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Nutrient Recovery and Reuse (NRR) in European agriculture

A review of the issues, opportunities, and actions

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About the RISE Foundation

The Rural Investment Support for Europe (RISE) Foundation is an independent foundation which strives to support a sustainable and internationally competitive rural economy across Europe, looking for ways to preserve the European countryside, its environment and biodiversity, and its cultural heritage and traditions. It works as a think tank, bringing together experts to address key environmental/ agricultural challenges in Europe and develops high quality accessible research reports with clear recommendations for policy makers. It draws on its extensive network of rural stakeholders to highlight innovative practises developed at the farm level and provides a platform for debate on issues that affect rural communities.

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This report has been financially supported by

Aqua e Sole
Carlsen Lange Foundation
Fertilizers Europe

Recommended Citation

Buckwell, A. Nadeu, E. 2016. *Nutrient Recovery and Reuse (NRR) in European agriculture. A review of the issues, opportunities, and actions.* RISE Foundation, Brussels.

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Nutrient Recovery and Reuse (NRR) in European agriculture

A review of the issues, opportunities, and actions

2016

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PREFACE

As concern grows over the looming nexus of climate change, population growth and resource depletion, the agricultural sector has inevitably come under the spotlight. Whilst advances in technology over the last century have enabled a rapid increase in agricultural productivity in line with expanding demands, it is becoming clear that this growth can no longer be sustained in its current form. The impacts on the environment have been huge, causing wide scale water and air pollution, loss of biodiversity and soil erosion.

Inappropriate management of nutrients is a critical part of this story. It is now recognised that the growing leakage of nutrients from agriculture into the environment is affecting Europe's environmental security and clear steps must be taken for improved nutrient stewardship. Nutrient recovery and reuse from waste streams, such as animal manure, human sewage sludge, and food chain waste, can offer an important contribution to improve the efficiency of nutrient management and support Europe in its transformation to a more circular economy.

The RISE Foundation has launched this study to build on the previous report on the Sustainable Intensification of European agriculture: a review[4], in which nutrient management featured as a case study. The Foundation saw that nutrient recovery and reuse had great potential to address some of the key issues surrounding nutrient use in the food chain, namely pollution, waste management and dealing with finite resource depletion. The intention is to bring together the key challenges to nutrient management and the potential offered by Nutrient Recovery and Reuse (NRR) to engage policy makers and stakeholders who are working in this field. The NRR sector is still in its infancy and therefore collective actions will have to be taken if it is to grow.

The study engages a multi-disciplinary approach to bring together in a more integrated way, knowledge and expertise which is found in the separate worlds of agricultural science and farming, the food industry, water and sewage treatment industries and environmental and waste regulation. Specifically it aims to provide greater clarity on the following questions:

- What is the scope for nutrient recovery and reuse in Europe?
- What are the issues and opportunities that this involves?
- What are the actions that could support the development of nutrient recovery and reuse in Europe?

This report has been developed at a particularly relevant time following the release of the European Commission's Communication on the Circular Economy and we hope that through its conclusions and recommendations, it will support the thinking and development of the Communication's roll out in the coming years.

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[4] *Buckwell, A. et al 2014. The sustainable intensification of European agriculture. The RISE Foundation, Brussels*

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Executive summary

Key Messages

1. Exponential growth in the flow of nutrients (nitrogen N, and phosphorus P) through the global agricultural and food system to feed the longer-living, wealthier more numerous population is causing serious environmental and public health impacts because the processes involved have serious leakage.
2. International studies have quantified the flow of nitrogen and phosphorus through the food chain (from farm to fork) and show that a large proportion of the unwanted side effects from nutrient flows have resulted from expansion of the livestock sector which, is inherently biologically inefficient and leaky.
3. The three main levers available to try and contain the growing damage are to change dietary goals towards lower consumption of livestock products, to improve crop and animal nutrient use efficiency through more knowledge intensive, precision agriculture and to reduce all waste. Nutrient Recovery and Reuse (NRR) contributes to the second and third of these.
4. In coming decades it is not any shortage, and thus high prices, of the raw materials used in mineral fertiliser manufacture which threatens global or European food and environmental security. Rather, it is the growing leakage of nutrients into the environment which poses the greatest threat.
5. Nutrient recovery and reuse in the EU would represent an intelligent diversification of sources of nutrient supply, which would add resilience in the event of supply disruption of phosphorus from N Africa, USA and Russia, or natural gas from Russia.
6. Every tonne of nutrient which is intercepted from a waste flow and processed into a form suitable to be used to fertilise crops represents a tonne less which would have leaked into water, the air, or the atmosphere, or ended up in land fill.
7. There is substantial scope to recover and reuse nitrogen and phosphorus from the European food chain. The most promising three substrates to work on are: animal manures, sewage waste and food chain waste, especially slaughterhouse waste.
8. Between 2 and 5 Mt of N and 0.6 Mt of P are currently not being recovered for agricultural use from these three major waste streams. These quantities represent 18-46% of the 11 Mt of mineral nitrogen currently applied to EU crops, and 43% of the 1.4 Mt of mineral based phosphorus applied to crops.
9. Significant challenges are posed by the characteristics of the waste flows from which nutrients are to be recovered, and the nature of the recovered products. The issue is complex, many actors are involved, it difficult to draw up simple lines of action.
10. As nutrient recovery and reuse is being promoted to rectify significant environmental market failures, NRR activity will not spontaneously, swiftly and significantly increase in scale without further collective actions – many of which are signalled in the Circular Economy action plan of the European Commission. This report offers sixteen suggestions of specific actions to take Nutrient Recovery and Reuse to the next level.

General conclusions

Current global mega-trends, climate change and population growth, are stimulating a rethink of the way all sectors of the economy are operating, and not just how food is produced and consumed. Change is already happening. In some areas these are already quite visible, for example in mobility, while in other areas, including food production, the transition is lagging and the resistance to change is somehow stronger. The way nutrient flows are managed should be a core part of this rethink. The challenges are global, so this requires international efforts to find solutions. This was clearly recognised by important decisions reached at the global level during 2015. Adoption of Sustainable Development Goals (SDG's) in September and the Climate Change agreement reached in Paris in December are showing the way to a more sustainable future. As a highly developed region, with a highly intensive agriculture, Europe can perform a leadership role in improved nutrient management. Since the transition is unavoidable this would also create first mover advantage and economic opportunities.

The primary task of agricultural systems is to provide essential nutrients and other natural products for the human population. Human beings are omnivores and have always consumed, in varying proportions, a diet of vegetable and animal products. As the human population has risen, it has also greatly increased material living standards, these have resulted in diet change towards the consumption of more livestock products, and human life expectancy has also significantly increased. The combined effect of these developments has seen an exponential growth in the flow of nutrients through the global agricultural and food system especially in the last six decades. It turns out that this is causing serious environmental and public health impacts because the processes involved have serious leakage.

It is only comparatively recently that gross flows of the two most important macro-nutrients, nitrogen (N) and phosphorus (P), have been rigorously studied, quantified and brought to the attention of scientists, policy makers and the public. This work has been done by large international teams of biological, environmental and agricultural scientists with substantial European input. The European Nitrogen Assessment, the German Council on the Environment (SRU) and the work of the Global Partnership on Nutrient Management provide accessible descriptions of this work[5]. Most of these large international projects have concentrated on nitrogen while the phosphorus work has been more *ad hoc*. A key message from these studies is that a large proportion of the unwanted side effects from nutrient flows has arisen because of the expansion of the livestock sector which, unfortunately, is inherently biologically inefficient and leaky.

The surge in these two nutrient flows is overwhelming the absorptive capacity of natural nutrient cycles. The processes through the whole food chain are associated with large leakages into the environment. This applies to all four major stages: fertilising crops, with either organic or inorganic nutrients; it especially applies to feeding farm animals and managing their waste; it applies to processing food and feeding the human population; and then managing human waste. The four principal signs of the damage of this over-extended system are: the eutrophication of water courses, lakes, inland seas and oceans; pollution of the air breathed by citizens with damaging health impacts; greenhouse gas (GHG) emissions which are changing the climate in harmful ways; and damage to terrestrial and aquatic biodiversity.

The growth in nutrient flows shows every sign of continuing in coming decades, and therefore the scale of the associated damage can be expected to grow. Human population is expected to rise another 30% by mid Century. It is policy everywhere to drive income growth and to further increase human life expectancy. There is no possibility that these three factors will change. Therefore, the three main levers available to try and contain the growing damage are to change dietary goals towards lower consumption of livestock products, to drive hard to improve nutrient use efficiency at each stage in the food chain, and to reduce all waste. Without strong corrective actions there is every prospect that the damage resulting from nutrient leakage will continue. This damage, through water and air pollution, biodiversity loss and harmful climate change, threatens the very sustainability of the agricultural system itself and thus global food security.

The origins of this report came from a rather different aspect of food security. This concerned fears about the security of relying for our food production on non-renewable mineral phosphorus and the manufacturing of nitrogenous fertiliser using the fossil fuel natural gas which should be curtailed for climate protection reasons. An obvious way to reduce such risks would be to recover nutrients not taken up by plants, animals and humans, and reuse them. This would reduce reliance on mined, and mostly imported, phosphorus and manufactured nitrogenous fertilisers based on imported natural gas and it would be a practical demonstration of the circular economy in action.

The critical point about nutrient recovery and reuse is that each tonne of recovered and reused N and P offers the following benefits:

- Less water and atmospheric pollution, because the N and P in some waste streams has been captured and is thus prevented from leaking.
- Less depletion of finite reserves (P) and use of fossil fuel natural gas (N) contributing to GHG emissions.
- Reduction in environmental pollution associated with the mining, processing and transport of phosphorus and the manufacture of nitrogenous fertilisers.
- Diversification of nutrient supply thereby reducing reliance on imported phosphate rock and natural gas.

[5] *Sutton M and Van Grinsven et al (2011) Summary for Policy Makers, European Nitrogen Assessment, SRU (2015) Nitrogen: strategies for resolving an urgent environmental problem, and GPNM (2013) Our Nutrient World.*

The report therefore assesses the relative role that nutrient recovery and reuse can play in addressing 5 goals and concerns related to current nutrient use:

1. **Food production** to feed a growing population.
2. **Farm viability**.
3. **Pollution of water, air and soil and impact on the climate.**
4. Reduction and recycling of **food chain waste.**
5. Confront the dependence of the food system on **finite, insecure, non-renewable resources**.

The geographical focus of this report is the European Union. A conclusion of this study is that over the next few decades it is not any shortage, and thus high prices, of the raw materials used in mineral fertiliser manufacture which threatens global or European food and environmental security. Rather it is the growing leakage of nutrients into the environment which poses the greatest threat. Nutrient Recovery and Reuse (NRR) in the EU would represent an intelligent diversification of sources of nutrient supply, which would add resilience in the event of supply disruption of phosphorus from N Africa, USA and Russia, or natural gas from Russia. However, the larger and more important contribution of NRR to food security is to improve European nutrient use efficiency. Every tonne of nutrient which is intercepted from a waste flow and processed into a form suitable to be used to fertilise crops represents one tonne less which would otherwise have directly leaked into water, the air, or the atmosphere or ended-up in land fill. To the extent that recovered nutrient displaces some manufactured mineral fertiliser, its use may also reduce pollution associated with the mining and manufacture of phosphorus fertilisers and the manufacture of nitrogenous fertiliser[6]. There is an important proviso that life cycle assessments of recovered nutrients are needed to determine their energy and resource efficiency relative to that of conventional mineral fertilisers. Nutrient recovery and reuse therefore offers an important contribution to improve the efficiency of nutrient management.

It is emphasised that NRR is not the whole answer to the disruptive environmental effects of inflated nutrient flows, it is just the chosen focus of this report. This in no way diminishes the importance of constantly seeking to improve nutrient stewardship in crop and livestock production. This can be done in many other ways. The current moves to more knowledge-intensive precision crop and livestock farming indicate the direction of travel. There is considerable scope to do this. For example, increasing soil carbon stocks by increasing the return to soil of recovered organic material will improve soil quality. This would contribute to a higher nutrient use efficiency and a reduction in losses to the environment. There is large scope to improve the efficiency of nutrient use in crop production by balanced nutrition and precision fertilisation of crops. There is similarly large scope to improve the nutrition of farm livestock by better breeding and more precise data-led livestock feeding. These aspects are not the main focus of this report, and neither is the need to, nor methods of, inducing better diets and thus nutrition of the human population. These are inescapably part of the larger agenda to achieve sustainable nutrient flows but they take us outside the prime focus on Nutrient Recovery and Reuse.

Specific conclusions on the use of nutrients in the EU and the scope for recovery and reuse

Nitrogen and phosphorus are essential nutrients that play key roles in the development and functioning of plants, animals and humans. In order to feed the expanded population, agriculture heavily relies on the inputs of mineral nitrogen and phosphorus. It is estimated that around 16.7 Mt of N enter the EU agricultural system annually, 10.9 Mt of which in the form of mineral fertilisers and 2.7 Mt N as feed, while external inputs of phosphorus include 1.4 Mt P of mineral fertiliser and 0.4 Mt P of feed.

Mineral fertiliser inputs in the EU have fallen over the last twenty-five years and P fertiliser inputs are back to levels of the 1950s. Nitrogen fertilisers now account for 70% of all mineral fertiliser inputs. Despite the significant falls in use of mineral fertilisers the efficiency of nutrient use through the whole food chain unfortunately remains low. For every five tonnes of nitrogen entering the EU agricultural system, only one tonne is converted to finished products for human consumption, that is a 20% Nutrient Use Efficiency (NUE). For phosphorus, the corresponding figure is 30%. While crop production shows a relatively high NUE due to advances in crop genetics and management and fertiliser application techniques (53% for N and 70% for P), livestock makes a particularly inefficient use of nutrients (18% NUE_N and 29% NUE_P).

These low efficiencies result in large leakage of nutrients into the environment with negative impacts on soils, water and air, and are associated with unacceptable health and environmental costs. In soils excess P build-up can lead to increased phosphorus losses through runoff and soil erosion, while atmospheric nitrogen deposition is reducing biodiversity. P and N in waters contribute to eutrophication, reducing water quality, aquatic biodiversity and increasing greenhouse gas emissions. In the atmosphere, nitrogen oxides and ammonia reduce air quality, contribute to atmospheric deposition and have a strong impact on human health. Nitrous oxide, derived from the application of synthetic fertilisers and manure to soils, and methane, from ruminant digestive fermentation, are the main agricultural contributors to climate change while ammonia, resulting mainly from livestock and manure management contributes to air pollution.

[6] *Strictly this latter benefit should be measured as the net saving of energy and pollution associated with the collection and processing of the recovered nutrient compared to the corresponding effects involved in the manufacture of the equivalent amount of N and P in the form of mineral fertiliser. One tonne of recovered nutrient may not necessarily equal one tonne of mineral fertiliser.*

Increased nutrient recovery and reuse can contribute to reducing these losses and increasing nutrient use efficiency. This study suggests the key waste streams on which to focus. A large number of nutrient recovery techniques are currently available or under development to perform this function. In short, increasing the potential of nutrient recovery and reuse requires that three parallel tasks be undertaken: (i) to increase the **total amount of recovered nutrients** from waste streams; (ii) to increase the **fertiliser equivalence value** of recovered nutrients (as formulated by Sutton *et al* 2011); and (iii) to create recovered products that are safe, easy to store, handle and use by farmers and which reduce current N and P leakage associated to nutrient recycling.

The two prime questions posed in this report are:

Is there scope and are there workable processes to recover and reuse nitrogen and phosphorus in the European food system? In what quantities and from which substrates can this be done?

Yes, there is substantial scope to recover and reuse Nitrogen and Phosphorus from the European food chain. The following figures are based on the summary Tables 4 and 5 in Chapter 4. It is emphasised that these figures are the best available estimates based on the nutrient assessments conducted in recent years for the EU. The sources of these figures and details are explained in Chapter 4. The figures are orders of magnitude, they show estimates of nutrients in material flows which are not currently being recovered and reused in agriculture but potentially might be. Because some of this may not be easily recovered these figures should be taken as upper limits considering current waste collection rates.

With current technology and incentives for implementing the circular economy for nutrients, the most promising three categories of substrate to work on are: animal manures, sewage waste and food chain waste especially slaughterhouse waste. The potential volumes of recoverable nutrient from these three waste streams are estimated to be in total, approximately, 12 Mt N and 2.5 Mt P annually. About 60% of N and 75% of P in these waste streams are already being recovered and reused – a large part of this is in the form of animal manure and after very little processing.

It is suggested that between 2 and 5 Mt of N and 0.6 Mt of P are currently not being recovered for agricultural use from these three major waste streams and these therefore constitute the prime targets for further nutrient recovery and reuse. To put these quantities in perspective, they represent 18-46% of the 11 Mt of mineral nitrogen currently applied to EU crops, and 43% of the 1.4 Mt of mineral based phosphorus applied to crops. Technologies for such recovery are available. Some are already in commercial operation in several Member States, but much of this development is at the pilot plant stage and its commercial viability is yet to be proven.

Returning animal manure to land is almost as old as agriculture itself, it must be the longest-established example of the circular economy in action. It is estimated that a little under 8 Mt and N and 2 Mt of P are returned to land in the form of animal manure. These seem impressive

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figures in comparison to the scope for further recovery. However, much of this existing recycling of nutrients back to land is imprecisely applied resulting in unbalanced fertilisation and by no means all of these quantities are available for up-take by crop plants and therefore much is lost to the environment.

Manure is the single largest waste flow of nutrients and provides over 70% of the current total recovered N and P from all sources. However, manure handling and application results in large amounts of nutrient losses (calculated to exceed 6 Mt N per annum) through gas emissions, leaching and runoff. Some of the gaseous nitrogen emissions could be reduced by improving manure field application and ammonia could be recovered by sealing manure storage facilities. There is also scope to reduce ammonia emissions and facilitate nutrient collection by better design and management of animal housing. Such actions often require large farm level investment which can be difficult in small scale operations, although imaginative farmer cooperatives are finding ways to surmount these challenges. In addition, there is scope to further process manure to make it a more targeted fertiliser by providing nutrients in combinations best suited to crop needs and presenting it in a form that is easy to handle and apply by farmers while contributing to reduce nutrient leakage into the environment. Solutions will have to be tailored to suit the differing conditions in the regions of the EU.

In the case of **sewage**, about 10 Mt of dry sludge is produced annually in the EU, representing 3.3 Mt N and 0.3 Mt P. 42% of this sewage sludge is already being returned to agricultural soils after stabilisation, but often with application rates not well matched to nutrient requirements. There is often a high P content which leads to P accumulation in soils. There may be spatial constraints on the extent to which this material can be spread on land because of transport costs. There is also some reticence in some Member States to reuse sludge. There is sometimes insufficient knowledge and specification of the plant-available nutrients present in the sludge to be applied to land. Second there are concerns about possible presence of pathogens, pharmaceuticals and complex organic compounds which could threaten plant, human and long-term soil health. Technological improvements in recovery techniques can address these concerns and increase societal confidence.

Strategies for N and P recovery from sewage differ. One of the main issues for nitrogen recovery is that between a third and a half of the N is lost through nitrification/denitrification processes but could be recovered by implementing appropriate technologies (e.g. ammonia stripping). Therefore, avoiding denitrification in wastewater treatment plants and shifting to nutrient recovery technologies to remove N could significantly increase its recovery from sewage. In the case of phosphorus, many recovery techniques have appeared over recent years. However, only a few are operating at full-scale or even as pilot plants. Most of the processes recover P from sludge dewatering reject streams or sludge liquor with recovery rates ranging between 15-30%. However, higher recovery rates (70-90%) can be obtained from sewage sludge ash from mono-incineration, but this is currently a minor treatment route still being tested at pilot plants. The majority of the systems currently in operation recover P in the form of struvite with maximum potential recovery of 30%. Further investment in technical improvement is needed.

Some of the challenges for nutrient recovery from sludge are therefore to (i) increase central collection of sewage; (ii) switch from nitrification/denitrification to ammonia stripping in order to recover N; (iii) encourage anaerobic digestion to obtain a stable sludge, produce biogas and allow for further nitrogen stripping, and (iv) support research on technologies to separate P in sludge and sludge ashes from pollutants.

Municipal and food chain waste pose their own unique challenges. The total potential quantities appear to be large but the sources are numerous and heterogeneous. Also there is considerable uncertainty about the quantities available because food waste definitions are not agreed. This results in many different estimates of the quantities available. There are long-established recovery and reuse channels in some areas, for example, municipal green waste for composting, and more recently anaerobic digestion. Meat, blood and bone meal have a long history of use as fertilisers. Recovery of phosphorus is technically not difficult, but nowadays this use is subject to animal by-product regulation. The use of offal in pig swill for animal feed ran into difficulty with the discovery of BSE (Bovine Spongiform Encephalopathy) in the mid-1990s. But other food chain waste such as brewers grains have a long history of recycling in their use as cattle feed. For Municipal waste one of the major challenges is to encourage the separation and collection of the organic fraction in laggard counties to catch up on those where this is now routine. A particular feature of the development of nutrient recovery and reuse based on municipal and food chain waste is the policy goal to significantly reduce this waste. The highest priority in the well-accepted waste hierarchy is to prevent waste appearing in the first place. This consideration has therefore to be factored into planning and investment in nutrient recovery from this substrate stream.

The encouraging conclusion is that there is substantial scope for more NRR. The more sobering conclusion is that there is no single new source of nutrients nor single new process which is going to revolutionise NRR and drive it to a new level. What is required is a new determination to push many activities to reach their potential. This is precisely the purpose of the Circular Economy initiative. It is a vehicle to inject energy and enthusiasm to focus attention on sustainable consumption and production, and to ensure the regulatory landscape encourages and does not inhibit the transformation of waste into secondary raw materials. It is a way to stimulate innovation, and in the process to create jobs and growth especially in the rural economy as many of these recovery processes will be decentralised activity.

What is impeding the rapid development of NRR, and what actions could be taken to propel it?

Significant challenges are posed by the very nature of the waste flows from which nutrients are to be recovered. These flows are comprised of very large volumes and masses of materials, many of which are highly dilute and heterogeneous especially the 'outputs' from livestock and humans. They arise in continuous daily flows, widely spatially dispersed in multiple sources over all human-occupied territory; and whilst nutrients *per se* are welcome, many of the output flows are considered wastes and distasteful. They are associated with substantial soil, water and air pollution risks some of which also risk harm to human health; and they are destined to be added to the soil where there is potential for long-run accumulation of any undesirable contaminants present, even if in very low concentration.

These characteristics, particularly the use of human sewage in food production, can bring with them some fairly deep negative attitudes towards this aspect of NRR. Fears about contamination of food by heavy metals, pathogens or pharmaceuticals, and about odour and troublesome traffic in rural areas associated with storage, transport and spreading of recovered nutrients, have to be, and can be, allayed by appropriate technologies and practices. This demands sound monitoring and good communication. In addition the very structure of the nutrient recovery industry, its dispersed, relatively small scale operation compared to mineral fertilizer manufacture, and the heterogeneity of its inputs and products, create a further challenge to the development of the sector. It cannot be taken for granted that the products from nutrient recovery processes are perfect substitutes for existing fertilisers. Farmers will judge them primarily on their price, nutrient composition, consistency, ease of handling and storage, and their crop production performance. They will choose to purchase, or use them if provided free, accordingly.

For these reasons, and the very fact that establishing nutrient recovery and reuse is being promoted to rectify significant environmental market failures, it is suggested that the take-off for this sector will not happen spontaneously but will require a variety of collective actions.

Many of these actions are already well acknowledged and are underway in the EU. There is recognition that nutrient management is a heavily regulated area. It has to be, public safety and confidence are paramount. However, a process of review of some of this regulation is underway. Revision of the fertiliser regulation to more clearly define 'end of waste', and provide for certification of recovered nutrients is work in progress. Raising the ambition of waste separation and collection, establishing a common EU definition of food waste and encouraging nutrient recovery and reuse are amongst the many actions proposed in the European Commission's Circular Economy package of December 2015. The EU research programmes have certainly identified the importance of establishing a sound scientific basis for NRR. In parallel, the private sector has been imaginative and active in creating stakeholder platforms for the sharing of knowledge, ideas and experience in sustainable nutrient use. However, such is the complexity of the legislation affecting the fertiliser industry, farms, food industry and the water treatment sector at both the EU and national levels that it is not possible to assess the coherence of this legislation and whether it is optimally structured to stimulate NRR to realise its potential. This could be a priority for a further research project.

