aren’t too high; the higher the P level, the harder it is to deal to snails and slugs. The inappropriate and over-use of various herbicides can significantly change nutrient availability and the efficient uptake of nutrients by binding up micronutrients (chelation immobilization), and through toxic effects on soil organisms important for nutrient turnover and supply.

Continuous conventional cultivation can impact negatively on the environment with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO₂), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades

PLATE 53 A good maize crop



Photo: Courtesy of Kenneth G. Cassman

A good maize crop producing a grain yield in excess of 20 t/ha due in part to the adoption of good management practices that promote a good root system. Note the good potential rooting depth and root development to > 2m. Compare with Plate 16, p. 23

soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. Conventional cultivation should be practiced on a rotational basis with 2 years of cropping followed by 5–7 years pasture.

The fundamental difference between continuous conventional cultivation and conservation tillage is their relative environmental and economic sustainability. The long-term affects of continuous conventional cultivation can be cumulatively negative whereas the long-term affects of conservation tillage can be cumulatively positive. This is provided that good residue management practices are applied and the herbicides used are 100% biodegradable and have no adverse effects on soil or human health.

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for maize*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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