A large remaining question is whether more active steps should be taken to stimulate more recovery of nutrients and their use in agriculture or to incentivise this by restricting, or taxing, non-recovered nutrients? The qualitative arguments assembled and discussed lead to the conclusion that, even with the favourable assistance currently underway through regulatory reform, research and information provision, NRR activity will not spontaneously, swiftly and significantly increase in scale. Therefore, further collective action is justified. It should start with an appraisal of suitability of the current legislative landscape to test if it is most appropriate to stimulate the next stage of development of NRR. Then it should examine in detail the benefits and costs of each of the ways that could be undertaken to provide this stimulus.

The report reviews eight kinds of further collective actions. It looks at five ways of providing positive stimulus (obligations, targets, investment grants, subsidies, fiscal reliefs) and three ways of giving advantage to recovered nutrients by penalising the alternatives (fertiliser tax, land fill and incineration fees or restrictions, nutrient surplus tax). This overview cannot provide the basis on which conclusions can be drawn on the overall or specific costs and benefits of such measures. Policy in this area therefore requires rigorous research to answer two questions:

(1) Do the potential environmental, human health and economic benefits in the EU merit the deployment of a combination of active positive and negative actions to stimulate a step up in Nutrient Recovery and Reuse?

(2) If so, what is the best such combination of measures?

In short, this study has identified that there is substantial scope to increase NRR in the EU. It suggests that NRR could be an important contributor to better nutrient management. The NRR sector is growing, there are suitable technologies being developed, and the regulatory environment is improving. But it concludes that because of the intrinsic character of the materials involved, the processes, products and businesses likely to be engaged, without purposive further incentives and actions NRR activity is unlikely to expand rapidly. However, before such incentives are given, rigorous cost benefit, including life cycle, analyses are required.

Recommendations

Nutrient recovery and reuse has the potential to contribute to better nutrient stewardship and provide some degree of diversification of nutrient supply to help nutrient security. What is also evident is that the lack of uniform data makes it hard to estimate precise potential for recovering nutrients in Europe. Although there is apparently a large recovery of nitrogen through the use of animal manure, the effective reuse of this nitrogen is low because current manure storage and distribution are themselves inefficient. There seem obvious benefits to be gained from nutrient recovery and reuse if done properly. But the path to increase NRR uptake is complex, requiring multiple actions. Unless the many obstacles that block its way are addressed, the industry will remain in its infancy. Some of the actions to do this are summarised here.

1. **Better data**. To assess more accurately the scope for the recovery of nutrients from various waste streams, policy makers, entrepreneurs, and investors in Europe require better data than currently are available. This calls for clearer standardised definitions, measurements, monitoring and analysis of the flows of the relevant waste materials in Europe.

   Recommendation 1: *Develop a common methodology and define indicators to monitor nutrient flows and organic carbon in waste streams as suggested by the DONUTTS project*[7].

   Recommendation 2: *Apply this new methodology in the EU, and at Member State level to provide regular updates on progress towards the goal of increasing nutrient recovery and reuse and meeting the targets set for the Circular Economy.*

2. **Regulatory coherence**. There are a large number of directives and regulations already in place concerning the use of nutrients at the EU level. However, there is a great variety of corresponding regulation at national and regional level which can hinder entrepreneurial impetus, investment and knowledge transfer. If there is to be a greater development and uptake of nutrient recovery and reuse, the regulations that govern the sector require some coherence across the Member States, whilst recognising diversity of conditions and priorities. Do the EU level regulations hinder nutrient recovery in Europe, and are they adequate? What needs to be changed at the national level to better develop this sector?

   Recommendation 3: *Conduct a full review of the legislation affecting all aspects of nutrient management in Europe and changes in European and National legislation that could help stimulate more NRR.*

3. **Appropriate policies for NRR**. There are very important revision processes underway for specific legislation concerning recovered nutrients for use in agriculture (End of Waste Criteria and the Fertiliser Regulation) and it is hoped that these will go a considerable way to support the development of the NRR market in Europe. However, the characteristics of the NRR market structure make it unlikely that this sector will flourish without some form of further policy support: either positively through inducements, or through penalties on polluting activities. Experience has shown that the correct mix of these policy tools cannot be identified without careful and detailed analysis and impact assessment.

   Recommendation 4*: Analyse the impact that nutrient recovery and reuse could have on the environment, and on resource security, and its potential to create jobs, income and growth in rural areas to help establish the case for collective action to drive a step up in NRR.*

   Recommendation 5*: Analyse the feasibility and costs and benefits of the deployment of specific measures, including subsidies and taxes, to directly stimulate NRR, or to restrict or penalise alternative nutrients.*

   Recommendation 6*: Provide public funding to help take technologies for NRR being developed in the laboratory to the pilot project phase and the development of pilot projects towards full scale commercial enterprises.*

   Recommendation 7: *Ensure that NRR projects are flagged as eligible for consideration for EU funds for Rural Development, and activities undertaken by the European Investment Bank.*

   Recommendation 8: *Encourage coordination of R&D activities on NRR across Europe, through more clustering of science centres for the different recycling areas, including the European Commission's Joint Research Centre.*

[7] *See: http://www.phosphorusplatform.eu/platform/news/698-data-on-nutrients-to-support-stewardship-donutss*

4. **Circular Economy Package**. This is a highly welcome development given its comprehensive review of the actions that should be taken to address nutrient recovery and reuse in Europe. Particularly helpful to drive NRR would be the following:

   Recommendation 9: *High priority should be given to make rapid progress with the clear delineation, and establishment of standards and certification procedures for recovered nutrient products, and traceability protocols for recycled nutrient products which could contain organic contaminants. These should cover the nutrient content, the maximum level of impurities which could be a threat to health, safety and environment, and product quality and application techniques.*

   Recommendation 10: *Establish an EU level analytical framework for nutrients as well as a practical check list of potential actions to develop NRR further in Europe.*

   Recommendation 11*: Establish Best Available Technologies and the Best Practices Exchange for nutrient recovery and reuse and their promotion through current Information exchange platforms.*

5. **Consumer acceptance and land managers mobilisation**. It is clear that this can be a significant impediment to further NRR. Some consumers may be anxious about products fertilised with nutrients derived from sewage sludge. In some cases food processing and retailing companies are choosing to pre-empt their customers' views by refusing to buy products if they are fertilised in this way. There can also be resistance from land managers if they are not convinced of the nutrient value, consistency and performance of recovered nutrient products. Remedying this aspect is mostly the responsibility of the enterprises conducting the nutrient recovery, but research and development assistance may also be justified. Even without their own concerns about the quality and efficacy of recovered nutrients, farmers may be nervous about the willingness of their purchasers to buy their products. To overcome these attitude and cultural barriers there has to be in place the appropriate quality and safety standards for recovered nutrients, monitoring of the operation of these standards and their correct use by farmers notably through appropriate extension services. It is also advisable to devote resources to create an awareness raising campaign explaining the rationale and environmental benefits of NRR. This in turn should raise awareness of the consequences of the leakage of nutrients into the environment, and the ill health effects of nutrient mismanagement as well as creating greater clarity regarding concerns over the public health impacts of using recovered nutrients on land. This narrative can explain how waste separation and collection and NRR can reduce reliance on imported non-renewable resources, increase security of EU food, and the recovery processes can contribute to local jobs and growth and ensure productivity and sustainability of managed land in the long term.

   Recommendation 12: *Develop an awareness raising campaign to inform consumers about the impact of current nutrient use and the benefits of nutrient recovery and reuse.*

   Recommendation 13*: Provide research funding for analysis, understanding and risk-assessment of organic contaminants in nutrient recycling, including both processed sewage sludge and manures and recovered nutrient products.*

   Recommendation 14: *Inform, educate and motivate food processors/retailers to engage with the need for the application of circular economy concepts in food production to help create consumer and retailer 'pull' for products that are produced with recovered nutrients.*

   Recommendation 15*: Integrate NRR and soil carbon benefits into EU policies for renewable energy as well its contribution to adaptation and mitigation for climate change.*

6. **Optimal level of livestock product production and consumption**. The detailed research on nutrient flows through the highly sophisticated and complex EU food system which has been reviewed in this report has drawn attention to the worryingly large magnitude of the negative impacts on human health and on the environment and climate of the leakages associated with these flows. In particular it has become clear that a major contributor to this damage is the inherent inefficiency of producing human nutrition though livestock products. This is far from a simple matter. Livestock and its manure have an enormous, positive role in balanced agricultural systems – they currently provide over 50% of all EU crop nutrients and, of course, a high proportion of crop nutrients for organic farming. Livestock products provide valuable nutrients for human development and functioning, and there is a long-established cultural attachment to consuming these products. People enjoy them. But it is hard to avoid the conclusion that, over and above the need for a review to assess more active policy to stimulate nutrient recovery, there is a need for a thorough review of the optimal place of livestock in EU agriculture and livestock product consumption of citizens.

   Recommendation 16: *Conduct a high-level, wide-ranging, review of the optimal place of livestock in the EU, embracing both the health and environmental impacts of meat and dairy products in the human diet, and the spatial distribution and concentration of livestock production and its contribution to cultural landscape.*

ABBREVIATIONS

CH_4	Methane
CO_2	Carbon dioxide
EC	European Commission
EEA	European Environment Agency
EU	European Union
EU12	Member States that joined the EU between 1/5/2004 and 1/1/2007
EU15	Member States that joined the EU before 1/5/2004
EU27	Member States after the enlargement on 1/1/2007
GHG	Greenhouse Gas
Kg	Kilogram
MBM	Meat and Bone Meal
MS	EU Member States
MSW	Municipal Solid Waste
Mt	Megatonne (1 million tonnes)
N	Nitrogen (reactive nitrogen)
N_2	Nitrogen gas (unreactive nitrogen)
NH_3	Ammonia
NH_4	Ammonium
NGO	Non-Governmental Organisation
N_2O	Nitrous Oxide
NOx	Nitrogen oxides
NRR	Nutrient Recovery and Reuse
NVZ	Nitrate Vulnerable Zone
P	Phosphorus (element)
SDG	Sustainable Development Goals
SME	Small and Medium Enterprise
STW	Sewage Treatment Works
Tn	Tonne
UN	United Nations
WWTP	Waste Water Treatment Plant

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1. Introduction, context, objectives and scope

1.1 Introduction, why nutrients?

One of the stunning achievements of the twentieth century was the increase in agricultural productivity which enabled growth in food production to match the tripling of human population[8] with an equally impressive rate of economic growth and accompanying dietary change, all contributing to significantly increased life expectancy. Meeting this unprecedented growth in food consumption was achieved through the successful and systematic application of science to crop and animal genetics, nutrition, health, reproduction and growth. This was made possible through public and private sector research and commercial development of a sophisticated and now globalised food chain in partnership with a dynamic farming sector willing to take up new technologies and restructure their businesses to do so. Through this process agriculture released a large portion of its labour by substituting it with capital and knowledge, and real food prices fell throughout the century.

The challenge is now to repeat this performance during the twenty first century. Population growth has slowed, and it is to be hoped this continues, leading to stabilisation peaking at approaching 10 billion by the end of the century. In other words, the world population increase this century might be rather similar to the last, about 4 billion. This too, it is to be hoped[9], will also be accompanied by economic development in the poorest regions where nearly all the population increase will take place. In turn, the rising middle classes in Asia and Africa will expect to enjoy some of the dietary and lifestyle changes experienced in the developed parts of the world, and improvement in their life expectancy too. Thus there is every reason to expect, broadly, a similar growth in food consumption this century as in the last.

A cheery optimist might observe that if we managed to accommodate and feed an extra 4 billion people last century then surely with the knowledge and technology now at our disposal we can repeat this task this century? This is not an appropriate response. There are strong reasons to suggest that the challenge of providing sufficient nutrition for the world population this century is much greater – and this is principally because our twentieth century success was bought with a substantial degradation of climate security and natural capital. Of course climate change is fundamentally and mostly a result of the burn-

8 *From 1.8 billion to over 6 billion.*

9 *Not just hoped, but empowered by the Sustainable Development Goals 1 and 2 to eliminate poverty and hunger by 2030 (UN, 2014)*

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ing of fossil fuels, and whilst modern agriculture is a significant user of (fossil based) energy, it is small in relation to total energy consumption. However, our highly productive agricultural systems, and the land use changes which accompanied the expansion of agricultural output, are significant[10] contributors to the major greenhouse gases (carbon dioxide, nitrous oxide and methane). They are also associated with substantial shares of water pollution, soil degradation, air pollution harmful to human health, and biodiversity degradation.

Therefore, the strategic goal of the twentieth century to improve agricultural productivity to feed the growing population is now replaced by the much tougher assignment of maintaining productivity growth in agriculture for the same reason, but doing this without significant further agricultural land use expansion and whilst significantly cutting greenhouse gas emissions and the other leakages into soil, water and the air. A short hand for this task is to find a development path for agriculture which can truly be called sustainable intensification[11].

The route into this large subject area in this report is to focus on nutrients as one component of sustainable intensification. There are three reasons for this. The initial motivation for this study was the concern that continued growth in consumption might run up against limits imposed by finite resources, and phosphorus is nearly always mentioned in this context. The study was therefore seen as part of the important new initiative towards strengthening the circular economy in Europe. Second, the fundamental challenge is to provide nutritious diets for the growing, enriching, and longer-living human population. Third, on close inspection, the ways in which we use nutrients to grow the food crops which we eat, and to grow feeds for farm animals which we also consume, turn out to be significant contributors to some of the most damaging side effects of our agricultural systems.

Focusing on, and understanding, the complex flows of nutrients applied in agriculture is a very important step in devising ways to reduce these undesirable effects, and avoid potential limits. This task has already been launched in the scientific community and the last few years have seen the publication of a number of large research projects centred on the two principal nutrients nitrogen and phosphorus. A broad and global account of how mankind is disturbing natural cycles of nitrogen and phosphorus and the impacts of so doing is found in the report 'Our Nutrient World' Sutton *et al* (2013) and signed by the Global Partnership on Nutrient Management (GPNM) and the United Nations Environmental Programme (UNEP). There have also been several studies focusing solely on nitrogen, the most prominent ones being the European Nitrogen Assessment (Sutton *et al* 2011), the report on Reactive Nitrogen by the German Advisory Council for the Environment (SRU 2015) and the recently published report "Nitrogen on the Table" (Westhoek *et al* 2015), which followed the European Nitrogen Assessment. In addition, much work on nitrogen budgets and its use in agriculture is being done by the International Nitrogen Initiative and the Task Force on Reactive Nitrogen[12], the latter sitting under the Working Group on Strategies and Review of the UNECE Convention on Long-range Transboundary Air Pollution. The task force on reactive nitrogen includes three subpanels (i) the Expert Panel on Mitigating Agricultural Nitrogen; (ii) the Expert Panel on Nitrogen Budgets and (iii) the Expert Panel on Nitrogen and Food. In contrast, to date, phosphorus has not received the same international attention or the same level of funding. The most prominent work at the global scale has been conducted by Cordell (2010) and in Europe it can be found in van Dijk *et al* (2016) and the EU's research framework programme, FP7, which funded the P-REX project[13] In addition, a large amount of information is provided through the European Sustainable Phosphorus Platform[14]. Along with these scientific studies, non-governmental organisations (NGO) have also reported on issues through the publishing of several reports on N and P[15].

An important attribute of this developing body of work is that it has been produced by the independent scientific community. These accounts of nutrient flows start from the overt recognition that human beings will feed themselves, and to do this their food and feed crops and farm animals all require nutrients. There is no implied condemnation of the sectors which supply the nutrients, the mineral fertiliser and animal feed industries, nor of the arable and livestock farmers who use these nutrients to grow their crops and animals. But equally there is no hiding that on close inspection the processes of applying nutrients – whether organic manures or manufactured mineral fertilisers – to crops, feeding farm livestock and

[10] *According to the latest IPCC report, agriculture, forestry and other land use accounted for 24% of global GHG emissions in 2010 (Edenhofer et al 2014), half of these coming from agriculture (Smith et al 2014).*

[11] *See RISE report* (Buckwell *et al* 2014).

[12] *http://www.clrtap-tfrn.org/*

[13] *Practical implementation of phosphorus recovery and recycling from wastewater stream in Europe (2012-2015)*

[14] *Some examples: the European Sustainable Phosphorus Platform, the UK Nutrient Platform, the Dutch Nutrient Platform or even the Global Partnership on Nutrient Management.*

[15] *Greenpeace's "Phosphorus in agriculture. Problems and solutions" (Tirado and Allsopp 2012) and WWF's "Nitrogen. Too much of a vital resource" (Erisman et al 2015).*

in turn feeding the human population are rather inefficient, leaky and wasteful. In general, this is not due to bad intent or incompetence. The inefficiencies, leakage and wastes are not in the business self interests of those engaged. Rather these features are an intrinsic part of the biological processes of nutrient absorption, and utilisation in crops, animals and humans. They partly result from the necessarily fragmented and dispersed nature of crop and livestock production. They are compounded by the lifestyle and dietary preference for livestock products exhibited in developed economies over the last century. These processes are complex, not fully understood, and it has been rare until recently to think through nutrient cycles *per se* and how they can be better managed. Noting that these processes are inefficient is definitely not to conclude that the leakages are all inevitable or unavoidable. There is large scope to improve efficiency of nutrient use at all stages, and this is the focus of this report.

Another way of saying this is that current global trends (climate change, population growth) are stimulating a rethink of the way all sectors and systems are operating, and not just how food is produced and consumed. Change is already happening in some sectors, for example with regard to mobility, but other sectors such as agriculture and housing are lagging and showing greater resistance. This necessitates a stronger systemic change in agriculture. The way nutrient flows are managed should be a core part of this rethink. The challenges are global, but as a highly developed region with a highly intensive agriculture Europe can perform a leadership demonstration role in improved nutrient management.

The immediate policy context of this project is the heightened interest in the concept of the Circular Economy[16]. This is the notion that mankind must more carefully husband its resources, especially non-renewables. It makes sense to safeguard and delay the time when resource shortage drives up prices of vital materials and also to intercept resources from waste streams and prevent them causing environmental damage. These motives have obvious application to nutrients, all the more so as the scale of the leakage into the environment and its negative impacts are understood. Thus the motive of changing mindsets from linear to circular thinking, to switch from disposing of wastes to recovering and reusing resources are the core ideas behind this report. The specifics of the Circular Economy action plan are taken up in Chapter 5.

This project grew directly out of a previous RISE study on the sustainable intensification of European Agriculture. This was a broad review of the strategic direction for Europe's already intense agricultural sector to make an appropriate contribution to global food security – a conclusion was that the EU emphasis should be on the 'sustainable' word of this couplet. The RISE foundation had previously been closely associated with efforts to define a scientific, pragmatic and policy approach to foster the positive environmental services that farming could provide. This work centred on the idea of public goods. These are products and services – like landscape features, flood protection, carbon sequestration, and biodiversity such as pollinators – which are not transacted through market exchange and are consequently chron-

[16] *See European Commission (2015) Action Plan for the Circular Economy, 'Closing the Loop'.*

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ically under-provided. The result was the report, 'Public Goods from Private Land', RISE (2009). The public good approach is designed to try and enhance the production of what economists refer to as the positive externalities of agricultural land management, so it was therefore natural that the next report should switch focus to reducing the negative externalities of agriculture, essentially pollution of air, soil and water. The immediate impetus for the idea to focus on nutrient recovery came through the innovative work of one of the RISE Foundation's Advisory Committee, Guiseppe Natta. Snr. Natta has a long experience in industrial waste management and wanted to engage his experience on matters relating to nutrients in the food chain. Situated in the rice and grain cultivation area of Lombardia, in close proximity to the city of Milan and also with significant food processing activity in his locality, Natta's idea was to recover as much of the nutrient requirements for his region as is feasible from farm, food industry and human waste and reuse it on farm land. He saw this as a way of turning from waste management to resource utilisation, removing the need for waste incineration or land fill, returning vital organic matter as well as nutrients to the soil, and reducing the dependence of the region on imported mineral fertilisers. The plant he conceived, with some novel processing to ensure the quality and safety of the nutrients being returned to land, is entering into full production in spring 2016.

1.2 Objectives and scope

The objectives of this study are threefold, to:

- improve understanding in the EU policy community of the issues and interactions involved in the two principal nutrient flows in EU food production and to assess the relative importance of five goals and concerns about these flows (listed below) and the role that nutrient recovery and reuse could play in addressing these concerns;
- try and quantify the potential scale for enhanced recovery and reuse of N and P as components of improved nutrient stewardship, and to investigate the the major substrates available and the possible pathways for nutrient recovery from them;
- better understand the impediments to a wider adoption of nutrient recovery and reuse and especially the most helpful legislative and incentive framework to enhance nutrient recovery and reuse.

The structure of the report is as follows:

Chapter 2 provides an overview of **five goals and concerns** about nutrients:

1. **Food production** to feed a growing population.
2. **Farm viability**. Examine how the outstanding success in achieving goal No. 1 has resulted in agricultural systems which are all too frequently **economically precarious.**
3. **Pollution of water, air and soil and impact on the climate** due to inefficient and wasteful nutrient management with deleterious effects on biodiversity.
4. Reduction and recycling of **food chain waste.**
5. Confront the dependence of the food system on **finite, insecure, non-renewable resources**.

Chapter 3 provides a more detailed explanation of how the essential nutrients nitrogen and phosphorus are being used in the European agricultural and food system. It then summarises the results of the recent research efforts to quantify the annual flows and fate of these nutrients as they work their way through the food chain from fertiliser manufacture to crop and animal production, to food processing, food consumption by humans, and the subsequent processing or disposal of wastes including human sewage. This framework identifies and quantifies the leakages into the environment, and provides information to assess the efficiency of nutrient use at various stages in the chain. This information also provides a basis for estimating the potential scale of nutrient recovery.

Chapter 4 is focused on nutrient recovery. It reviews the range of substrates, technologies and processes which are available to recover nutrients. It explains the development stage which has been reached with these, some of which are still experimental, others have been in commercial use for many years. The chapter focuses on three principal streams for recovery from manures, sewage treatment works and from some of the larger material flows in food processing and consumer food waste.

Chapter 5 explains how the Sustainable Development Goals and the EU's Circular Economy package, both published in autumn 2015, have put in place the top-level motivation for the development of nutrient recovery and reuse. The chapter then considers the challenges and impediments to the further development of nutrient recovery and also the challenges of ensuring that recovered nutrients are actually reused. It reviews the regulatory landscape and identifies some blockages which are limiting investment in nutrient recovery and reuse. The Chapter also draws conclusions about the qualitative contribution that nutrient recovery and reuse can make to the nexus of goals and concerns identified. Finally, it provides some indication of the potential scope for expanding nutrient recovery and reuse and the private sector and public policy actions which may be needed to realise this potential.

Nutrient flows are complex. Their management involves technical, environmental and economic issues, business sectors and policies which are not often considered together. It is hoped that the value of this report is to increase communication and understanding about these issues between the usually rather separate worlds of agricultural supply industries, farming, the food industry and the water and sewage treatment sectors.

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The scope of the study is confined to the two principal nutrients nitrogen[17], N, and phosphorus, P. These are chosen because they are the most important crop macro-nutrients used in large quantities. They are also associated with significant environmental concerns. Nitrogen is associated with concerns about climate, air quality for human health reasons, water quality and biodiversity. The environmental concerns about phosphorus are principally as a contributor to water pollution and eutrophication. There are concerns about the supply security of the raw materials for both nutrients. Phosphate rock is a finite, mined mineral found in substantial deposits in very few countries. Whilst inert nitrogen gas is abundant in the atmosphere, to 'fix' it into a reactive fertiliser demands the use of natural gas to supply hydrogen as well as energy. The process of decarbonising the economy suggests the use of this fossil fuel may have to be curtailed for climate protection reasons. The geographical focus of the study is the European Union, although, of course the issues of nutrient management in the food chain are global.

[17] *Throughout this study, the term "nitrogen" is used to refer to "reactive nitrogen" only (the nutrient). Un-reactive nitrogen is referred to as "nitrogen gas or N_2" (Section 3.1 explains this further).*

2. The nexus of goals and concerns about nutrients in EU Agriculture

There are many issues of concern in the way agriculture uses two of its most critical plant nutrients: nitrogen and phosphorus and how these interact with the biosphere and the economy. This study is an attempt to bring these issues together in an integrated way, assembling ideas, knowledge and expertise which are usually found in the generally separate worlds of agricultural science and farming, the food industry, water and sewage treatment industries, environmental and waste regulation and renewable energy.

This chapter provides an overview of the issues which are then picked up in more detail in the subsequent chapters. The intention is to explain the motivation for the study and the need to focus more policy attention on nutrients. The story starts with food production and the astonishing success story of how, *inter alia*, improved crop and animal nutrition has enabled a much larger, longer living, higher income, European population to have a consistent supply of a bewildering variety of higher quality food products, at lower real prices. This has been accomplished through agricultural science, and wholesale technical and structural changes in the food chain. Despite these successes significant parts of the European agricultural sector remain economically marginal and highly dependent on public support. There is also constant questioning of the environmental sustainability of many aspects of modern agriculture, and increasingly on the balance of crop and livestock production.

The very success of our intensive agricultural systems has increased the nutrient loading on agricultural land, waters and the atmosphere. These developments, in turn, have lead to consideration of the health impacts of current food consumption and agricultural production patterns, the efficiency of resource use in agriculture, pollution of soil, water and atmosphere and the challenge of dealing with the numerous waste streams in the food chain. Newer thinking casts these issues into a wider systems approach which seeks to understand how agriculture can work with, rather than against, natural cycles and indeed how aspects of the economy generally can switch from a linear to a circular model which, *inter alia*, recovers and reuses resources rather than disposes them as wastes. A further specific motive for examining nutrients more closely is that the debate on continuing global population and economic growth often points to the dangers of depending on finite non-renewable raw materials. In the food chain the principal such concern relates to farming's dependence on finite, non-renewable phosphorus, and non-renewable natural gas used in the manufacture of mineral nitrogen fertiliser, which releases damaging greenhouse gases into the atmosphere. This defines the central question of the study, which is to assess the contribution that scaling-up nutrient recovery and reuse[18] could make to address this nexus of issues.

2.1 Food production

The first goal is, of course, to feed the growing population. During the last 60 years the population of the countries whose territories currently constitute the European Union (EU28) has expanded by a third, from 377 million in 1950 to 504 million in 2010, and life expectancy has increased by 17% from 65 to 76 years. Over the same period material living standards of the population as measured by GDP per person more than quadrupled[19].

The success story of feeding this larger, longer living, better-off population has been possible through massive technical and structural change in farming itself and in the industries which support agriculture. The upstream agricultural supply industries have provided the genetics, energy, mechanisation, plant and equipment, crop nutrition, plant protection and animal health products. The downstream food industry has transported, stored, processed and distributed the hugely expanded range of food products which make up the modern food chain.

Because of the changing mix of products produced, and consumed, over the decades it is hard to reflect with precision how the sheer volume of EU agricultural output has grown over this post-WWII period. The majority of this growth in agricultural output has come about by a significant increase in the intensity of farming as expressed by crop yields per hectare or livestock product yields per head. The agricultural area of the EU27 fell by 32 m Ha, (14%) in the 48 years between 1961 to 2009[20]. To produce the increase in agricultural product during this period has therefore required a commensurate rise in other inputs improved genetics, mechanisation, management and of course nutrients, into agricultural production.

The contribution of agricultural science has been to help better understand the relationship between plant and animal growth and nutrient availability and uptake. In the early half of the 19th century, Carl Sprengel and Justus von Liebig pioneered the theory of mineral nutrition of plants, and established the importance of nitrogen, phosphorus, potassium and other nutrients required for crop growth. Until then, traditional agricultural systems had relied on local organic fertiliser materials such as animal manure, human sewage waste (night soil), and food industry waste such as meat and bone meal to return nutrients to the soil. From the mid-to-late 19th century, natural nutrient deposits such as Peruvian guano (N+P) and Chilean Saltpeter (N) were discovered and shipped in substantial quantities from South America to Europe. Soon however, these nutrient resources started to decline, and alternative supplies were critically needed to fuel the rapidly growing European population and its agriculture. A new era was on the horizon, the era of global mineral fertiliser manufacturing and use.

Production of inorganic P fertilisers, based on sulphuric acid treatment of small local supplies of low-grade phosphate rocks, began in the UK in the 1840s. Subsequent discoveries and mining of huge deposits of high-grade phosphate rocks in Florida (1870s), Morocco (1910s) and Russia (1930s) laid the foundations of the global phosphorus fertiliser industry. At the turn of the 20th century, the Birkeland-Eyde process (1903), later replaced by the more efficient Haber-Bosch process (1913), allowed for the large-scale fixation of atmospheric nitrogen, paving the way for the modern nitrogen fertiliser industry[21]. However, it wasn't until after WWII that the production and use of mineral fertilisers underwent rapid and massive global expansion. These developments occurred in parallel with the mechanisation of agriculture, which enabled the more efficient spreading of fertiliser and manure, and the harvesting of denser crops. The technically and economically favourable response relationships of crop yield to mineral fertilizer application was soon apparent. This plus its relative ease of application, its consistent quality and nutrient analysis, and predictable performance compared to the highly variable (and largely unmeasured) nutrient content of stored manure, encouraged the use of mineral fertiliser as a principal source of crop nutrients. These advantages of mineral fertilizer eventually contributed to the emergence in some situations of an attitude that manure spreading became an exercise in waste disposal rather than applying crop nutrients.

These are highly complex developments. Technical progress in agriculture and the changing prices of land, labour and capital mean that the input mix in European farming has changed dramatically. There has been a large fall in labour, a smaller fall in land input, and thus a widespread substitution of land and especially labour by numerous forms of capital, energy and management. Simultaneously the structures of farms and farming systems have changed. There has been significant farm enlargement to gain scale economies, some sectors for example pig and poultry production became regionally concentrated, farm systems tended to specialise and simplify, especially for example into crop production or animal production with less mixed farming. These interlinked technical and structural changes in the breeding, feeding and management of crops and livestock has enabled consistent, and continuing, technical efficiency gains as conventionally measured.

The progressive application of knowledge of the breeding, growth and development of plants and animals together with improved recording and management of crop fertilisation and livestock feeding has resulted in steady improvements in the uptake and efficiency of

[18] *The acronym NRR is sometimes substituted for the whole phrase Nutrient Recovery and Reuse.*

[19] *Crafts and Toniolo (2008) show Western European real GDP rose almost 4.5 fold between 1950 and 2005.*

[20] *IEEP report on Land as an Environmental Resource, December 2012.*

[21] *Hager (2012) The Alchemy or Air, provides a highly readable account of the development of the mineral fertiliser industry.*

utilisation of these nutrients. In addition, the reforms of European agricultural policy from the mid 1990s, which have eliminated the drive for over production and grain and meat surpluses, have had the effect of reducing consumption of fertilisers (Figure 5 in Chapter 3) and driving livestock numbers, and thus feed consumption, down.

Looking ahead, it is unlikely that this decline in EU nutrient consumption (that is, both, fertiliser and feed) will continue. The EU population is still growing, albeit slowly, and based on past human fertility, mortality and migration rates is expected to peak in the early 2030s and then slowly decline. The picture is quite different amongst three groups of Member States (MS): in a third of the MS the population is already declining, in another third it is expected to peak and decline by 2033, whilst the population of remaining MS is expected to continue growing throughout this century. The extraordinary migration from the Middle East and Northern Africa in 2015 is not factored into these projections. Economic growth in Europe has been sluggish since the financial crises starting in 2008. It is more rapid in some of the newer Member States which start from a lower income base and thus have more scope for growth in consumption, including livestock products. Pulling these factors together it is prudent to assume that some continued growth in food demand can be expected in the EU, and thus the annual supply of nutrients to grow. Two other factors could impact the demand for nutrients for the EU food chain. These are food exports and any systematic attempts to modify European diets[22].

This is not the place to enter into a full analysis of the prospects for EU food exports. Suffice to say that although the EU has relatively high tariffs on agricultural imports and is a zone of high labour and land costs, and with demanding regulatory standards and corresponding costs, it also has high productivity and product quality which are the basis for considerable exports of processed food and drink rather than agricultural commodities. Also the price differential between the EU and world market has considerably narrowed. For these reasons, and because parts of the EU might be relatively less negatively impacted by climate change than some other agricultural producing and exporting regions, the growing food demand in third world countries could manifest as a growing demand for EU food exports. This would add further demand pressure for the nutrients to produce such food in Europe.

There are some forces which could push demand for nutrients in the EU in the opposite direction. The key such development would be systematic attempts to encourage, or even induce, European citizens to reduce their consumption of certain foods – particularly sugars and livestock products. These pressures already exist on public health grounds stemming from the increased incidence of obesity and associated non-communicable disease such as diabetes and coronary heart disease which impose considerable personal and health service costs on European society. As will be examined in more detail in section 2.3 and also in Chapter 3, the large scale disturbance of the natural nutrient cycles associated with agricultural production also raises human health concerns associated with ammonia pollution from livestock production. In addition there is mounting evidence concerning the direct and indirect[23] negative environmental impacts of livestock production arising from greenhouse gas emissions (N_2O and CH_4) and water pollution by nitrates and phosphorus compounds. These concerns are leading to calls that serious consideration should be given to reduce consumption of livestock products, and the case is being made specifically on grounds of the scale of disturbance to nutrient cycles by that sector[24].

2.2 Farm viability

The second concern about the food system which has evolved is its persistent economic fragility. EU farming is a highly fragmented sector of small and micro businesses. These, mostly family-based, farm businesses are sandwiched between concentrated, large scale, often globalised manufacturers and suppliers of fertilisers, seeds, feeds, machinery, finance and many other inputs, and the equally large scale and concentrated (though less globalised) purchasers, processors and distributors of farm produce[25]. The consequence of this structure is that farmers have little or no market power and have to accept the trading terms offered by input suppliers and output purchasers. By establishing sound and professionally run cooperatives or collaborative structures, they can sometimes acquire some bargaining power, but generally the market structure in which they operate means that farming operates on slender margins. The sector is therefore vulnerable to market shocks, and being squeezed both by their input suppliers and the purchasers of their (generally) perishable products.

It is precisely for these reasons that the EU has been generous in the public support provided to farmers through the Common Agricultural Policy, and a protective common external tariff for agricultural products. However, (except for the newest EU Member States) this support has been in place now, in one form or another, for many years. Its benefits therefore have had plenty of time to be competed away through the food chain in the prices farmers receive for their products, pay for their inputs, and capitalised into the least responsive input, land, in land prices and rents. CAP supports have not been provided uniformly by Member State or by commodity, and so direct payments per hectare vary considerably, although there is in place a slow movement towards more uniform

[22] *The IARC classification of red meat as a probable carcinogen and sausages as a certain carcinogen in 2015 could contribute to a dietary change.*

[23] *The particular indirect effect is through induced land use change in countries from which Europe imports considerable quantities of animal feed, maize and soya.*

[24] *See report: Nitrogen on the Table, Westhoek et al (2015).*

[25] *These highly concentrated economic structures are called oligopolistic – competition amongst the few.*

payments. Historically the least supported sectors have been horticulture and intensive livestock production, pigs and poultry. The result is that farming is highly dependent on the support payments under the CAP. On average these payments account for about 40% of farming income, but this varies widely and the most dependent sectors are those in more marginal, extensive livestock grazing areas, often in the most remote regions. In short the farming industry has many businesses whose economic viability is highly insecure. The important implication for the nutrients story of these structural features is that these numerous, geographically-dispersed, highly-fragmented, micro-businesses often operating on low, and in some cases negative, margins and highly dependent on public financial support make up a sector which is particularly difficult to regulate[26].

2.3 Pollution of water, air and soil and impact on the climate

The third concern about nutrient use in the EU is the associated pollution. The characteristics of farm structures discussed above pose a substantial challenge because there is much to regulate. As an extensive, outdoor, biological activity which depends on soil and terrestrial biodiversity for a variety of functions agriculture interacts intimately with water, carbon, nitrogen and phosphorus cycles and is described as having pervasive external effects[27]. It could hardly be otherwise. It is a truism that agriculture depends on the environment, and that the condition of the rural environment depends critically on how that agriculture is conducted. The full impacts of the quantities of nutrients farmers apply to their land is a case in point. From a farmer's perspective nutrients, especially in the form of purchased mineral fertilisers and animal feeds, are an integral, and essential part of normal farming business. They are used because they profitably improve the yield and dependability of crop and animal production. As energy costs rose in the last decade (until mid 2015) farmers were certainly aware of the rise in nutrient cost and adjusted their use to economically justifiable levels.

European farmers are generally aware that the use of these nutrients has unintended environmental impacts. All EU farmers have access to direct payments under the Common Agricultural Policy and a condition of the receipt of these annual payments is that farmers must respect a series of good agricultural and economic conditions and statutory management requirements[28]. These conditions cover soil, water, manure and a number of

26 This explains the unusual situation in EU agriculture whereby farmers are granted annual direct payments in return for complying with certain EU regulations, the so-called statutory management requirements.

27 Buckwell (2007) suggested this correctly describes the extent of the environmental impacts of agriculture.

28 See http://ec.europa.eu/agriculture/direct-support/cross-compliance/index_en.htm for an explanation of cross compliance under regulation EU No 1306/2013 17 December 2013, on the financing, management and monitoring of the common agricultural policy.

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aspects of biodiversity management. In applying for their annual support payments farmers receive detailed guidance on these rules and conditions and also on the necessity of managing agriculture's GHG emissions. In sensitive areas, such as Nitrate Vulnerable Zones (NVZ), farmers are required to prepare soil management plans to demonstrate they are using fertilisers responsibly in relation to crop requirements and for the avoidance of soil erosion and pollution of water courses.

Farmers and their organisations are certainly aware that there is criticism about the negative environmental impacts of their activities. As the evidence of these impacts accumulated there has been some acceptance that there is a problem to be addressed. Reactions to this evidence are partly conditioned by economic circumstances. For example following the successive commodity price spikes after the 2007/8 financial crisis attention reverted from environmental concerns back to food security and increasing food production. Over the whole period the accumulating evidence on soil erosion, soil organic matter loss, eutrophication, GHG emissions, and more recently ammonia and particulate air pollution, and the loss of biodiversity and ecosystem function which accompanied these processes is now beyond dispute. The more recent analyses of nutrient flows demonstrating the low proportion of nutrients applied to the system which are actually taken up in human food add even greater momentum to these concerns.

All this evidence is collected and displayed at regional, national and EU level. This provides the fuel for the policy debate, but it is of little operational value for those actually managing the environment on the ground, the farmers. European agricultural policy debates have, for two decades now, explicitly used the language of integrating environmental concerns into the CAP[29]. Indeed there has been steady progress in implementing this policy[30] since the term 'agri-environmental measures' appeared in the late 1980s, and culminating in the most recent CAP reform in which 30% of direct farm payments for the period 2015 to 2020 will be made for actions which are beneficial for environment and climate, the so-called greening payments. The glaring deficiency is the absence of progress in providing practical farm and field-level environmental indicators and benchmarks so that farmers can become aware of the environmental impacts of their systems in their own immediate locality. Immense resources have, rightly, been devoted to collecting systematic, representative farm economic data on an annual basis both to guide policy but also to encourage the establishment of farm-level economic performance indicators and benchmarks[31]. This work has been underway for several decades, and it has undoubtedly been a major contributor to the professionalization of farm management practice. However, this system has been very slow to recognise

[29] The project director was invited to chair a Policy Integration Group within DG Agriculture by the then Commissioner Fischler in 1995, Buckwell et al (1997)

[30] The steps in this process are described in Cooper, Hart and Baldock (2009). http://ec.europa.eu/agriculture/analysis/external/public-goods/report_en.pdf

[31] This refers to the Farm Accountancy Data Network, see http://ec.europa.eu/agriculture/rica/ which collects such data for all EU Member States.

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that the focus of policy has been changing to integrate farm environmental performance. The result is that there is almost no generally available, officially endorsed, statistically-sound farm level monitoring and benchmarking of farm environmental performance. As it is frequently observed that 'what isn't measured isn't managed' this partly explains both why environmental performance is not as high as society desires, but also what could be done to improve this situation.

It has to be acknowledged that measurement of local level environmental impacts is not straightforward, and neither is interpretation of results and understanding causation. Obtaining reliable, spatially referenced data on a systematic basis is not going to be costless. However, new GPS, information technology, the potential of satellites and drones as well as farmers' own equipment to collect data together with data processing capability is rapidly opening the possibilities, and reducing the costs, of recording and analysing detailed information. This is the big data promise. It is already being used in arable agriculture with significant economic and environmental benefit, to combine soil and yield mapping, and other measurements to ensure optimal fertiliser and pesticide applications. Similarly, utilisation of electronic tagging and automated feeding is being used in some livestock activities to improve feed efficiency. The challenge is to roll out such developments over the majority of production, which, as has been pointed out, is dominated by micro-businesses.

2.4 Food chain waste

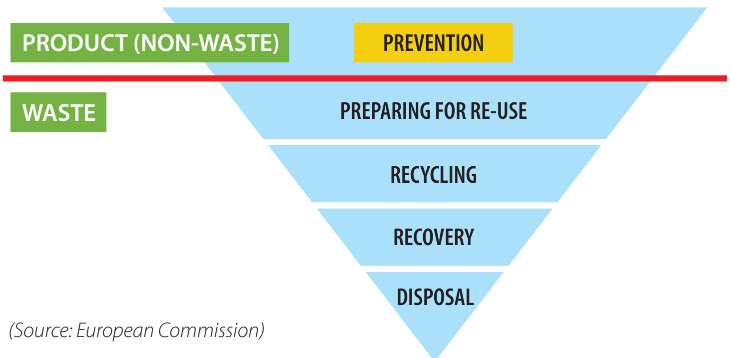
The fourth goal is to see the existence of waste flows as a resource management opportunity. Nutrient use can be polluting and wasteful. The leakage of some expensive-to-produce reactive nitrogen into the atmosphere, or nitrogen and phosphorus to water is certainly a waste of the resources used in its production and farm application. In addition the pollution itself can cause damage and costs to other businesses (e.g. clean up costs in water treatment works), to citizens (e.g. health damage of ammonia) and to society (e.g. the costs of climate change). These costs can be viewed as yet another waste of resources which would be reduced or avoided if there was less, or no pollution. The difference with wastes is that they are unwanted by-products of processes and activities which then require specific actions and more resources and costs to dispose of them. Wastes are seen as such by the businesses and citizens who generate them because the cost of disposal appears to them to be less than the value created by making further use of the material.

A great deal of attention has been given in recent years to the scale of the wastage in the food chain[32]. It is estimated that 30% of food which leaves the farm gate is not consumed but wasted, and in addition food is grown but not marketed for a variety of technical and economic reasons. Much of this waste is avoidable, and there are now in progress substantial efforts to raise consciousness, and change attitudes which have led to this prolificacy. Food waste appears at all stages in the food chain, on farms, during storage, transport, processing, retail, especially in food service, and in the home. It is partly a cultural phenomenon, no one wants their family or friends to go hungry or think they are stingy! Some food waste is inevitable in that biological processes are highly variable. This variability shows up in many ways. Some product is thought not desirable for consumption (e.g. too much fat). There are inedible fractions in most products (e.g. skins, stones, cores, husks, entrails, offal and bones). Also, because consumption is daily, year round, whereas most production is seasonal or periodic storage and processing are required with some inevitable deterioration. Moreover production and consumption occur in different places so transportation is required, again with some inevitable handling losses.

The cost of the waste is in the resources which were deployed to produce food which is not consumed, and the further wastage of the resources expended during its disposal – collection, processing or dumping in land fill. In the case of the latter it is the opportunity cost of using land for this purpose plus future pollution from these sites to water and atmosphere.

The optimal approach to waste management in Europe has been agreed in the concept of the waste management hierarchy the depicted in Figure 1.

FIGURE 1. *Waste management hierarchy*



(Source: European Commission)

The first priority, applying to all product and material, is to avoid or prevent the waste generation in the first place. Prevention might be achieved through the way products and processes are designed and run. The intention is that the other actions, i.e. preparing for reuse, recycling and recovery then apply to progressively smaller fractions of material so that the final, and least desired option, disposal is eliminated or reduced to a minimum.

Throughout this report, the terms, nutrients, collection, recovery, reuse, recycling and applications are used as defined in the Table 1. The definitions of recovery and recycling applied here are not identical those used in the

[32] *Waste Directive 2008/98/EC of the European Parliament and the Council, 19 November 2008; European Week for Waste Reduction (in 2013)*

Waste Directive but seem more naturally applicable to the nature of the nutrient nexus involved[33].

TABLE 1. *Definitions of nutrient recovery and reuse used in this report*

Term	Decision / definition
Nutrient	The study focuses on nitrogen and phosphorus given their relative importance, quantity used, pollution effects and finiteness.
Nutrient collection	The gathering of waste material including preliminary sorting and storage prior to a subsequent direct use or processing.
Nutrient recovery	A process through which a nutrient is extracted, purified or concentrated from a substrate.
Nutrient reuse	The act of applying recovered or collected nutrients to agricultural production or some other non-agricultural use.
Nutrient recycling	A more general term which can refer to the reuse in agriculture of collected or recovered nutrients.
Nutrient application	Spreading, spraying, injecting or fertigating crops to add nutrients.

2.5 Dependence on finite, insecure, non-renewable resources

The fifth concern about nutrients is their apparent finiteness. There is scarcely a paper written on global food security which does not refer to the dependence of food production on phosphorus[34] and the fact that this essential element is a non-renewable, mined, resource found in significant quantities in only five parts of the world: North Africa, China, USA, the Middle East and Russia. The EU imports almost all of its phosphorus thus the reliability of supply is a material concern. There are widely differing and scientifically contested estimates of the availability of global phosphate rock supplies (phosphate rock is the principal source of phosphorus-based mineral fertilizers). These differences result from differing definitions and methods to estimate "reserves and "resources"[35]. Some suggest that reserves may only provide a few decades of supplies at current rates of extraction, reaching a "**peak phosphorus**" situation around 2070 (Cordell *et al* 2011) (more details on Box 1). Other authors, for example the United States Geological Survey USGS, are more optimistic suggesting that there is considerably more phosphate resource which can ultimately be extracted especially if scarcity raises the price to cover higher costs of dealing with less concentrated ores with higher impurities.

It is beyond the scope of this report go into the details of this evolving debate, though there appears to be a growing consensus that the world is not going to run out of phosphorus within the next 200 years. At the same time, however, there is also a growing recognition that phosphorus should be stewarded - from production to end use - as efficiently as possible, as is the case for any non-renewable resource. The European Commission recently included phosphate rock in their list of **20 Critical Raw Materials**[36]. This list is based on economic importance and political risks associated with the material supply to the EU. The vulnerability of supplies given geo-political uncertainties is clearly an important consideration. At present rates of utilisation, with current modest rates of P recovery and reuse, and with appropriate new technology and management of the processing of rock, currently known phosphorus resources could match projections of likely consumption for the foreseeable future.

BOX 1. *Peak Phosphorus*

Rock phosphate reserves are geographically highly concentrated, with **85% of known phosphate rock resources located in just four countries**, Morocco, Western Sahara, China and the US. Despite being of such an importance, there is a large uncertainty surrounding the level of global phosphate reserves (i.e. the amount assumed recoverable at current market prices) and resources (i.e. total estimated amounts in the Earth's crust). In 2008, a spike in phosphorus fertilizer (and food) prices renewed concern about global food security and triggered a revival of interest in phosphorus and its availability. This gave rise to a large body of new publications, the organisation of international meetings and the creation of the Global Phosphorus Research Initiative (2008) and the European Sustainable Phosphorus Platform (2013).

The concept of peak phosphorus - equivalent to that of peak oil – is often used to explain the point in time in which the highest global production high quality phosphate rock will occur. Although the peak is predicted to happen well before resource depletion, it is not a static figure and may fluctuate according

[33] *In particular the Waste Directive Article 3 defines recovery as "an operation the principal result of which is the waste … replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function". It defines recycling as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for original or other purposes. Annex II of the Directive is a non-inclusive lists of 12 recovery operations, in which the three which are relevant for nutrients are R3 Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes), R5 Recycling/reclamation of (non-metallic) inorganic materials and R10 Land treatment resulting in benefit to agriculture or ecological improvement. In the context of nutrients and the kinds of processes involved in extracting reusable forms nitrogen and phosphorus it is suggested that the proposed narrower definition of recovery and similarly wide definition of recycling provides a clearer and more understandable fit.*

[34] *See for instance UNEP Year Book 2011 section on "Phosphorus and Food Production" or Cordell et al 2009 "The story of phosphorus: global food security and food for thought"*

[35] *"Reserves" refers to the amount assumed recoverable at current market prices and "resources" means total estimated amounts in the Earth's crust (Sutton et al 2013, Our Nutrient World)*

[36] *COM/2014/0297 final*

to changes in reserves and market dynamics. As an example, Cordell *et al* (2010) estimated in 2009 that over the following 50-100 years phosphate rock reserves could be depleted, and that "**peak phosphorus**" would occur before 2035, after which lower quality and less accessible reserves would come into play. The publication of a report by the International Fertilizer Development Center in 2010 (Van Kauwenbergh 2010), suggesting that there are phosphate rock reserves to cover the fertiliser needs for the next 300-400 years (60,000 Mt of available reserves within 290,000 Mt of rock resources), lead to a revision of the peak P predicting it to occur somewhere between 2051 and 2092 (Cordell *et al* 2011).

There seems to be consensus that the world is not going to run out of phosphorus in coming decades (de Ridder *et al* 2012). At present rates of utilisation, with current modest rates of P recovery and reuse, and with appropriate new technology and management of the processing of rock, currently known phosphorus resources could match projections of likely consumption for the foreseeable future. From an economic perspective, scarcity of phosphate reserves would be expected to lead to high phosphate ore and fertiliser prices. These, in turn, will cover the costs of using lower concentration ores and more expensive processing and purification technologies (e.g. due to increasing cadmium and uranium content) and should also encourage more efficient use by farmers. A further complication in assessing the extent of usable phosphate reserves is the treatment of impurities of the raw material, some of which can have a high impact on the manufacturing process (e.g. chlorides, aluminium and iron), while others raise severe environmental concerns (e.g. cadmium, uranium). Inevitably, increasing levels of impurities lead to increased processing costs and waste. In the future, higher prices will also enable recovered phosphorus to more easily compete with the mined material. But equally, the diversification of supply source by recovering more phosphorus within the EU is a step towards greater resilience and supply security of this vital element.

There is no comparable finite supply concern for nitrogen because it makes up 80% of the atmosphere as di-nitrogen (N_2). The concern arises because the fixation of atmospheric nitrogen into reactive nitrogen requires natural gas (CH_4) consumption. Natural gas is the main conventional feedstock used to supply the hydrogen required to convert (fix) N_2 into ammonium NH_4, according to current practice. This, in turn, is the primary compound for the manufacturing of a wide range of nitrogen-based mineral fertilizers. This process raises two concerns. First, natural gas is a fossil fuel and its use in fertilizer manufacture results in emissions of green house gas. Second, just as with phosphate, Europe is highly dependent on imports of this raw material, some of which is coming from countries whose supply reliability may be uncertain (Withers *et al* 2015). Such concerns are high in the political agenda in an era of growing awareness about climate change, sustainability, and political instability. To provide some perspective it is noted that nitrogen fertilizer production consumes about 5% of global natural gas supplies (or about 2% of global energy use), to produce fertilizers which provide food for about half of the global population (IFA Statistics).

A seemingly obvious solution to address the twin concerns of large volumes of waste material containing much nutrient on the one hand, and finite and potentially vulnerable supplies of the raw materials used to manufacture nutrients on the other, is to recover the nutrient contents from waste flows, thereby increasing domestically sourced nutrient supplies. This is exactly the concept of moving from the linear to the circular economy, which is examined in detail in Chapter 5.

2.6 Concluding remarks

Agriculture[37] is the process of managing the growth of crop and livestock biomass – carbohydrates, fibres, vitamins, proteins and fats – by capturing carbon from the atmosphere through photosynthesis, and utilising nitrogen, phosphorus and potassium (plus many other minor nutrients and trace elements) from the soil and from fertilisers or, in the case of livestock, from animal feeds. Because of the unprecedented growth in human population, and in the agricultural production required to feed this population, the sheer magnitude of the usage and flows of nutrients has expanded beyond previous experience. These nutrient flows and the agricultural activities through which they are manipulated represent a major disturbance to natural cycles of nitrogen, phosphorus, carbon and water. The production chains involved have relatively low efficiency, they leak nutrients into water and air, and generate large volumes of animal manure, human sewage and food chain waste. On the face of it there seems to be considerable scope to maintain and, if necessary and desirable, increase Europe's food production (and thus nutrient use), whilst reducing much waste by turning it into secondary raw materials from which nutrients can be recovered and reused and organic matter brought back to soil. The rest of this report digs more deeply into this set of issues to assess the real scope for developing a greater circular economy for nutrients, and the incentives which might be required to give greater impetus to this development.

[37] *Forestry has not been considered in this report.*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3. Nutrients for crops, farm animals and humans

This chapter first describes the two essential nutrients and their role in plant, animal and human nutrition. The second section summarises information on the use of these nutrients in the EU food chain. This leads to a consideration of the unwanted side effects on soil, water and air of their use.

3.1 Essential nutrients N and P

Healthy plant growth requires the uptake of nutrients and water from soils, and carbon in the form of CO_2 from the air. Plants require 14 essential mineral elements, all of which are important for good growth. Macro-nutrients are those required in larger amounts and micro-nutrients are required in smaller amounts. Among the macro-nutrients, nitrogen, phosphorus and potassium are the most important. Providing the exact amount of nutrients needed for healthy crop growth is the objective followed by balanced nutrition (Box 2).

BOX 2. *Essential Crop Nutrients and Balanced Crop Nutrition*

Mineral nutrients are vital building blocks for the life of plants, animals and people. In undisturbed natural ecosystems, plants derive these nutrients mainly from the soil. The nutrients are intensively recycled, with relatively few losses to the environment.

In agricultural ecosystems, however, nutrients are continuously removed from the soil through crop harvesting, runoff and erosion, leaching and volatilization. To sustain proper soil health and abundant crop yields, farmers must apply nutrients, usually annually, in the form of organic fertilizers, mineral fertilizers, or a combination of both. To obtain the best results, crop fertilization must be done on the basis of good agricultural practices.

Just as it is the case for people and animals, plants require a balanced nutrient diet. In an agronomic context this is often referred to as balanced crop nutrition. There are 14 known **essential mineral nutrients**, chemical elements which plants require to complete their normal life cycle. These nutrients are all equally important, but have different biological functions, and are required in very different quantities. If one nutrient is absent in the soil, or present in insufficient quantities, it will critically limit crop growth and yield production (also known as "Liebig's Law of the Mimimum").

The concept of balanced crop nutrition is generally well-accepted among agronomists and practitioners, but it is still quite often not fully translated into routine good practice. It mainly involves the following **5 key principles:**

Balanced fertiliser application. Often, a combination of mineral and organic fertilisers gives the best results, from agronomic, ecologic, and farm-economic perspectives. Organic fertilizers commonly serve as base application, while mineral fertilizers can be added for nutrient balance fine-tuning.

Balanced application of all essential nutrients: N, P, K (primary nutrients; needed in largest amounts), Mg, S, Ca (secondary nutrients; needed in smaller amounts), and Fe, Cu, Zn, Mn, Mo, B, Ni and Cl (micronutrients; needed in smallest amounts).

Balanced application of nutrient forms. Several of the essential crop nutrients naturally occur in different chemical forms [eg N: ammonium NH_4^+, nitrate NO_3^-, and urea $CO(NH_2)_2$]. Each of these forms has its specific benefits and weaknesses. Depending on local factors (soil, climate, crop type, cropping system), one form might be preferred over the other.

Balanced application in function of crop type and/or market use. The key principles of crop nutrition apply to all types of crops, but significant differences in the optimum nutrient amounts and forms exist depending on crop type and end-use (eg fresh consumption vs processing; or extra Ca gifts for crops that are especially vulnerable to Ca-deficiency).

Balanced timing of application. Crop requirements for specific nutrients vary significantly throughout the crop cycle. Best practice is to apply nutrients when the crops need them most, which may often involve the need for split-applications (in particular for N).

(Source: based on Marschner (2012) and International Plant Nutrition Institute)

Managed ecosystems such as croplands, where only a small portion of the crop plants is returned to soil after harvest, inevitably face depletion of nutrients from soil. To balance these losses and achieve and maintain high productivity, nutrients are added to the soil via organic and mineral fertilisers. Farmers continuously face the challenge of maintaining adequate nutrient balances in soils to prevent shortages that reduce crop yields whilst avoiding surpluses that threaten the environment (pollution) and involve unnecessary expenditure (wastage). Ensuring a balanced nutrient status in soils is an intensely local decision taken by every farmer. However, nutrient management is increasingly also regarded as a global issue due to the scale of the environmental, health and economic impacts associated with current fertiliser use and practices. Scientists, policy makers and industries are focusing on issues related to the use of nitrogen and phosphorus in agriculture because these two elements pose unique challenges that will now be examined.

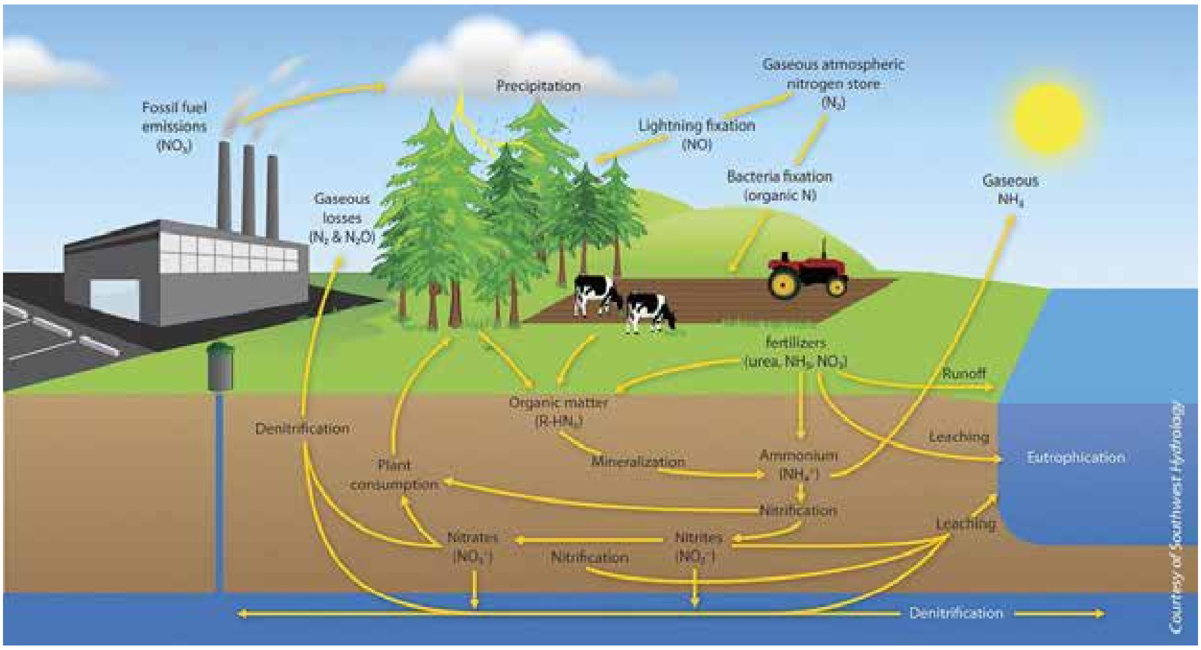
3.1.1 The importance of nitrogen and its cycle

Nitrogen is an essential plant nutrient. Although plant dry material typically contains only around 1% nitrogen, this element plays a critical role in the growth and reproduction of all living organisms. It is a major component of proteins and nucleic acids (i.e. DNA, RNA), the biological molecules that control plant development and it is also a key component of chlorophyll, a group of molecules that allow plants to absorb light and convert it into carbohydrates (Mengel *and* Kirkby 2001).

Nitrogen is one of the most abundant elements in nature, constituting 78% of the Earth's atmosphere. However, nitrogen gas N_2, representing 99% of all nitrogen on Earth, is inert. This means it does not easily interact with other compounds or molecules nor can it be used as a nutrient. Plants take up nitrogen from soils in the form of ammonium (NH_4) and nitrate (NO_3), therefore, in order to be available for plant nutrition, the strong triple bond that holds together the two nitrogen atoms in nitrogen gas must be broken and the molecule transformed into chemically and biologically active compounds (**reactive nitrogen**) in a process called nitrogen fixation. In natural ecosystems, this takes place mainly through biological fixation and to a minor degree from lightning and biomass burning. Through biological fixation, atmospheric nitrogen is converted to ammonia (NH_3) by bacteria. Certain plant families, such as the legumes, establish symbiotic relationships with nitrogen fixing bacteria in their root systems giving them access to atmospheric nitrogen sources, but the majority of plants depend on reactive nitrogen present in soils, making it a limiting growth factor.

Nitrogen cycles continuously between the biosphere, the hydrosphere and the atmosphere and nitrogen atoms are present in these three spheres in a large variety of chemical forms. This cycle is depicted in Figure 2. Before the advent of the industrial revolution, soils represented both the main terrestrial reserve of nitrogen and the main environment for the transformation of nitrogen compounds, playing a key role in the cycling of reactive nitrogen. Soil organic matter, and especially the microorganisms it supports, is involved in nutrient availability directly through the supply of nitrogen compounds and indirectly through the preservation of a good soil structure that leads to higher soil water storage capacity and stable aggregates that reduce soil erosion. In fact, nitrogen is found in soils primarily in an organic form linked to soil organic matter while mineral nitrogen compounds account for less than 2% of total nitrogen in soil except where large amounts of mineral fertilisers are applied (Brady *and* Weil 2010). The majority of nitrogen in soil is, thus, not directly available for plant uptake and must be transformed to reactive nitrogen (i.e. mineralised).

FIGURE 2. ***The nitrogen cycle***



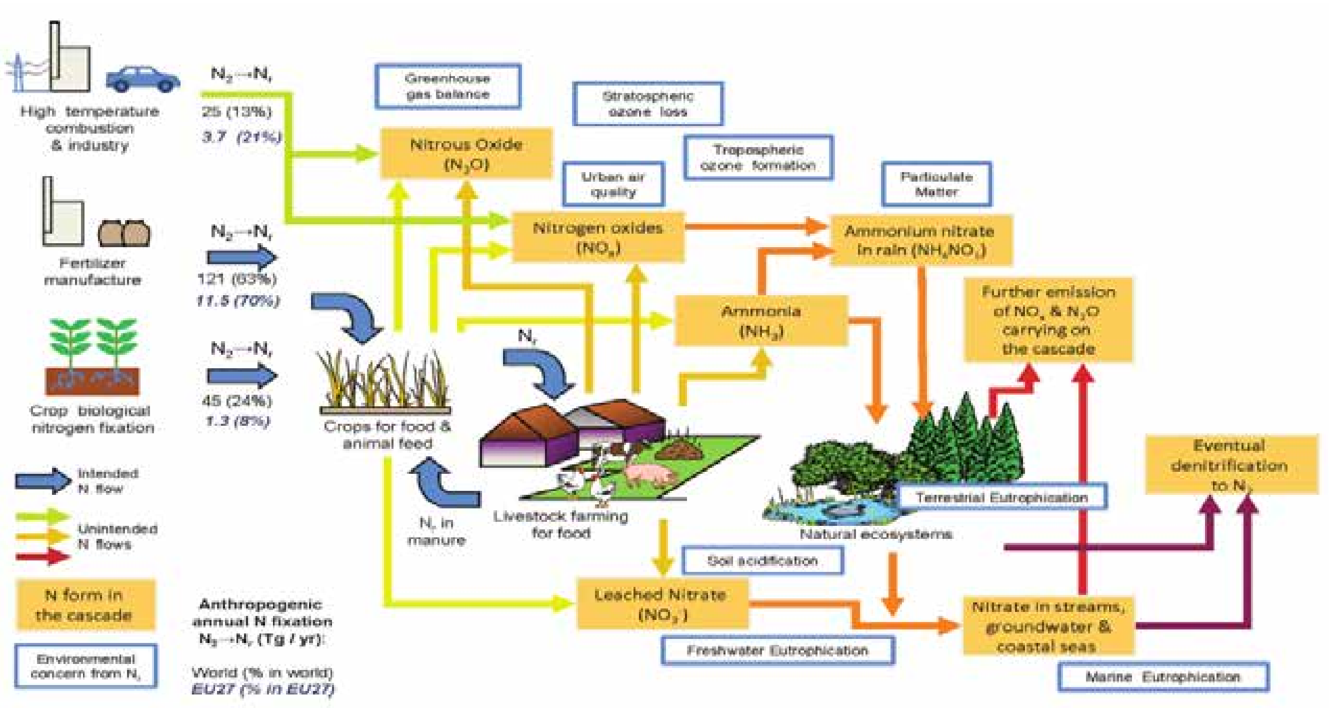
(Source: UC Davis)

The limitation of plant available nitrogen for crop uptake has always been a central concern in agricultural systems. The Haber-Bosch[38] process that we now use to produce nitrogen fertilisers allows the transformation of atmospheric nitrogen gas into ammonia under high pressure and temperature using natural gas (or coal) as a source of hydrogen and energy. Ammonia can also be produced without fossil fuels, in which case, hydrogen is obtained from water through electrolysis. The process, however, is not widely used due to its very high electricity requirements which make it very expensive, but it could develop in the coming decades. The large impact of the Haber-Bosch process on the increased productivity of agriculture, global food production and the consequent increase in world population over the last century is well recognized. Currently, it is estimated that **48%** of the world population is fed through this process (Erisman *et al* 2008). In the EU, cereal production would be reduced by one third or even one half without fertiliser application (Sutton *et al* 2011). Given the quadrupling of the human population in the 20th Century and thus the demand for food crops, nitrogen fixation through industrial production of ammonia (i.e. 170 Mt) has grown to exceed nitrogen fixation by microbes (90-130 Mt) (Galloway *et al* 2003).

The main processes through which nitrogen is fixed, transformed or lost from soils are: immobilisation, plant uptake, fixation in soil, volatilisation, leaching, nitrification and denitrification (these terms are explained in Annex I). These processes depend on environmental factors such as moisture, temperature or oxygen concentration, on soil properties e.g. texture, clay mineralogy, and the presence or absence of other ions in soils. In natural systems, reactive nitrogen does not accumulate because these reactions have found equilibrium and reactive nitrogen cycles back to the atmosphere as un-reactive nitrogen gas through a process called denitrification. The sequential transfer of reactive nitrogen between ecosystems has been named the "**nitrogen cascade**" (Galloway *et al* 2003) depicted in Figure 3. The figure illustrates how increasing inputs of reactive nitrogen into water and the atmosphere have disrupted the equilibrium between nitrogen forms and have led to the accumulation of reactive nitrogen in the environment. Although the rate of reactive nitrogen accumulation is unknown, Galloway and colleagues have estimated that in the year 2000, over 200 Mt of reactive nitrogen were released globally into the environment, equivalent to almost two thirds of the annually fixed nitrogen through Haber-Bosch and biotic fixation (i.e. 260-300 Mt). Of these 200 Mt, half derived from fertiliser application (organic and mineral), 40 Mt from biomass burning, 40 Mt from the cultivation of nitrogen-fixing crops, 20 Mt from fossil fuel combustion and an additional 10-20 Mt from oxidation of organic matter in soils as a consequence of land drying and clearing.

[38] The process consists of several steps but can be summarised as: $N_{2\,(g)} + 3H_{2\,(g)} \Leftrightarrow 2NH_{3\,(g)}$ (T= ~450 °C)

FIGURE 3. ***The nitrogen cascade for the agricultural system***



(Source: Sutton et al *2011)*

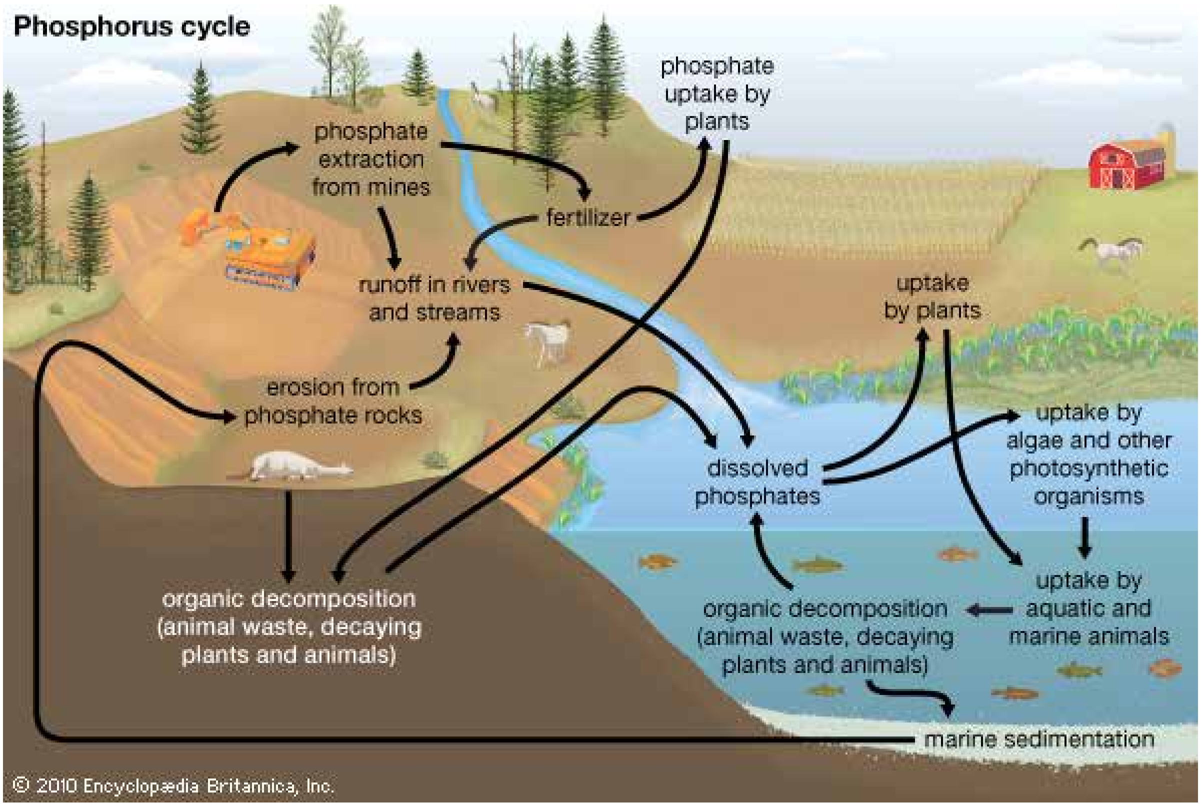
3.1.2 The importance of phosphorus, phosphate reserves and the phosphorus cycle

Like nitrogen, phosphorus plays a vital role in plant and animal physiology and growth. It is involved in plant photosynthesis. It is part of the Adenosine Tri-Phosphate (ATP) molecule that acts as energy carrier for cells. It is vital for important phases of plant development and maturity such as flowering and fruiting. In natural ecosystems, phosphorus is present in low concentrations in soils and, for the most part, found in the form of compounds that are not available for plant uptake. Due to its scarcity, ecosystems have evolved to be very effective in the use of phosphorus. The phosphorus cycle is depicted in Figure 4. The natural cycle can be disrupted by the establishment of agriculture in which crops are removed from fields accelerating phosphorus losses which are not replaced. In some African countries, phosphorus uptake through cultivation is still larger than phosphorus inputs indicating continued phosphorus depletion in soils and their degradation that leads to major social and environmental problems. The opposite is true in Europe; mineral phosphorus fertilisers and manures have contributed to high phosphorus stocks in soils since the modernisation of agriculture.

In natural environments, phosphorus enters soils through rock weathering over very long (geological) time scales. Nowadays phosphorus used in agriculture is mostly derived from mineral and processed phosphate rock. This is considered a non-renewable resource on a human time scale because the rock takes about 10 to 15 million years to form. A high demand of phosphorus in agriculture has led to an acceleration of the phosphorus cycle made possible by mining the mineral. There are no substitutes for phosphorus in crop production. Today, world agriculture depends on the supply of mined phosphate to keep its food production levels and it is estimated that 1,000 million tonnes of mined phosphorus have been added to the environment (to soils and waters) (Tiessen 2011).

Rock phosphate reserves are geographically highly concentrated and there is a large uncertainty surrounding the level of global phosphate reserves and resources (see Box 1 for more information). The production of phosphate is highly resource intensive. Phosphate mining is carried out in open mines, requiring large areas of land and considerable energy (although not large in comparison to N manufacture). Water is used in considerable amounts although up to 95% of it can be recovered. Large amounts of waste are produced in these mines. After extraction, phosphate rock is converted to phosphoric acid for fertiliser production. It is estimated that the production of one tonne of phosphoric acid requires over 9 tonnes of phosphate ores and generates over 21 tonnes of waste (Villalba *et al* 2008). One quarter of this waste corresponds to phosphogypsum, a by-product of the production of phosphorus fertiliser and regulated because of its radioactivity caused by the presence of uranium and thorium (Cordell 2010).

FIGURE 4. ***The phosphorus cycle***



(Source: By courtesy of Encyclopaedia Britannica, Inc., copyright 2010; used with permission)

Due to the relatively low inorganic phosphorus levels present in soil, plants have developed specialised mechanisms to extract it from very low concentrations in the soil solution. Plants take up phosphorus through their roots in the form of phosphate ions. Several studies have observed highest uptake rates in acid soils with pH of 5-6 (Schatchman *et al* 1998). As in the case of nitrogen, the presence of mycorrhizae (symbiotic association between fungi and plant roots) can enhance phosphate uptake.

The low mobility of phosphorus in soil and its limited availability for uptake by plants implies that a large fraction of the annual inputs to agricultural land accumulates in soils or is lost by soil erosion processes. van Dijk *et al* (2016) estimated that as much as 30% of total inputs from mineral fertiliser and manure in the EU27 Member States may remain in soils while a small fraction (<5%) is annually lost through runoff. In contrast, for the global context, Cordell *et al* (2009) estimate a higher erosion loss (33%) and a smaller soil build-up (16% of all inputs).

Nitrogen and phosphorus are also vital nutrients for humans. A special focus of EU regulation has been placed on decreasing the concentrations of nitrate in water. This has been done as a result of its effects on the environment but also due to some concerns about health impacts. Nitrate itself is not toxic to human beings. However, the human body can transform ingested nitrate into nitrite and other nitrogen compounds that may cause harm. Nitrates and nitrites have also been associated with diabetes, stomach cancer, thyroid problems and birth defects. However, several research studies suggest that nitrate ingestion is harmless for human beings or even beneficial to protect the body against cardiovascular diseases and stomach cancers (Brady *and* Weil 2014).

Among the most widely known functions of phosphorus in the human body are the formation of bone and teeth, which result from the combination of calcium and phosphorus into calcium phosphate. However, phosphorus is also an essential component of cell membranes, nucleic acids and is a key component of ATP, the energy currency of the cells. Dietary phosphorus is absorbed in the small intestine. Vitamin D controls phosphorus (and calcium) levels and, when in excess, is involved in their excretion through the kidneys. Humans obtain nitrogen from the consumption of protein rich foods such as meat, fish, legumes, eggs and dairy products. 30-53% of intake of dietary phosphorus in the EU is through the consumption of milk and dairy products, while grain provides 27-38% and meat the between 10-25% (EFSA 2015). In addition, phosphorus additives are contained in many processed foods and beverages, contributing to dietary intake. Phosphorus in food additives is presented in an inorganic form, which is more rapidly absorbed by the body than the organic form contained in plant and animal foods (EFSA 2015). Fruit and vegetables are minor contributors to phosphorus intake. European adults consume higher amounts of phosphorus (1000-1767 mg P/day) than the recommended minimum by the European Food Safety Authority (550 mg/day) (EFSA 2015). There is epidemiological evidence that high serum levels of P are associated with health issues, in particular cardio vascular disease. However, a recent study has shown that high levels of dietary P intake may not be associated to increased baseline serum P (Trautvetter *et al* 2016).

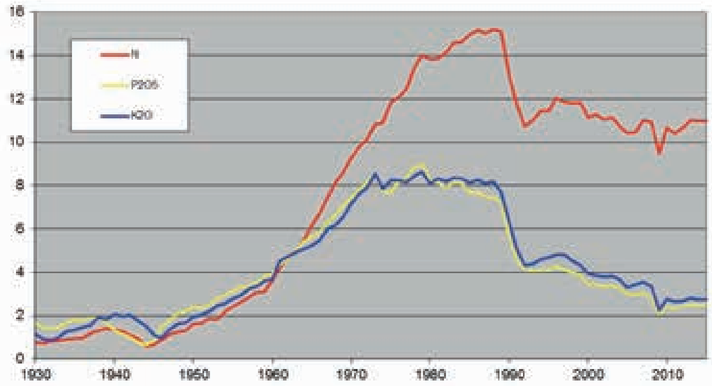
3.2 The use of N and P in the EU food system

3.2.1 Nutrient use in EU agriculture

In the year 2004, N total external inputs to EU cropland and livestock amounted to **16.7 Mt N**. Of this total, 10.9 Mt took the form of mineral fertiliser produced in the EU after industrially fixing nitrogen; 2.7 Mt were produced and imported feed concentrates while the remaining 3.1 Mt resulted from nitrogen deposition and biological nitrogen fixation (Leip *et al* 2014). In the case of phosphorus in 2005, the total input to crops and animals amounted to **1.8 Mt P** comprising 1.4 Mt of mineral fertiliser P and 0.4 Mt P in feed imports (van Dijk *et al* 2016).

Looking back in time, consumption of mineral fertiliser in the EU was low and unstable until early 1950s (Figure 5). It sharply increased after World War II reaching a peak in the 1980s – 1990s. Along with the developments in crop breeding and plant protection, this increase in fertilizer consumption was strongly associated with a major increase in crop production between 1965 and 1990 (Vall and Vidal n.d.). Since the early 1990s, however, EU27 mineral fertiliser consumption has decreased dramatically. This was particularly due to the collapse of the Soviet system in 1989, and the consequential disruption to agriculture in the EU Members in Central and eastern Europe. In addition, the decrease was driven by the large switch in the European agricultural policy away from commodity price support, and also by environmental legislation, and other economic factors. Mineral nitrogen consumption fell from its peak of 15 Mt in 1990 back down to 11 Mt in 2000, and has remained relatively stable since – although with a noticeable drop in 2008 following the financial and commodity crisis at that time. The peak consumption of mineral phosphorus (and potash) in the EU occurred around a decade earlier than for nitrogen and has followed a continuous downwards trend since. The consumption of phosphorus (expressed as P_2O_5 in Figure 5) has been reduced by 70% since the late 1970s.

FIGURE 5. ***Evolution of EU27 mineral fertiliser consumption between 1930- 2015 in Mt of nutrients***



(Source: Fertilizers Europe 2015. Note that P fertilizer is expressed as P_2O_5)

In the EU27, nitrogen accounts for almost **70%** of the volume of all applied fertilisers. **Nitrogen** inputs to cropland take the form of mineral fertilisers, manure, and other organic fertilisers. The largest single source of nitrogen inputs to cropland for the EU27 is derived from **mineral fertilisers,** 51% of the total[39]. **Manure** provides the next largest share, 34% of total N input. There are smaller N contributions from crop residues, atmospheric deposition, and biological fixation) (Figure 6). It is interesting to note that fertiliser use in Europe is different than that of the rest of the world. Calcium ammonium nitrate and ammonium nitrate represent almost one half of N fertiliser in the West and Central Europe consumption but are hardly present in large fertiliser consuming countries like China, India or the United States (Yara 2014). In contrast, urea has a relatively small, 21%, share of the EU market yet it represents 56% of the nitrogen fertilisers consumed globally because it is a cheap and concentrated fertiliser (Yara 2014). In cooler areas such as large parts of Europe the conversion of urea to ammonium is hindered and so fertilising with nitrate (which is readily taken up by plants) is more effective.

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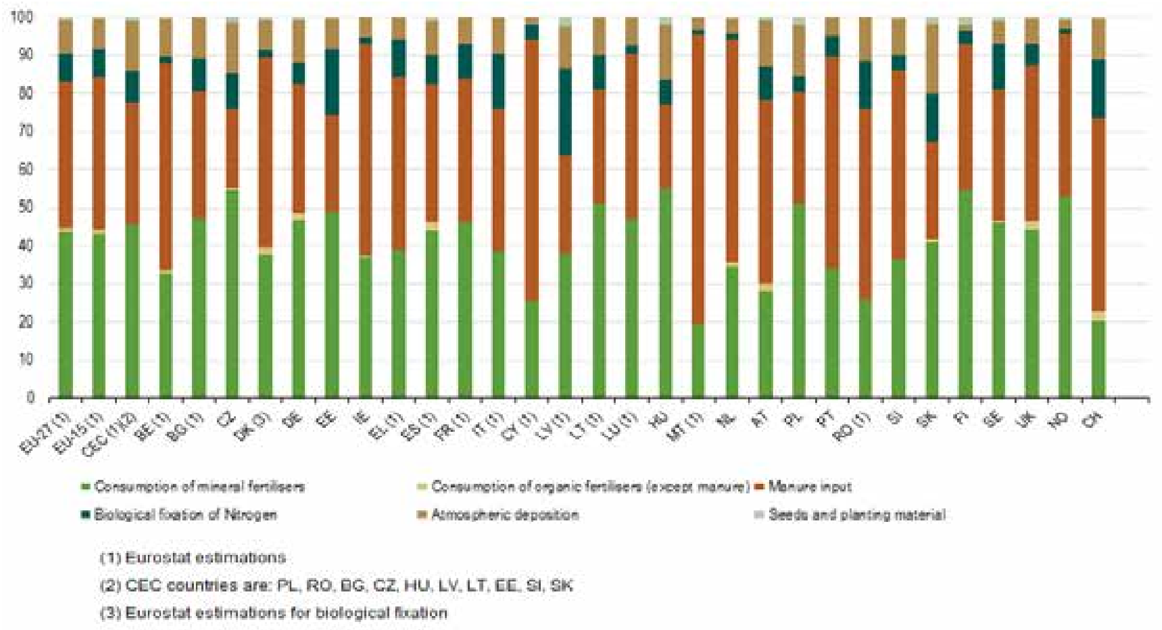
[39] *Mineral fertilizers are the dominant nitrogen source in agriculture in Hungary (55%), Czech Republic (54%), Finland (54%) and Poland (51%). In other countries, the largest share of nitrogen inputs come from manure. This is the case of the Netherlands (59%) and Slovenia (50%).*

FIGURE 6. ***Share of the different nitrogen inputs (average for 2005-2008)***



(Source: Eurostat 2012a)

The main **phosphorus** inputs to agricultural soils include mineral fertilisers, manure and minor inputs from recovered waste streams such as: compost, sewage sludge and industrial waste. Currently, mineral fertilisers account for **43%** of phosphorus inputs and manure contributes **53%** (Eurostat 2012b)[40]. The most common mineral phosphorus fertiliser is in the form of a compound fertiliser, NPK, (32%) followed by direct application of ammonium phosphates (32%) and superphosphates (16%)[41]. The high rates of phosphorus fertiliser application in European soils particularly from the mid-1960s until the early 1990s, have resulted in a large accumulation of phosphorus in soils and waters. Soluble sources of phosphorus entering the soil are easily fixed to the soil matrix so less than 20% of phosphorus remains available for plant uptake (Brady *and* Weil 2010). As a consequence, farmers have applied more phosphorus fertiliser than needed with its consequent build-up in soils. In their study, van Dijk *et al* (2016) estimate that in 2005, **0.9 Mt** of phosphorus, more than half of the mineral P inputs, were stored in European agricultural soils.

Mineral fertiliser use by crop. Plant response to nitrogen fertilization depends on a number of factors including water supply and the presence of organic nitrogen and other nutrients in soil. Therefore, optimal nitrogen application rates in cropland will be site and crop specific. In the EU27 mineral fertilisers are applied to a total of 133.5 million hectares, the large majority of which are occupied by cereals. The total area occupied by a crop and its nutrient requirements determine its total nutrient use. Table 2, shows N and P use in European croplands in the 2014/2015 season. Wheat is the dominant crop in European landscapes and uses about one third of all N and P applied to cropland and grasslands. On average, wheat is also at the top in nitrogen input per unit area, second only to oilseed rape. In the case of phosphorus, potatoes and sugarbeet require the largest inputs. Regional differences also apply; western Member States apply more mineral fertiliser compared to those in Central Europe. The difference is broader for nitrogen use than phosphate. For example, in 2010/2011 fertiliser application in wheat was higher than 130 kg/ha in Western Europe while it did not reach 80 kg/ha in Central Europe.

[40] *Countries with the largest share of phosphorus added to soils through mineral fertilizers were: Poland (58%), Hungary (58%), Estonia (53%) and Spain (54%), this last one estimated by Eurostat. Countries with the largest share of phosphate derived from manure were: the Netherlands (75%), Denmark (71%) and Ireland (66%). Estimates from Eurostat suggest that also Malta (89%), Belgium (76%), Luxembourg (74%) and Cyprus (71%) had very high levels of P input from manure.*

[41] *Data for 2014/2015 from Fertilizers Europe*

TABLE 2. ***Fertiliser use of nine major crops in the EU27 in the 2014/2015 season***

	Crop area (million ha)	Total N use (Mt)	Per unit area kg N/ha	Total P use (Mt)	Per unit area kg P/ha
Wheat	25.9	3.2	120	0.20	7
Grassland	30.5	2.0	63	0.09	3
Barley	13.9	1.2	96	0.09	8
Grain Maize	9.0	1.1	117	0.09	10
Oilseed rape	6.1	0.9	141	0.07	11
Rye, oats, rice	8.7	0.5	65	0.04	5
Silage maize	4.7	0.3	62	0.03	6
Potato	2.2	0.2	113	0.03	17
Sugar beet	1.9	0.2	115	0.02	16

(adapted from Fertilizers Europe)

3.2.2 Nutrient flows in the EU

It is perhaps surprising that it is only in the last decade that research has investigated the complex flows of nutrients through the food system. Recent studies are filling this knowledge gap by estimating the inputs and outputs for nitrogen and for phosphorus as they move through the entire food chain from fertiliser manufacture to sewage treatment attempting to measure all the annual fluxes from and into the environment. This ambitious task requires substantial research into the N and P content of the multiple forms of crop nutrients and animal and human feeds. A material balance flow approach has been adopted in which all the annual input flows nutrients into the system are calculated to match the outflows of N and P from the system in all forms. Because other non-agricultural and food sectors use some of the materials used by the nutrients sector and are responsible for some of the flows into water and atmosphere these nutrient balance assessments had to take a multi-sectoral approach for each of the elements.

The studies looked at the flows of N and of P between the mineral fertiliser industry, crop production, livestock production, food processing, final food consumption and then the water treatment and sewage processing sectors and the exchanges to and from the environment: soil, water and atmosphere. They estimated how much is taken up by plants, farm animals and humans and how much escaped in each form into rivers, lakes and oceans, and in the case of nitrogen, how much found its way after complex transformations back to the atmosphere in one of the many gaseous forms of this element. The calculations had to examine the numerous transformations of crop and livestock products in the food processing and food service chains to calculate the N and P content of these waste flows. They also had to recognise international trade. The EU is the world's largest importer of agricultural products (animal feed and human food) and the largest processed food product exporter, as well as being a significant trader of fertilisers and raw materials for their manufacture. The flows, and in the case of phosphorus changes in soil stock, of N and P were estimated from aggregate data for the EU27 for certain years in the period 2000 to 2005 using nutrient content and emission factors from a wide variety of sources. The results of this path-breaking work are found in several publications: Sutton *et al* (2011), Leip *et al* (2014) and van Dijk *et al* (2016). The values shown in this study result from combining these EU scale fluxes. It is clear that there are temporal variations in these fluxes from year to year and, thus, that the values presented and discussed throughout this report are offered as approximations which indicate orders of magnitudes of the current nutrient flows in the EU.

Leip *et al* (2014) and Sutton *et al* (2011) estimate that the net annual flow of nitrogen into the domestic EU27 agricultural system amounted to **16.7 Mt** around the years 2000 and 2004 (Table 3). Inputs of P around that same period were one order of magnitude lower, **1.8 Mt P**, according to van Dijk *et al* (2016). An input component of unknown magnitude must be added to this amount representing P uptake by plants from soil organic P stocks. Although this flux is likely to be small compared to the inputs from mineral fertiliser, it remains largely unknown and, thus, we illustrate this with a question mark in Table 3. In addition to these amounts, 7.1 Mt of N and 1.7 Mt of P are applied to cropland annually in the form of manure. These values are not included in Table 3 as inputs because they represent at the same time an input into cropland and an output of the livestock sector (both part of the agricultural system), they nevertheless have a large impact on the outputs and the efficiency of nutrient use (see section 3.2.3).

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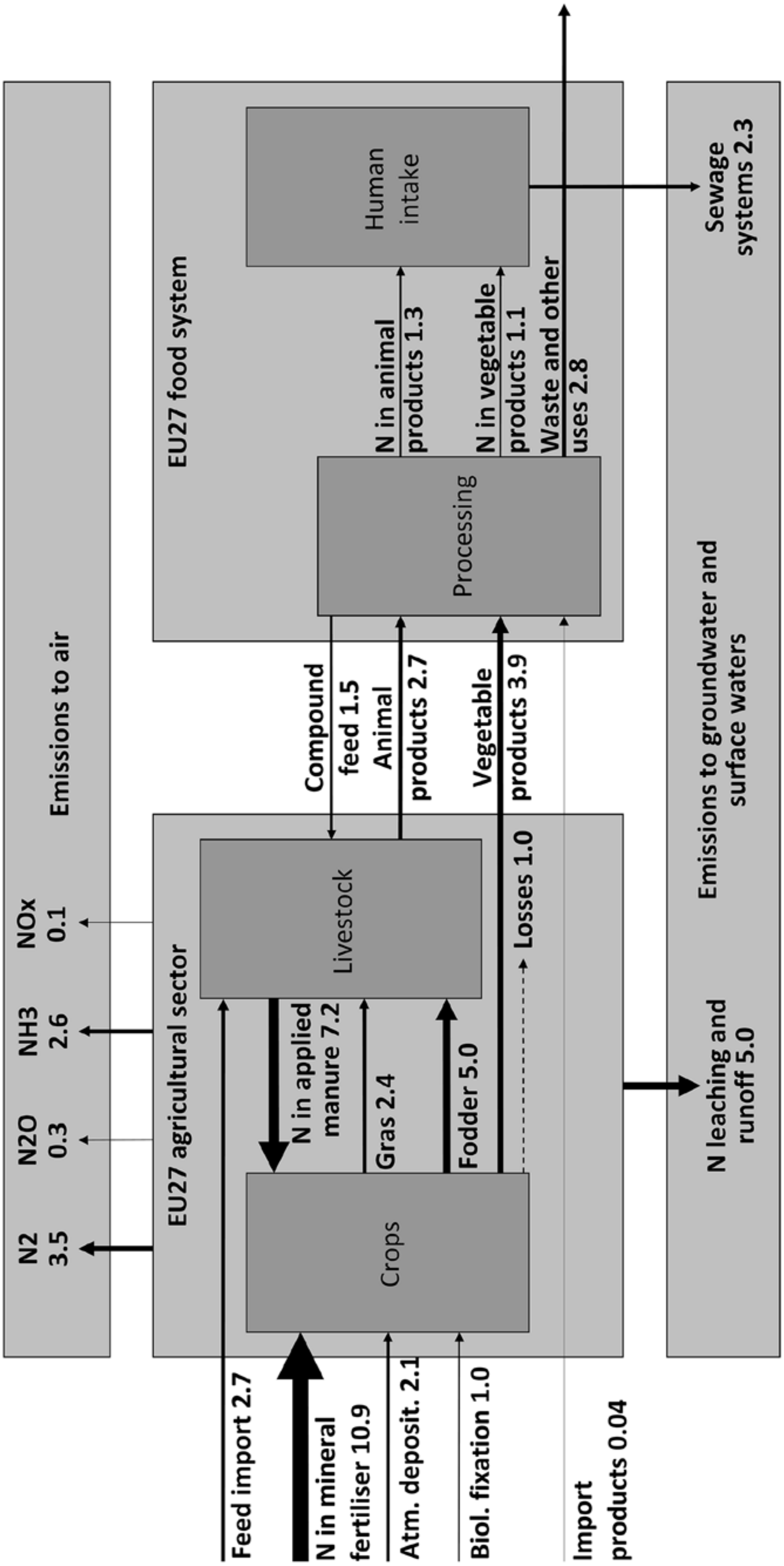
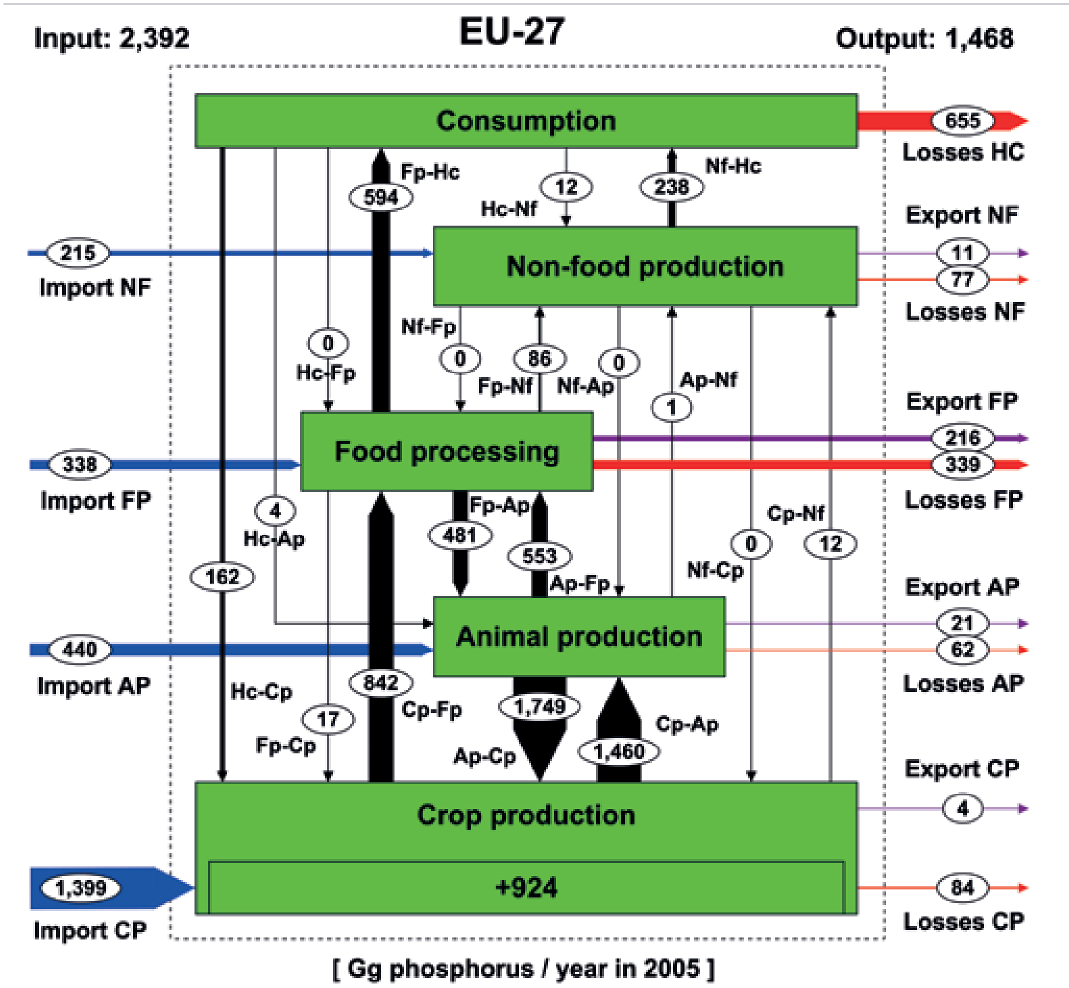
The complex pattern of nutrient flows through the system and the ultimate fate of the applied nutrients going into human consumption, the environment and waste flows are shown in Figures 7 & 8. Table 3, summarising these flows, illustrates that the fate of N is quite different to that of P and so too are their consequences. On average, 80% of nitrogen entering the agricultural system is emitted to the environment or routed to waste streams while only 20% ultimately reaches food consumers. The situation is similar for P, where around 30% of raw P inputs are converted into final products for consumers.

FIGURE 7. ***Nitrogen budget for the food system in the EU27 in the year 2004***



(Flows in Mt N/yr. Source: Leip et al 2014)

FIGURE 8. ***Phosphorus budget in the EU27 in 2005***



(van Dijk et al 2016)

TABLE 3. ***Gross annual nutrient inputs to the EU27 agricultural system and main output routes (years 2000, 2004, 2005)***

Nutrient fluxes in the European agricultural system	**Nitrogen** (2000 & 2004)		**Phosphorus** (2005)	
	Mt/yr	%	Mt/yr	%
Nutrient inputs				
Mineral fertiliser	10.9	65	1.4	78
Imported feed	2.7	18	0.4	22
Other sources (N fixation, atm. deposition, soil)[(a)]	3.1	17	?	?
Total nutrient inputs[(b)]	16.7	100	>1.8	100
Nutrient destinations				
Food consumers	2-3		0.5	
Other uses	1-2			
Solid waste and sewage system[(c)]	2-5		0.7	
Leakage to water, air and soil	11-12		1.3	
Consumer intake as % of total inputs		**~20**		**~30**

(All percentages are relative to net inputs. Source: based on data from Leip et al 2014, Sutton et al 2011 and van Dijk et al 2016)

[(a)] *P inputs from atmospheric deposition are estimated at 0.005 Mt/yr but plant uptake from soil P remains largely unknown (represented by question marks).*
[(b)] *Inputs from manure are not counted as input since they represent an internal recirculation flux. For reference, manure inputs to cropland amount to 7.2 Mt N/yr and 1.7 Mt P/yr (Leip et al 2014, van Dijk et al 2016).*
[(c)] *These include also inputs to the food and non-food systems outside of the agricultural system (e.g. import of non food products).*
[(d)] *We use NUEN to describe nitrogen use efficiency and NUEP for phosphorus use efficiency.*

3.2.3 Measuring nutrient use and its efficiency

A number of indicators have been developed to measure the performance (and leakiness) of the agricultural food system. Data are presented for two indicators measuring system performance and the potential environmental impact of nutrient use, namely nutrient use efficiency and nutrient balance.

Nutrient use efficiency

A simple way of expressing the performance of the food system is through the concept of **Nutrient Use Efficiency (NUE)[42]**. A NUE is generally calculated as the ratio of nutrients contained in a product relative to the total amount of nutrient inputs used to produce it. Its meaning will depend on the context and scale at which it is being applied. This can be done for the full food chain, or for a specific sector, or for an element within a sector (e.g. crop level). The EU Nitrogen Expert Panel suggest the following information is needed to estimate NUEs: (i) total nutrient inputs and outputs in harvested products; (ii) the boundaries of the system; (iii) the temporal scale considered; and (iv) changes in nutrient stocks.

To illustrate, the nutrient use efficiencies of the EU crop and livestock system are a NUE for N (NUE_N) of around 20% based on data from Leip *et al* (2014) and a NUE for P (NUE_P) close to 30%, based on data presented in van Dijk *et al* (2016) (Table 3). In other words, for every five tonnes of nitrogen entering the EU agricultural food system, only one tonne is converted into finished products ready for human consumption or other uses. These figures were based on the nutrients in agricultural products (crop and livestock products before food processing) comparing those to the raw nutrient inputs into the agricultural system, excluding manure, which is considered to recirculate within the system and not counted as a raw input and also excluding crop production which is directly consumed by livestock.

When analysing nutrient use efficiency for each part of the agricultural food system in the EU27 separately, **crop production stands out as the more efficient component**. For any specific crop, achieving high nutrient uptake efficiency depends on factors such as the form of the nutrient compound used, the rate of application, the time of application and the application method. In addition to these, soil type and environmental factors such as soil moisture, will also influence the NUE as well as the soil biodiversity (EC News Alert, 22 Jan 2015). For the EU27, NUE_N for crop production averages **53%**, ranging between 45-76% (Leip *et al* 2011) while NUE_P for crop production is estimated to be around **70%[43]** (van Dijk *et al* 2016). From a global perspective, these are considered relatively high nutrient use efficiencies for crop production (Westhoek *et al* 2015).

Substantial improvements in NUEs have been observed over the last decades in Europe. NUE_P rates more than doubled between 1965 and 2007 in the EU (Scholz *et al* 2014) with a 44% increase in NUE_N observed between 1990 and 2010 (Lassaletta *et al* 2014). Improvements in NUE of nitrogen have been attributed to improvement in crop genetics and fertiliser application practices and technologies (Hirel *et al* 2011). Among these, precision agriculture, based on the use of GPS and imagery technology to target crops needs based on the spatial variability of different soil and crop parameters, has seen rapid advances over the last decade and can still make a substantial further contribution to improving NUE.

Compared to cropland, **the livestock sector makes inefficient use of both nitrogen and phosphorus**. **NUE_N** in the EU27 in 2004 for livestock was only 18% (Leip *et al* 2014). This low efficiency is the result of: i) the large amount of manure produced by livestock (representing 81% of nitrogen outputs of the livestock sector), and ii) the large leakage of nitrogen to air and water resulting from the collection, storage and subsequent spreading of manure and animal slurry. In the case of phosphorus, van Dijk *et al* (2016) estimate a NUE_P for the livestock sector of 29% for the EU27 in 2005. This value accounts for outputs of animal production going into food processing relative to inputs. As in the case of N, about 60% of P output from animal production goes into manure, although much of this is then re-applied to agricultural land.

Within the livestock sector there are large differences in nutrient use between animal groups. Leip *et al* (2014) estimated the intensity of nitrogen emissions (to air and water) for different livestock products and concluded that the production of beef, sheep and goat meat results in the emission of 200 times more reactive nitrogen per kg of product than potatoes, fruits and vegetables. For pigs and poultry, eggs and dairy the proportion is lower, ranging between 20 to 70 times higher than those three vegetable products. Looking closer into NUEs for different animal species, pigs and poultry have higher nitrogen use efficiency than ruminants. Leip *et al* (2014) estimate that NUE_N for beef is in the order of 8%, while that of poultry is higher than 30%. Generally, little change in livestock nitrogen use efficiency has been observed over the last decades in Europe, although regionally some progress has been made[44].

Juxtaposing these very different efficiencies of crop and livestock production reveals what might be called the **paradox of livestock production.** Crop production is approximately twice as efficient in processing nutrients as livestock, yet continuous monocultures of the same crop is considered as an undesirable and risky practice. Crops are therefore beneficially mixed in rotations, often including some nitrogen fixing crops, but also with livestock production which unfortunately is much less nutrient efficient. Crop production benefits greatly from the use of

[42] We use NUE_N to describe nitrogen use efficiency and NUE_P for phosphorus use efficiency.

[43] This value is calculated as the ratio between P in crop outputs (2.3 Mt) and P in crop inputs (3.1 Mt) from manure and mineral fertilizer.

[44] In Denmark, nitrogen use efficiency for pig production has risen from 28% in 1985 to 42% in 2009 as a result of changes in the nutrient content in feed and reduced excretion (Sutton et al 2011, Chapter 3)

livestock manure. Indeed the proclaimed 'more natural' organic and ecological systems of agriculture are those embracing mixed crop and livestock production. The two together imply crop rotation, and the livestock contribute nutrients such as N and P but also organic matter which greatly improves soil structure, fertility and resilience for crop production. The challenge is to find the optimal mix for crop nutrition, but which is also economically viable.

Nutrient balances

Nutrient balances are another commonly used indicator of nutrient use. These are geographically referenced calculations which quantify the difference between the input of nutrients from mineral fertilisers, manure and other sources in a defined area, and the outputs of nutrients in harvested crops, crop residue removal and the grazing of fodder from that area. Thus, the nitrogen balance of a region is calculated as the sum of N inputs from manure plus N input fertiliser plus N deposition plus biological N fixation, less the N in crop yields and the N in grazed fodder. They are calculated for whole countries, regions or estimated for grid squares. When the inputs of nutrients are calculated to exceed the off-take this nutrient surplus represents a potential risk for the environment as it suggests there will be nutrient leakage into the air or water in the case of nitrogen and accumulation in the soil in the case of the less mobile phosphorus. If the calculation results in a negative balance, in which nutrients are being mined from soils by crops at a faster rate than they were replenished this indicates insufficient crop fertilisation.

Calculation and mapping of nutrient balances is now a well established way of demonstrating nutrient management in agriculture. Figure 9 shows such data for the EU27 nitrogen balance in 2005. It indicates that, apart from the north-most regions of Europe and mountain areas, most of the EU is characterised by nitrogen surpluses. The average gross N balance for EU27 for different years between 2004 and 2011 was a **surplus of 49-80 kg N/ha**[45] in agricultural land. For phosphorus, different authors come to quite different results on P surpluses with values ranging between **1.8 and 8 kg P/ha**[46]. There are strong differences in nutrient balances between countries[47]. The Netherlands has the highest surplus of nitrogen 175 kg N/ha and at the other end of the range Romania has an overall deficit of 4kg N/ha. Romania is the only EU country showing a deficit for N. For P the difference between the largest and lowest balances is 36 kg P/ha. According to Eurostat, the N surplus fell by 10% comparing the 2006-2011 period to the period 2000-2005, while the P surplus was reduced by 50% during the same time span. The largest reductions in P surplus have taken place in those countries with the largest nutrient surpluses. This is the case of the Netherlands and Belgium, where nitrogen surplus decreased by 50% between 1990 and 2011. A temporal comparison of the evolution of N and P balances shows that nutrient surpluses have been reduced in the EU27 and that the amplitude of the range of values in different countries has also been narrowed (Cyprus is the single exception to this in the case of P). In addition to the wide variations in nutrient efficiency and in nutrient surpluses between EU member states there is wide variation between farms, even farms of the same type in the same region.

Nutrient use overview

There are some strong and quite difficult lessons to be extracted from the data provided from the nutrient flows calculated in section 3.2.2 and the nutrient use efficiency and balances presented in this section. Nutrient use in agriculture has improved over the last decades but the overall performance still generates large amounts of nutrient leakages. Why is it so when there are plenty of measures available to reduce them?

Leakiness poses a serious economic problem: all farmers would prefer to reduce the inputs they have to purchase or grow to produce a unit of saleable product. Technical inefficiency is not in their interest. Equally seriously is that the leakage of nutrients has deeply undesirable human health, environmental and climate consequences. The nature and impact of these leakages is the subject of the next section. Many of these leakages in turn threaten the long term sustainability of food production itself. There are several possible answers as to why these changes are not happening faster when they are in everyone's interest. There may be a lack of awareness by farmers of the scale of the inefficiency, the methods of improving it, and the financial benefit of putting it right. To the extent that the remedy involves farm investment (in manure handling or storage, or spreading equipment) the private return on investment may be insufficient, and public supports unavailable to pay for the public benefit of reduced pollution. These nutrient management issues are complex and so it is also a challenge to harness consumer and citizen desires for less pollution, and thus more nutrient efficient production techniques, for example through their food choices. Although it is true that nutrient use has some inevitable inefficiency given that agriculture works with natural biological processes which (compared to electronic or some mechanical devices) are inherently exposed to the elements and therefore variability. It is also true that farms are often small independent businesses with a slow turnover of ownership, which reduces the opportunities to bring new, energetic, efficiency-seeking young blood into management. But these are not

[45] *Eurostat reports an average of 49 kg N/ha for the period 2006-2011. Using data from Velthof (2007) we obtain a value of 79 kg N/ha for the year 2000. Data from Leip et al 2015 result in a N balance of 80 kg N/ha. All transformations are based on an agricultural area of 172.8 million ha for the EU27.*

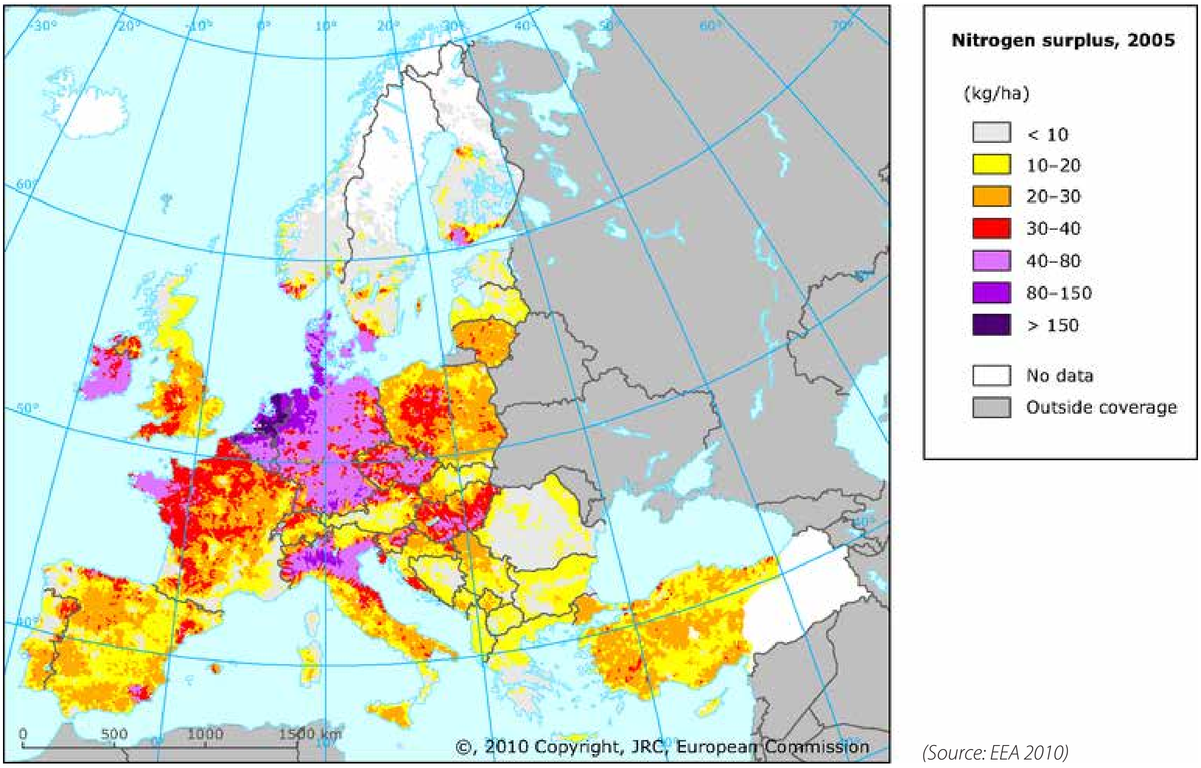
[46] *van Dijk et al (2016) estimate a surplus of 1 Mt P/yr for 2005 which would translate into 5.8 kg P/ha, and Richards and Dawson (2008) calculate a P balance in the EU27 for the year 2006 of 8 kg/ha (equivalent to 1.4 Mt P). However, Eurostat show the average gross P balance across the EU was a surplus of 1.8kg P/ha in agricultural land between 2006 and 2011.*

[47] *Even within most of the countries, there are large regional differences in nitrogen balance (Figure 3.2.4). High application regions in Europe include the main livestock producing areas of the Benelux countries, Denmark, Ireland and Germany plus the Po valley in Italy, and the Brittany, Poitou-Charentes region in France (JRC data from Eurostat).*

reasons to accept sub-optimal performance in nutrient management. It is a continuing task to help bench-mark farmer performance in their feed and fertiliser management, and to help through training, information, extension services, demonstration farms, and potentially through investment assistance to reduce the range of nutrient use efficiency in crop and livestock farming. This is true whether the nutrients in use have been recovered from waste streams or have been manufactured afresh. Nutrient recovery and reuse can contribute to improving nutrient efficiency but is no substitute for helping each and every crop and livestock farmer carefully ensure that the leakage from his system is minimised, and thus his efficiency is as high as it can be.

In the case of phosphorus, the cycling is slower and the majority of surplus phosphorus remains in the soil not taken up by crops (**29%** of total manure and mineral fertiliser according to van Dijk *et al* 2016). This continuous phosphorus build-up is not harmful *per se* but can lead to increased phosphorus losses through runoff and soil erosion, eventually reaching water courses. The risk of nutrient losses to the atmosphere and surface and ground waters will depend not only on the amount applied but also on the type of inputs and the characteristics of the application site such as soil type, timing, precipitation, temperature and soil properties.

FIGURE 9. ***Nitrogen surplus per hectare in agricultural land in the EU27 in 2005***



(Source: EEA 2010)

3.3 The disruption of natural cycles

The fate of nutrient surpluses in the agricultural system is different for nitrogen and phosphorus. Nitrogen surpluses are transferred to the atmosphere and water through leaching, runoff and emissions. As illustrated in figures 7 and 8 above showing the nitrogen and phosphorus flows through the food chain, about half of the nitrogen lost is estimated to leach into ground water or be lost in runoff to surface waters. The other half is mostly emitted to the atmosphere in the form of unreactive di-nitrogen gas (N_2) and reactive ammonia (NH_3). Smaller surplus components are the potent greenhouse gas nitrous oxide (N_2O) and the pollutant NO_x. Altogether, agriculture is responsible for 80% of all reactive nitrogen emissions in the EU.

Despite substantial effort to contain harmful N and P pollution the European Environment Agency in their State and Outlook 2015 report (European Environment Agency 2015) concludes the EU is still not ambitious enough to achieve its long term environmental goals. This is supported by the calculation that nitrogen pollution of air, water and soil **costs the EU between € 70 and € 320 billion per year** (Sutton *et al* 2011). The European Nitrogen Assessment calculates that the loss of excess nitrogen from agriculture into the environment has a fertiliser value of around **€ 20** billion per year (Brunekreef *et al* 2015).

The environmental side effects of the high nutrient flows in EU agriculture have long since been acknowledged. A great deal of legislation has been enacted since the Nitrates Directive of 1991 to contain and reduce the leakage. The combination of the legislation together with farmers' own self interest to apply nutrients only up to the requirements of their crops and farm animals has stimulated the large contraction in fertiliser use and corresponding rise in nutrient use efficiency summarized above. Notwithstanding this progress, there is still some way to go. This is, first, because current standards set by the Nitrates and Water Framework directives are still not being met. Second because new standards are sought to reduce agriculture's ammonia emissions[48] and agriculture will ultimately be confronted with the fact that it cannot be excluded from formal attempts to reduce greenhouse gas emissions. Third, it is expected that, in that absence of strong action to curb the consumption (and certainly the growth of consumption) of livestock products, there will be a resumption of the previous trend of expansion of nutrient use to keep pace with the growing population. The next four sections examine the impacts of nitrogen leakages on soil, water, air and climate.

3.3.1 Soil quality and pollution

Phosphorus and reactive nitrogen in soils are found mainly in the form of organic compounds. Since these compounds are not directly usable by plants, the practical approach of nutrient management has been to increase the amount of mineral phosphorus and nitrogen compounds in soils. This is mainly achieved through the addition of large amounts of manure and mineral fertilisers as well as ploughing crop residues back into soils and, in the case of nitrogen, also through inputs from nitrogen-fixing crops.

Holding the largest phosphorus and nitrogen reservoir in soils, **soil organic matter** plays an important role in bio-geochemical cycling and nutrient transformations. Therefore, changes in soil organic matter content will have an impact on nutrient status and availability in soils. The prevailing agricultural system in the EU, heavily relying on continuous inputs of mineral fertilisers and heavy machinery, threaten soil health and quality. The European Commission has recognised the impact of agriculture on six soil degradation processes: erosion from water, wind and tillage; soil organic carbon decline; compaction; salinisation; contamination and biodiversity loss. These six processes have a strong impact on soil structure, especially the upper part of the soil (topsoil), and, consequently, affect nutrient stocks and availability. Although there is not sufficient information to establish the combined impact of these processes on nutrient pathways, the effects of poor soil management come at a high cost for EU society. According to the European Commission, soil degradation could annually cost up to **€ 38 billion** in the EU (European Commission 2006). Long-term studies have shown that application of nitrogen fertilisers can lead to either a decline or increase in soil organic matter depending on circumstances. An increase may come about if there is enhanced crop production and thus residue returns to soil. Whereas, a decrease can occur if acidification or changes in C:N ratios take place after long term unbalanced fertiliser application, leading to higher soil organic carbon mineralisation. Several studies have found the combined application of mineral fertiliser and manure to be an effective way of preserving soil organic matter levels (e.g. Glendining *and* Powlson 1995).

Another impact of fertiliser use on soil quality concerns contaminants from impurities found in the fertiliser raw materials. This can apply both to mineral and organic fertilisers, and even if these are at very low levels, annual application over many years can lead to harmful accumulation of certain substances in soil. Average cadmium content in EU soils is 0.28 mg per kg of soil. Mineral phosphorus fertilisers contain small amounts of **cadmium**. European phosphate fertilisers contain on average 38 mg of cadmium per kg of phosphate (Smolders *and* Six 2013). In general, plants are not affected by cadmium; however, cadmium is a toxic element for many soil microorganisms and invertebrates as well as for aquatic organisms. Cadmium solubility is determined to a large extent by soil pH. As a consequence, the impact of cadmium in soils is variable throughout the European territory, which has a wide range of soil pH values. Current dietary exposure to cadmium is not believed to pose a risk for human health, however, the European Food Safety Authority recommends reducing exposure levels to avoid increased risk of associated diseases (EFSA 2012)[49]. Besides cadmium, other **heavy metals** as well as **pathogens** and **organic contaminants** (such as pharmaceuticals) can be incorporated into soil through organic fertilisers like sewage sludge and compost, and copper, added to animal feed, can be incorporated through manure.

Soil acidification is another environmental impact of large amounts of reactive nitrogen in the environment. Soil acidification results mainly from the application of organic and some mineral fertilisers (ammonium sulphate and urea) and **atmospheric deposition** of NO_x, NH_3 and SO_x (acid deposition). Acid deposition has decreased over recent decades, but the agricultural sector is the largest contributor to NH_3 emissions, which mainly derive from ammonia volatilisation from manure. Among the consequences of soil acidification are a decrease in crop growth, an increase in nitrate leaching from soils and the release of nutrients like calcium, magnesium (both of which enhance the hardness of drinking water) and iron, while also mobilising toxic cations such as aluminium and manganese and heavy metals, with otherwise very limited mobility. Soil acidification can also affect nitrogen transformations in soils by restricting the activity of certain soil microorganisms, resulting, for example, in increased shares of emitted N_2O during denitrification (Granli *and* Bøckman 1994, reference from ENA) and lead to water acidification, affecting aquatic ecology. Beyond agricultural systems, deposition of reactive nitrogen[50]

[48] Gothenburg Protocol (1999), National Emissions Ceilings Directive (2001, currently under revision), Industrial Emissions Directive (2010).

[49] Risk of kidney dysfunction and several types of cancer.

[50] Transfer of reactive nitrogen gases (nitrogen oxides and ammonia) from the atmosphere to the biosphere through dry deposition (particles) or wet deposition (rainfall).

has been a special concern for terrestrial ecosystems in Europe. Although low levels of atmospheric deposition of reactive nitrogen could actually promote biomass growth, large additions have harmful effects on terrestrial and aquatic ecology and biodiversity. Currently, two thirds of Europe's ecosystems are exposed to excessive nitrogen deposition (Posch *et al* 2012).

3.3.2 Water quality and pollution

Reactive nitrogen and phosphorus reach water bodies from soils through: leaching (nitrate), runoff (nitrogen and phosphorus compounds) and soil erosion. An additional pathway for nitrogen into water is via atmospheric deposition. Reactive nitrogen and phosphorus in water represent a major threat for aquatic ecosystems. The main environmental concern is **eutrophication** which results from high nutrient loadings into water leading to an exponential growth of algae (see Box 3 for a case study of the Baltic Sea). Upon their death, these algae drop to the bottom of the water body and decompose consuming large amounts of oxygen leaving the water in a state of hypoxia (low oxygen concentration, less than 2-3 mg of oxygen/l) or, in extreme cases, anoxia (oxygen depletion) (Brady *and* Weil 2014). As a consequence, aquatic species depending on oxygen migrate or die, biodiversity is reduced and ecosystem services such as water provision and purification, fishing and recreation, and potentially tourism are greatly diminished. Eutrophication also contributes to greenhouse gas emissions and a change in the nitrogen cycle, leading to increased emissions of N_2O while reducing the amount of nitrogen that is returned to the atmosphere in the form of N_2 through denitrification (Oren *and* Blackburn 1979). During organic matter decomposition in anoxic waters, gases such as methane and hydrogen sulphide can be emitted. In addition, the algae can also sometimes be toxic to plants and animals and pose a threat to livestock and humans (e.g. shellfish poisoning).

Eutrophication is mainly controlled by the most limiting nutrient in water. For freshwater, it is often phosphorus. As soon as the limiting nutrient becomes available, the algal bloom starts developing. In oceans, the atomic ratio of nitrogen to phosphorus in most phytoplankton is relatively constant at 16:1, and together with carbon C the ratio is known as the Redfield ratio (C:N:P; 106:16:1). Given that carbon (from CO_2 in the atmosphere) and nitrogen are abundant this signals that if the phosphorus constraint is lifted by a very small change in phosphorus concentration this is enough to trigger rapid algae growth. Reducing the risks of eutrophication requires limiting phosphorus and nitrogen inputs into waters. Currently, neither phosphorus application in agriculture nor phosphorus concentration limits in waters are directly regulated EU legislation, although they are indirectly addressed by the Water Framework Directive through water Quality Status objectives and obligations and Water Basin Management Plans. In addition, several member states have set limits for phosphorus application in agricultural fields and water bodies (Amery *and* Shoumans 2014).

3.3.3 Air quality and pollution

The agricultural sector emits reactive nitrogen in the atmosphere mainly in the form of ammonia (**NH_3**), but also as nitrogen oxides (**NO_x**) and nitrous oxide (**N_2O**). Reactive nitrogen emissions (excluding N_2) from agriculture account for 80% of total reactive nitrogen emissions in the EU (Westhoek *et al* 2015). These losses are predominantly from NH_3 emissions, which account for 95% of all NH_3 emissions in the EU, and almost 90% of which derive from livestock (Westhoek *et al* 2015). The agricultural sector is also still the major contributor to N_2O emissions in the EU, despite a 23% reduction between 1990 and 2010 (Eurostat). In the case of NO_x, direct emissions from agriculture represent a small contribution to the total NO_x emissions in the EU (<5%), which are dominated by fossil fuel burning. However, these values do not take into account that NO_x is also emitted when performing farming operations and transporting agricultural products.

Among the impacts of reactive nitrogen in the environment, its contribution to air pollution represents a major threat to **human health** causing strokes, heart attacks, and to a lesser degree lung cancer and respiratory diseases. NO_x contribute to the formation of ground level ozone[51] and together with NH_3 constitute particulate matter (PM)[52]. Therefore, the main air pollutants causing harm in human health are actually not directly the nitrogen compounds but secondary pollutants: particulate matter and ground level ozone, both of which require reactive nitrogen for their formation. Establishing the link between air pollution and human deaths is difficult due to its long term effects and estimates vary largely. Worldwide, annual numbers fluctuate between 1.3 and 3.3 million (Lelieveld *et al* 2015; Sutton *et al* 2013) and for the EU27 in 2011 there were between 180,000 and 430,000 deaths resulting from long-term exposure to air pollution (Guerreiro *et al* 2014; Lelieveld *et al* 2015). Air pollution is considered the largest environmental health risk in the EU and it is estimated that one in four Europeans will die or fall sick due to air pollution during their lifetime (WHO and OECD 2015). Between 2009 and 2011, 33% and 18% of the EU27 population were exposed to PM and ozone levels that exceeded EU quality standards (European Environment Agency 2013a). The costs for society are high; only in terms of health, the cost of air pollution in the EU was estimated to be between €330 and €940 billion a year (data for 2010, European Environment Agency 2015), somewhere between Belgium's and the Netherlands' GDP. Despite its importance, societal awareness of its threats and origins is very limited.

Agriculture plays a central role in the change in atmospheric chemistry, but it also suffers its consequences. High ozone exposure levels affected 18% of agricultural

[51] *Ozone is formed in the presence of sunlight when volatile organic compounds and nitrogen oxides interact.*

[52] *Ammonia can react with acid forming compounds (such as SO_2, NO_x) forming particles microscopic solid or liquid particles of ammonium sulphate and ammonium nitrate that contribute to air pollution and smog.*

area in the EEA33 countries[53] (Guerreiro *et al* 2014). The agricultural sector is mainly responsible for **ammonia** emissions, representing 95% of all ammonia emission in the EU27 (Leip 2011). These derive mainly from the production and handling of livestock manure and its application in the fields, as well as from decaying organic matter. Ammonia emissions from agriculture totalled 3 Mt in 2000 (Sutton *et al* 2011), although they had decreased by 28% between 1990 and 2010 as a result of changes in management practices and the communist collapse, which lead to a decrease in livestock numbers and fertiliser use (from COM/2013/0920 final). Agricultural soils, with 1.6 Mt, and livestock, with 1.4 Mt, contribute almost equally to NH_3 emissions from the agricultural sector (Sutton *et al* 2011).

3.3.4 Climate effects

Agricultural practices result in the emission of three greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Of the three, N_2O is a powerful greenhouse gas which has 300 times the warming potential of CO_2 (IPCC 2007). The agricultural sector is the largest contributor of N_2O emissions to the atmosphere in the EU with 400 Tonnes of N in the form of N_2O emitted in 2000 (a share of 56-84% of total EU27 N_2O emissions) (Leip 2011). N_2O is emitted through denitrification which takes place during manure management and the application of mineral fertiliser and manure in soils (Sutton *et al* 2011). Fertiliser use and crop type are key factors for N_2O emissions; however, it is the fertiliser application mode that has the highest impact on N_2O emissions. Together with N_2O, CH_4 is produced in a variety of biological processes such as: ruminant digestive fermentation, manure management, synthetic fertilisers, manure application to soils, decay of crop residues and rice cultivation.

The global contribution of agriculture to global CO_2 equivalent emissions is estimated at 10-12% according to the latest report on Climate Change by the IPCC (Smith *et al* 2014). In Europe the contribution of agriculture to total GHG is estimated to be 10% (Eurostat 2015b). These emissions derive from: the application of synthetic fertilisers and manure to soils (51%), ruminant digestive fermentation (32%) and manure management (17%) (Eurostat 2015c). Therefore, livestock are responsible for over half of the emissions of CH_4 and N_2O. Since 1990, EU emissions from the agricultural sector have declined by 22% due to a reduction in the use of nitrogen fertiliser and in livestock numbers. However, these reductions are partially compensated by increased imports of agricultural products especially of animal feeds. (Eurostat 2015c).

The climate impact of nitrogen-based emissions is a complex story. Although N_2O emissions contribute to global warming, reactive nitrogen in the air is thought to have an overall net **cooling effect** on climate (Sutton *et al* 2011). This occurs because there are several off-setting cooling mechanisms related to reactive nitrogen pollution which counteract the warming effect of N_2O. These cooling effects take place directly through the absorption of terrestrial radiation and scattering of solar radiation by particulate matter, and indirectly by influencing cloud formation and increasing CO_2 uptake by plants (through its fertilizing effect). However, whether N_2O is considered a damaging or helpful GHG, the scale of its harmful effects on human health provides enough reason to consider actions required to reduce its emissions.

The EU is currently revising accounting rules for GHG emissions and the treatment of land use, land use change and forestry (LULUCF) which considers the carbon sinks n soil and forests and is working to harmonise accounting rules. In due course this may lead to the incorporation of agriculture (and forestry) more formally into the EU's emission-reduction efforts.

3.4 Summary

Nitrogen and phosphorus are essential nutrients that play key roles in the development and functioning of plants, animals and humans. In order to feed the world population, agriculture heavily relies on the inputs of mineral nitrogen and phosphorus. It is estimated that around 16.7 Mt of N enter the EU agricultural system annually, 10.9 Mt of which in the form of mineral fertilisers, while external inputs of phosphorus amount to 1.8 Mt P. Mineral fertiliser inputs in the EU have fallen over the last twenty-five years and P fertiliser inputs are back to levels of the 1950s. Nitrogen fertilisers now account for 70% of all mineral fertiliser inputs. Despite the significant falls in use of mineral fertilisers the efficiency of nutrient use through the whole food chain unfortunately remains low. For every five tonnes of nitrogen entering the EU agricultural system, only one tonne is converted to finished products for human consumption, that is a 20% Nutrient Use Efficiency (NUE). For phosphorus, the corresponding figure is 30%. While crop production shows a relatively high NUE due to advances in crop genetics and management and fertiliser application techniques (53% for N and 70% for P), livestock makes a particularly inefficient use of nutrients (18% NUE_N and 29% NUE_P). These low efficiencies result in large leakage of nutrients into the environment with negative impacts on soils, water and air associated with unacceptable health and environmental costs. In soils excess P build-up can lead to increased phosphorus losses through runoff and soil erosion, while atmospheric nitrogen deposition is reducing biodiversity. P and N in waters contribute to eutrophication, reducing water quality, biodiversity and increasing greenhouse gas emissions. In the atmosphere, nitrogen oxides and ammonia reduce air quality, contribute to atmospheric deposition and have a strong impact on human health. Nitrous oxide, derived from the application of synthetic fertilisers and manure to soils, and methane, from ruminant digestive fermentation, are the main agricultural contributors to climate change. The next chapters investigate the contribution nutrient recovery and reuse could make to alleviate some of these challenges.

[53] *European Environmental Agency member countries include: EU28 + Iceland, Liechtenstein, Norway, Switzerland and Turkey*

BOX 3. Eutrophication in the Baltic Sea

The EU is considered a eutrophication **hotspot**. European rivers carry large amounts of nutrients that often accumulate in coastal waters. The Baltic Sea, considered one of the most polluted seas in the world, is an example of extreme eutrophication. Along with large nutrient loads resulting from human activities in its large catchment area, eutrophication in the Baltic Sea is enhanced because the sea has a relatively small body of water and limited exchange with the North Sea. To worsen the consequences, the Baltic Sea itself is comprised of several sub-basins with different temperature and salinity characteristics that create vertical stratification of water masses. This impedes adequate mixing of water that would locally reduce nutrient concentrations and provide the water layer next to the sea bottom with enough of oxygen (HELCOM, 2009). In 2005, it is estimated that over 700 000 tonnes of nitrogen and 35 000 tonnes of phosphorus entered the Baltic sea from rivers, point sources and atmospheric deposition (Savchuk *et al* 2012). Large as these quantities may appear, they represent a 40% reduction compared to 1980 levels. So the problem is still growing, although not at the rate of the past.

Several organisations and governments have been working to reduce eutrophication in the North and Baltic Seas. "**HELCOM**[1] the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area was established in 1974 to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental cooperation. The Contracting Parties are Denmark, Estonia, the European Union, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. The **Baltic Sea Action Group**[2], an independent non-profit foundation, has established itself as a coordinator between organisations at all levels of society with the aim to restore the ecological balance of the Baltic Sea. Among other organisations working to reduce eutrophication in European seas, the **OSPAR**[3] **convention**, established in 1972 with the goal of protecting and conserving the North-East Atlantic and its resources, has contributed to achieving large reductions in nutrient discharges in the North-East Atlantic. Governments from 15 countries in Europe are involved in the OSPAR and also the European Commission. The 2010 Quality Status Report identified agriculture and sewage as the main sources of nutrients into water. While reductions of 80% nutrient loads from point sources from industry have been achieved, the agricultural sector remains responsible for about two thirds of the remaining nitrogen discharges and one third of the phosphorus.

The large reductions achieved in nutrient loadings in the Baltic Sea case are a success. However, much remains to be done because eutrophication in the Baltic Sea has not decreased substantially. This is due to the legacy effects of the P concentration in water which means the area of anoxic sea bottom continues to increase. Previously settled phosphorus is being mobilised so the internal sources are just as important as the new additions of external inputs (Stigebrandt *et al* 2014). This study case shows that reductions in nutrient loadings into the environment will not lead to a full ecosystem recovery for a very long time. This has prompted investigation into the feasibility of trying to remove the legacy of accumulated P by extracting P-rich sediments after applying sediment oxygenation techniques to reduce P solubility. This task will take considerable time and resource.

1. http://www.helcom.fi
2. http://www.bsag.fi
3. http://www.ospar.org/

4. Scope, scale, technologies and the potential for nutrient recovery

4.1 An overview of the sources, amounts and processes

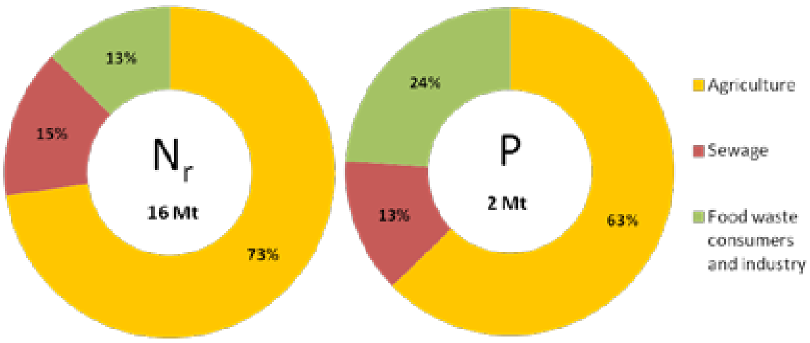
The idea of nutrient recycling in agriculture is not new. Before the discovery of Peruvian guano and Chilean nitrates, European agriculture relied heavily on three major pathways to bring back nutrients into soils. These were crop rotations, the incorporation of crop residues and organic waste on agricultural land and the use of animal manures, either directly deposited while grazing or collected and spread by the farmer. These techniques are still used today, and such recycled nutrients provide around half of the nutrients applied to European croplands, while the remaining half is supplied mainly by mineral fertilisers. Although recycled nutrients already represent an important share of total nutritional requirements for crop production, there is scope to increase this contribution by recovering and reusing nutrients from other waste streams and increasing the efficiency of those nutrients already returned to land. An additional benefit of recovering and reusing nutrients from waste streams is that it enables organic matter to be returned to the soil, playing a crucial role in the maintenance of good overall soil health and functions including nutrient cycling and soil fertility.

Nutrient recovery and reuse requires a close examination of where these nutrient waste streams and losses take place. Figure 10 summarises the magnitude of losses in three sectors of the food chain: agriculture, sewage and consumer and waste from the food industry. For both N and P the larger leakages occur through agricultural production activities. In the case of P, agriculture contributes to more than half of the total losses, mainly through P accumulation in soils (86% of agricultural losses). For nitrogen, agriculture is responsible for almost three quarters of all losses. The main pathways for nitrogen leakage from agriculture are nitrate leaching to ground and surface waters (43%), denitrification (conversion to N_2 gas) (30%) and ammonia emissions (23%) (Figure 7). These losses are for the most part associated with manure storage, handling and application on fields. Essentially, these values show that a significant proportion of nitrogen escapes as gases to the atmosphere, and most of the rest is leached into groundwater, waterways, and ultimately to seas and oceans. It may, in the future, prove technically possible and economic to capture or trap and recover the gaseous losses from housed livestock[54], but clearly this will not apply to grazing animals. Likewise for some lines of crop

[54] *Sutton et al (2013) point out the large quantity of NO_x gas produced in combustion (i.e. mostly outside agriculture) which could in principle be recovered by suitable chemical processes which convert the reactive nitrogen as NO_x to soluble NO_2 which could be captured and used for fertiliser production. They term this idea NO_x Capture and Utilisation (NCU) as a parallel to the Carbon Capture and Storage (CCS) concept.*

production, for example, the cultivation of intensive vegetable crops and soft fruit on substrates in contained or semi-contained systems already allows for the trapping and recycling of irrigation water with dissolved nutrients, thereby avoiding pollution and making efficient use of the applied nutrients. The situation is different in the case of nutrients present in waste streams (sewage and food chain waste), which represent around 30% of N losses and 40% of the total P losses (Figure 10). These flows are for the most part already being collected, but only a limited percentage of the nutrients are recycled back to agriculture land. The challenge is to devise viable technologies to make it worthwhile recovering the nutrients in a form and at a price which makes their reuse in agriculture attractive.

FIGURE 10. Total nutrient leakage in the EU27 from agriculture and the food chain



Note: This includes direct nutrient leakage from agriculture (cropland and livestock), nutrients in sewage and consumer and agro-industrial waste streams. Own calculations derived from data for EU27 for years 2000-2005 from Leip et al 2014, Sutton et al 2011, van Dijk et al 2016 and Velthof et al 2010. Nutrients currently recovered from sewage or solid waste are excluded from the Figure. Manure inputs to cropland (7.1 Mt N and 1.7 Mt P) are not directly included but indirectly accounted for through leakage from manure handling and application.

It is clear from the above that recovering all the N and P which leaks from the food chain is a challenging task. To address it, Sutton *et al* (2013) emphasize the need for a **holistic approach to a better nutrient stewardship,** i.e. focus on nutrient use efficiency across the entire food chain, thereby improving food and energy production, while reducing nutrient losses that pollute the environment. Among a series of actions identified by Sutton *et al* to achieve this, this study focuses on nutrient recovery from the three waste or leakage streams which seem most promising because of the quantities available and the technical practicality and likely economic feasibility of recovery. The selected waste streams are: (i) **manure**, with the twin objectives of increasing plant nutrient availability and fertiliser value in animal manure, while reducing nutrient losses and thus pollution during manure handling and application; (ii) human waste materials processed through **sewage** treatment works; (iii) and the **food chain waste** comprising consumer food waste collected by municipalities and the waste streams arising from various parts of the food processing chain. These

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are the three biggest material flows and they are also the flows from which most efforts to recycle N and P are already being made. There are other nutrient flows from which nutrients are being recovered to a smaller or larger extent (such as those from the paper industry) but this study focuses on those related to the food system.

Tables 4 and 5 provide an overview of the volumes and quantities of nutrients contained in the three selected waste streams and on the amount of nutrients currently being recycled to land, based on the current best estimates for the EU. The alert reader will have noticed that the terminology at this point has subtly changed from nutrient recovery and reuse to recycling. This is to reflect two facts which stand out from these tables revealing the volumes of materials. First, by far the largest flow of nutrient waste flow is manures, which represent over 70% of the nutrients in these three largest streams. Based on the definitions adopted in Table 1 of Chapter 2 the actions involved in manure management strictly do not constitute 'recovery'. Rather they are better described as a combination of nutrient 'collection' and 'application'. Together these are better thought of as 'recycling'. Second as seen in Table 5, a high proportion of manure, >90% is already being returned to land. The earlier discussion in Chapter 3 has indicated that this is not being done in the most efficient, least leaky way, therefore it is suggested that the terms recovery and reuse are restricted to refer to activities where there is more purposive, and effective attention to ensure that the nutrients in the material are appropriately processed so that they may then be reused in crop production. This certainly applies to the processing of sewage waste and food chain waste. It can also apply to certain techniques applied to more effectively utilise nutrients in manure. Tables 4 and 5 have not been able to include the total amount of nutrients recovered or collected but not reused in agriculture as the quantities involved are not known. It is immediately clear from Table 4 that nutrient recovery from waste streams implies dealing with **very large volumes of dilute materials** because the average concentration of solids in these flows is low, 15-30% of dry matter. Second, it can be seen that the total quantities of nutrients estimated in these three waste streams are 11.6 – 12.6 Mt N, and 2.6 Mt of P. For comparison, total nutrient inputs to EU cropland are: 21.2 Mt N and 3.1 Mt P.

TABLE 4. Gross fluxes of nutrients in waste streams (in Mt, million tons per year) for the EU27

Sources	Raw/wet mass (Mt)	Dry matter (%)	N (Mt)	P (Mt)	C (Mt)
Raw manure	1400[a]	15%[b]	7-9[c]	1.8[d]	130-146[e]
Food chain waste[f]	120-160[g]	25%	> 0.5-0.7[h]	> 0.5[i]	> 9.9[h]
Sewage sludge	9.5[j]	25-50%	2.3-3.1[k]	0.3[l]	1.9-3.8[m]
Total of these three flows			11.6-12.6	2.6	140-160

(a) *From Foged et al 2011.*
(b) *From Gendebien et al 2001*
(c) *Excreted by EU livestock (Leip et al 2014, Velthof et al 2015).*
(d) *Takes into account input to agricultural soils (1.75) and losses from stables (0.062) (van Dijk et al 2016).*
(e) *This is estimated considering that 80-90% of the dry mass is organic matter and using the 1.72 factor to convert organic matter into organic carbon.*
(f) *Includes the organic waste in household waste and waste from food industry.*
(g) *Eurostat and Gendebien et al 2001.*
(h) *Using a 2-3% N and 45% C in dry matter in household waste.*
(i) *It includes waste from food industry, food processing and household solid waste (van Dijk et al 2016).*
(j) *9.5 Mt of dry sludge could roughly translate into 9500 Mt of raw sewage water assuming 0.1% solids.*
(k) *Nitrogen in sewage from consumers/households (Sutton et al 2011 and Leip et al 2014).*
(l) *Includes P in centralised and decentralised sewage sludge (van Dijk et al 2016).*
(m) *Assuming 20-40% organic carbon in dry sludge.*

Table 5 shows that over 60% of the N and over 75% of the P in the selected waste streams are already being recovered and reused. This apparently high proportion of existing recycling of nutrients in agriculture demands closer examination. A great deal of the nutrient content of the large quantities of manure being applied to land is not being utilized as effectively as it should. This results in large environmental leakages. These result from inadequate nutrient application techniques and unbalanced application rates which are not determined by crop requirements but rather by regulation limits (in NVZ) or motivated by waste disposal needs (e.g. manure and sludge). Often, the form in which recovered nutrients are presented and applied also results in lower nutrient efficiencies for plant uptake. Therefore, increasing the potential of nutrient recovery and reuse requires that three parallel tasks be undertaken: (i) to increase the **total amount of recovered nutrients** from waste streams; (ii) to increase the **fertiliser equivalence value** of recovered nutrients (as formulated by Sutton *et al* 2011); and (iii) to create recovered products that are safe, easy to store, handle and use by farmers and which reduce current N and P leakage associated to nutrient recycling.

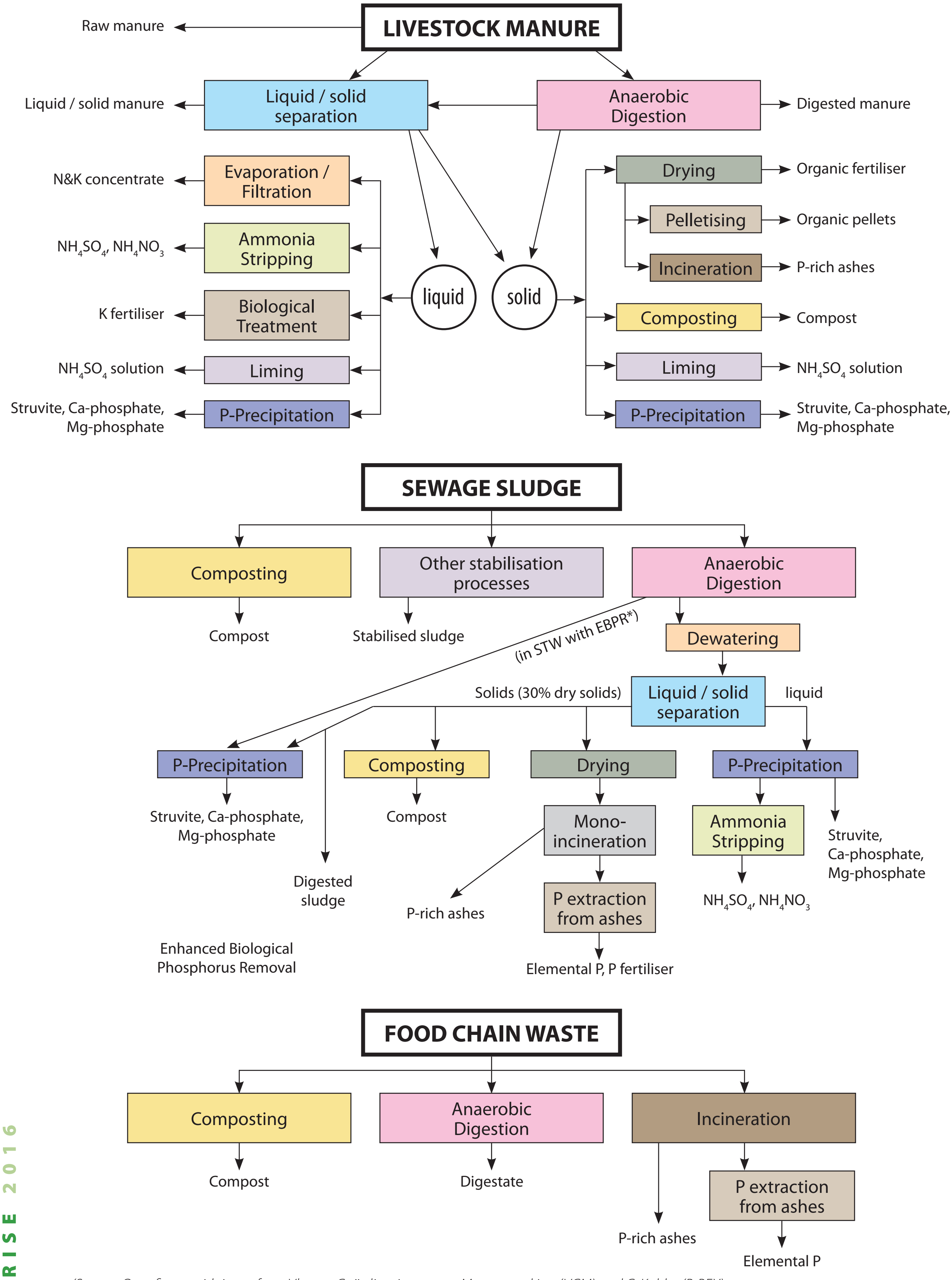
The main paths and processes through which nutrient recovery and reuse takes place are summarized in Figure 11 and defined in Annex II. The majority of the nutrients in manure are being returned to agricultural land with little or no processing. Sewage sludge mainly undergoes stabilisation treatments before land application, and some of the nutrients contained in household organic waste are being reused in domestic gardens as compost, but little data on the magnitude of such flows exists. There is similarly an absence of data collated at EU level on the recovery and reuse of nutrient rich flows from food processing industries (e.g. slaughterhouse waste). The remainder of this chapter looks more closely at the technologies and processes available for more effective recovery of nutrients from each of these three major waste streams.

TABLE 5. Gross estimation of recycled (recovered/collected + reused) amounts of N and P (Mt) for the three selected waste streams

	TOTAL N in stream	Recycled N	TOTAL P in stream	Recycled P
Raw manure	7-9	7.1	1.8?	1.75
Food chain waste				
Household waste	0.5-0.7	0.16	0.11	0.03
Slaughterhouse waste	?	?	0.28	0.02
Sewage	2.3-3.1	0.5	0.32	0.10
Totals of these streams	> 10-13	>7.8	2.5	1.9
Current recycling (%)		**60-80%**		**76%**
Not recycled (Mt)		**2-5**		**0.6**
For comparison, mineral fertiliser use in crop production (Mt)		**10.9**		**1.4**
Not recycled nutrient as percent of mineral fertiliser		**18-46%**		**43%**

(Sources: see Table 4 for total nutrients in streams. Recycled amounts from Leip et al 2014, Milieu et al 2010, Saveyn and Eder 2014 and van Dijk et al 2016)

FIGURE 11. Overview of the main routes for nutrient recovery and reuse and the products obtained



(Source: Own figure with input from Vlaams Coördinatiecentrum Mestverwerking (VCM) and C. Kabbe (P-REX). For a description of the processes see Table A1 in Annex II and sections 4.2-4.4).

4.2 Manure

Manure is defined as an animal by-product according to the Animal by-products Regulation ((EC) No 1069/2009) as *"any excrement and/or urine of farmed animals other than farmed fish, with or without litter"*. The regulation establishes limitations on its handling, transport and traceability. Manure use on land is regulated by the Nitrates Directive (91/676/EEC), that establishes a threshold of 170 kg N/ha only in Nitrate Vulnerable Zones.

4.2.1 Manure production and characteristics

The EU27 has a large livestock sector. Total farm livestock populations are estimated at 147 million pigs, 88 million cattle (~25% dairy cattle), 1.3 billion poultry (mostly broilers and laying hens), 83 million sheep and 10 million goats (Eurostat 2014)[55]. Together these animals are calculated to excrete[56] around **1400 Mt** of liquid and solid manure annually (Foged *et al* 2011). Of this, 600 Mt are in the form of liquid manure from pigs and cattle and about 300 Mt represent solid cattle manure, while the rest is produced by other livestock groups much of which is deposited on land by grazing animals (de Vries *et al* 2015). The first and most obvious point is that these are enormous volumes of material which arise across the farmed landscape. They contain large amounts of valuable nutrients but they are invariably in a highly dilute form. Total N and P excreted by livestock in the EU27 are estimated at **7-9 Mt N/yr** and **1.8 Mt P/yr** and have not changed substantially over the last fifteen years (Leip *et al* 2014, Sutton *et al* 2011, van Dijk *et al* 2016, Velthof *et al* 2015). However, there is some uncertainty about these values due to a lack of a standardised approach to calculate excretion coefficients[57] (Oenema *et al* 2007, Velthof *et al* 2015).

TABLE 6. Amounts and composition per type of manure for several EU countries – not specified

Manure type	Dry Matter (%)	Organic Matter (kg/Tn)	N (kg/Tn)	P (kg/Tn)
Cattle (liquid)	2-12	10-75	2-7	1.4
Cattle (solid)	14-30	140-200	3-8	2.4
Pig (liquid)	2-9	5-64	1-8	2.1
Pig (solid)	15-33	130-245	4-11	5.4
Poultry (solid)	22-70	180-560	10-58	16.7

Source: (data from de Vries et al 2015 and ICHS et al 2002)

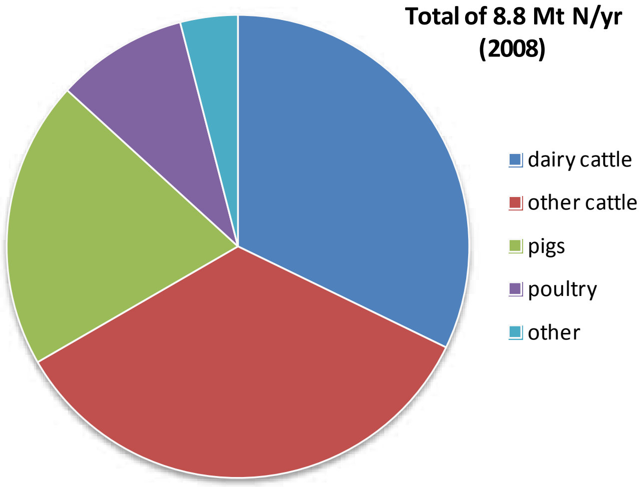
[55] *There are differences in the composition of livestock between countries, some countries are more cattle oriented (Ireland, Luxembourg and Lithuania), some are pig intensive (like Denmark, Spain, Belgium and Cyprus), others are more sheep and goat oriented (e.g. UK and Greece), or focus on poultry (Hungary).*

[56] *To explain excretion and production: excretion is the amount of excreted material while production refers to the fraction applied to land.*

[57] *Nutrient excretion coefficients provide a measure of the amount of nutrients excreted annually per animal type and are calculated as the difference between nutrient intake and nutrient retention in the animal body.*

Table 6 shows the composition of animal manures. Contents of N and P in manure vary by type of animal, their breed, their feed and milk/egg/meat production rates (Velthof *et al* 2015). Poultry manure has the highest concentration of N and P (34 g N and 9 g P per kg of manure) while pig slurry contains a lower percentage of dry matter resulting in more diluted nutrient concentrations (2 g N and 0.3 g P per kg of manure). Over the course of a year, however, a pig will excrete between 8 - 20 kg N, chicken excretes less than 1 kg of N (Velthof *et al* 2015). As a consequence, when looking at the total amounts of nutrient excretion, poultry represent less than 20% of all excreted N, while pigs contribute between 20-30% and cattle are responsible for two thirds of all excreted N with roughly half of this coming from dairy cattle, and the other half from beef (Velthof *et al* 2010) (Figure 12). A downward trend in total manure excretion has been observed over the last decade, due to slowly declining cattle numbers (Velthof *et al* 2015).

FIGURE 12. Nitrogen excretion[58] by farm animals in the EU27



(Source: adapted from Velthof et al *2010)*

4.2.2 Manure treatment and fate

In the EU27 manure is applied to land, incinerated, exported or used to produce dry manure products (Figure 11). The main disposal route is land application. More than **90%** of manure produced in the EU27 is currently returned to agricultural fields either through the spreading of collected manure or directly by grazing. This represents about **53% of the P and 33% of the N** applied annually to agricultural soils (Sutton *et al* 2011, van Dijk *et al* 2016). The most common treatment for the remaining **7.8%** of manure (108 Mt) is an initial liquid/solid separation (through filtration, sieving or centrifuging) or anaerobic digestion. The solid fraction can then be dried before pelletising or following incineration, or alternative-

[58] *Note that excreted does not mean available for application, since there are losses during storage, transport and application.*

ly, biothermal drying is used to produce compost. The liquid fraction can be concentrated through evaporation or filtration methods to produce a mineral concentrate (Foged *et al* 2011). The percentage of incinerated manure is very low and is mainly confined to chicken manure due to its higher dry matter content. This process enables some energy production and that of P-rich ashes as a by-product.

Deficient storage of manure contributes to ammonia emissions and nutrient leakage into soils and water. The result is that following such leakage there is a lower nutrient content available for crops. These losses could be greatly reduced by increasing the share of manure kept in dedicated stores. However, only one third of holdings with livestock appeared to have such manure storage facilities in 2010 (Eurostat 2013). These facilities are mostly used for the solid fraction (up to 82% of the holdings), while only 36% of the manure facilities could store liquid manure and 32% had slurry tanks or lagoons. Although these values indicate that there is considerable room for improvement, the situation is diverse among different holding sizes and among member states. For instance, the number of holdings storing liquid manure and slurry that use a cover in their storage facility ranges between 0% (Romania) and over 90% (e.g. Belgium, Netherlands and Poland).

There is similar variability in the attitude towards and methods used for manure spreading. A characteristic of direct manure application on agricultural fields is that it is sometimes driven by the motive to **dispose conveniently of material considered a nuisance rather than valued as a nutrient**. In such situations the dosage may not always be based on calculations of crop nutrient demands, and sound measurement of the nutrient content of the waste. The data has revealed that livestock manures contribute in total across Europe about the same order of magnitude of N and P to agriculture as that provided by mineral fertilisers, although there is large variation in this ratio between Member States. However, not all nutrients present in manure are effectively incorporated into soil when applied to land and only a fraction is readily plant available. Nitrogen in manure is mainly found in the form of urea, ammonium and stable organic nitrogen. Typically, half of the total nitrogen in manure is found in the form of ammonium and the other half in organic form, but this varies widely according to livestock group. The relative proportion of these chemical forms in manure will determine both its fertilization potential and also the potential nitrogen losses to the environment. Ammonium is plant available but can be easily converted to ammonia (gas) and be lost to the atmosphere unless adsorbed in the soil matrix. This explains why manure spread on fields that is left on the surface can quickly lose up to 90% of its ammonium following application under specific temperature, pH, humidity and wind conditions (Meisinger *and* Jokela 2000).

Loss of ammonium from soils is important for three reasons. First, it represents a loss of nitrogen fertiliser available to plants. Second, it reduces the N:P ratio in manure, contributing to P accumulation in soils[59]. Third, ammonia emissions contribute to nitrogen deposition that leads to

[59] *N:P ratios of plants (6:1 to 8:1) are higher than those of manure (from 2:1 to 4:1), which implies that a large percentage of P remains in soils and can be potentially exported. Further lowering of N:P ratios will only lead to higher P accumulation in soils.*

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water eutrophication (Meisinger *and* Jokela 2000). It is therefore important to reduce these losses from manure. Ammonia emissions can be minimised by adopting manure incorporation techniques, changing the timing of manure application and the application rates. A change from manure spreading to injecting or band spreading slurry and liquid manure into soil can significantly reduce ammonia losses. Incorporating spread manure a few hours after application can also reduce ammonia losses. Mixing bedding material with manure can also contribute to immobilise ammonium and, hence, reduce ammonia emissions. Another technique being used (especially in Denmark) is the acidification of slurry before or during its application in fields, which can reduce ammonia emissions up to 70% (Webb *et al* 2013). However, issues concerning the storage and manipulation of the acid (mainly sulphuric acid) and long term effects of acid inputs to soil call for caution.

4.2.3 Nutrient recovery and reuse from manure

Reducing nutrient losses through changes in manure storage and application are two ways to increase nutrient use efficiency. Another approach is to further process manure to concentrate nutrients and produce organic fertilisers which are stable for application, and more easily handled and transported. High livestock concentrations in several parts of the EU have led to excess manure production which cannot be applied in nearby fields. This creates high costs for farmers and such movement of quite dilute material does not seem a long term solution. So it is not surprising that it has stimulated interest in improved processing to recover the nutrients from these local-excesses of manure. At the same time there is a demand in other agricultural regions for good quality organic fertilisers both for their organic material and nutrients.

The concentration of livestock production in some European regions, with corresponding nutrient surpluses as discussed in section 3.2.3 is causing intractable pollution problems. If the manures and their nutrients cannot practicably be treated and transported to nutrient deficit areas, there may be few alternatives other than reducing the concentration of livestock production. This provides the motivation to find cost effective manure processing technologies to recover and transport locally excess manure without increasing the pressure on the environment.

An inescapable challenge in utilising animal manures is that the processing concentrates very large volumes of dilute material and this can lead to the accumulation of the minute traces of harmful substances to levels that might pose health threats. Newer techniques much expanded in recent years have opened the opportunity for increased **digestion and processing** of manure into safe and stable fertilisers that farmers can easily handle and apply. Such processes will also generally produce some biogas, a saleable product. In general, nutrient recovery from manure implies de-watering, concentrating and converting manure into a stable product that can be easily stored, transported and applied. Manure recovery processes use two types of substrates: raw manure or digested manure (Figure 11). Initially, a liquid and solid separation is typically performed. The liquid fraction (i.e. mineral concentrate) can undergo ammonia stripping or be directly used as fertiliser in fields. The solid fraction may follow a digestion process or be composted (Foged *et al* 2011). Often, the solid fraction is transported to an arable area in the region where it originated. New developments are underway to devise ways of separating solid and liquid animal excreta for example in pig stables at Wageningen University. Currently the largest output product in volume is digestate from anaerobic digestion, but manure compost is the main market oriented product derived from manure, next to dried manure pellets and separation solids (Sommer *et al* 2013). Other products valued for their nutrient content but produced in lower quantities are liquid mineral concentrates, ashes and char (Sommer *et al* 2013)[60]. Most of these manure products can be directly applied to fields and will produce a fertilizing effect or a soil improver effect.

To date, most of the research on manure processing has been conducted on pig slurry. This is because pig farms often do not have enough land to dispose of the slurry they produce, and pig slurry has a high water content which makes it expensive to store and transport (Schoumans *et al* 2010). The aim of such processing is to reduce the volume of the slurry and concentrate the nutrient content while minimizing emissions, especially ammonia, and energy use. One of the most common ways of achieving this is through an anaerobic digestion process, to which biomass and ammonia stripping can be added to increase biogas production[61].

The **success of nutrient recovery and reuse** from manure will depend on many factors including the evolution of the livestock sector, the availability and cost of recovery technology and the alternative disposal paths. High economic costs remain for the separation of liquids and solids, their drying and transport (Schoumans *et al* 2010)[62]. Phosphorus industries have shown interest in P extraction from the ashes of incinerated manure, which are to a large extent already used as a P-K fertiliser. The EU has invested in new technologies by funding research projects - through the Framework Programme FP7 and this continues under Horizon 2020 research programmes. These projects are aimed at converting manure into a fertiliser while potentially solving current challenges in manure management (storage, transport and application). In addition to public spending, a limited number of industrial full-scale processes focusing on nutrient recovery from manure are already implemented and operational. Some

[60] See Table A2 in Annex III for more information on P recovery.

[61] The environmental performance of such systems is controversial. If the biomass added to increase the energy yield of anaerobic digestion is maize, and if this, in turn, is associated with high nutrient input and a poor record with regard to soil erosion and water pollution then this route for NRR might be of questionable value.

[62] Schoumans et al (2010) estimate that treating pig slurry into marketable products had a cost of 14-18 euros per kg of P, half for nutrient recovery from the liquid fraction and half for the treatment (separation, drying and transport) of the solid fraction.

companies operate under a full-chain approach, taking into account all aspects involved from animal breeding to building construction, animal feed production and nutrient recovery and reuse. One such example is COOPERL, a farmers' cooperative in Brittany, France, that not only recovers N and P from pig manure and converts them into a mineral fertiliser, but also produces biogas during the process and is involved in what they call "360 degree pig chain profitability". The cooperative is involved at stages of the meat production process; from building stables to feed, and from slaughtering to consumer sales. The group has a turnover of €2 billion and slaughters 5.5 million pigs annually.

4.3 Sewage

Among currently identified potentially recoverable nutrient waste streams, wastewater and sewage sludge have received significant attention over the last decade. The enforcement of EU legislation[63] pushing for sewage treatment and the progressive limits placed on disposing of sludge in landfill have resulted in the need to find alternative disposal/recycling routes for increasing amounts of sewage sludge production.

Sludge is defined in several ways, all agreeing upon the fact that it is constituted of a solid and an aqueous phase and derived from treatment of human sewage in Sewage Treatment Works (STW), sometimes called Waste Water Treatment Plants (WWTP). The CEN (European Committee for Standardization) defines sludge as a "*mixture of water and solids separated from various types of water as a result of natural or artificial processes*". The European Environmental Agency glossary provides a slightly different definition: "*A semifluid mass of sediment resulting from treatment of water, sewage and/or other wastes*". According to the **Directive 86/278/EC** on the use of sewage sludge in agriculture, sludge stands for:

(i) residual sludge from sewage plants treating domestic or urban waste waters and from other sewage plants treating waste waters of a composition similar to domestic and urban waste waters ;

(ii) residual sludge from septic tanks and other similar installations for the treatment of sewage ;

(iii) residual sludge from sewage plants other than those referred to in (i) and (ii)

4.3.1 Sewage sludge production and characteristics

Sewage sludge can arise through different routes in the sewage treatment process. Sewage sludge production has increased in the EU over the last years as a result of the implementation of the Urban Waste Water Treatment Directive (91/271/EEC), through which towns with population over 2000 inhabitants are obliged to collect and treat their sewage. In northern and southern EU27 countries 80% of the population has its sewage treated in Sewage Treatment Works, a percentage that rises to 90% in central EU but is only 67% in Eastern EU. South Eastern Europe is behind in the implementation of the Directive, with only 40% of its population served by Sewage Treatment Works. In addition to differences in the population having their sewage treated, there are also large differences among member states in the treatment of the sludge in these plants (Figure 13). The treatments are classified as primary, secondary and/or tertiary, ranging from partial removal of physical particles and some of the organic matter to removing almost all organic matter impurities. The population connected to plants with tertiary treatments, those removing nutrients and organic matter, is in the order of 70% in Northern and Central Europe but only about 50% for Southern and Eastern Europe (European Environment Agency 2013b).

TABLE 7. Sludge production (dry matter) and use in agriculture

	Production (Mt)	Per capita Kg/person/yr	reused in agriculture (%)
EU27	9,5	19.2	44.2
EU15	8,1	21.1	49.3
EU12	1,3	13.0	17.0

(source: ESWI 2012, for 2007-2009)

Two reports produced for the European Commission, Milieu *et al* (2010) and ESWI (2012) show that around **9.5 Mt** of dry sewage sludge per year were produced annually between 2007 and 2009, over 8 Mt of which originated in the EU15[64]. This represented around **19 kg** per inhabitant per year of dry sewage sludge in the EU27; **21 kg** for EU15 and **12-13 kg** for the EU12[65] (Table 7). The lower values in EU12 are explained by the lower degree of waste water collection (Evans 2012). Sludge production in the EU27 has increased by more than 80% relative to 1992 values, when EU production was estimated at 5.5 Mt due to increasing levels of collection and treatment.

Sewage sludge is an organic substrate relatively rich in nutrients and trace elements. Sludge composition varies regionally and seasonally and there is little monitoring of the concentration and amounts of nutrients in sewage reaching Sewage Treatment Works. In the EU27, it is estimated that annually generated sewage sludge contains **2.3-3.1 Mt of N** and around **0.23 Mt of P** (Leip *et al* 2014, Sutton *et al* 2011 and van Dijk *et al* 2016)**.** In Sewage Treatment Works operating N and P removal, up to 90% of phosphorus in the inflow ends up in sludge, while over half of the total nitrogen is released to the atmosphere

[63] *Urban Waste Water Treatment Directive (91/271/EEC)*

[64] *EU-15 includes: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom.*

[65] *EU-12 includes the following countries: Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Malta, Poland, Romania, Slovenia and Slovak Republic.*

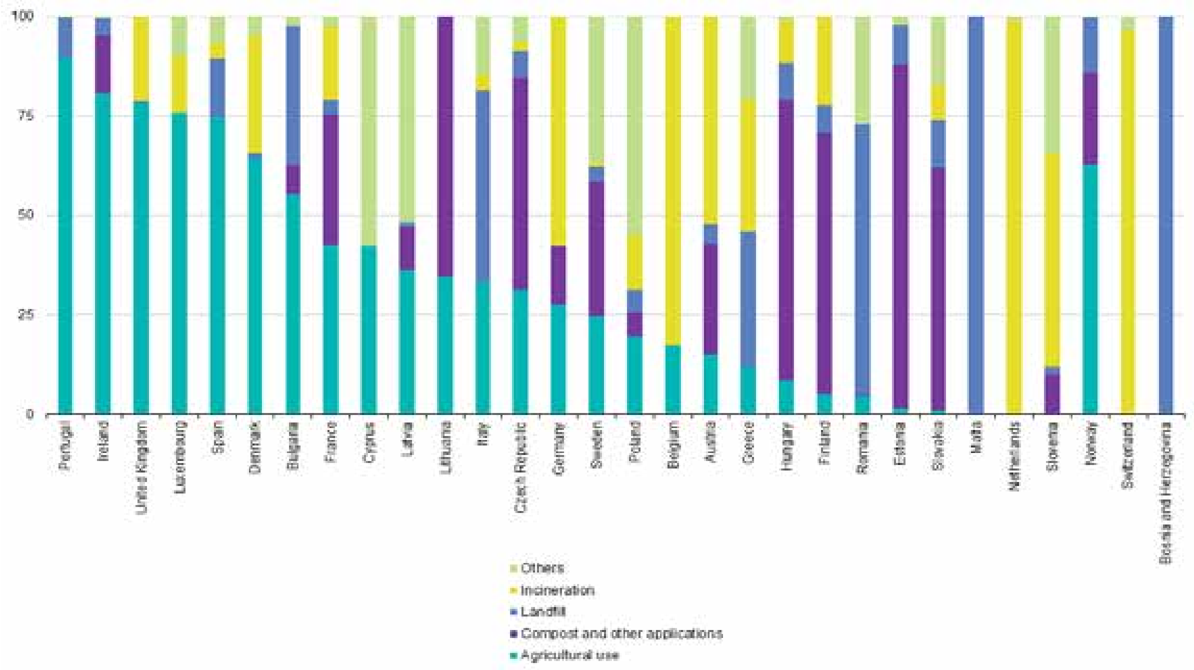
as nitrogen gas (N_2) through nitrification/denitrification processes (van Drecht *et al* 2009), reducing the amount of nitrogen available for recovery. In addition to nutrients, sewage sludge also contains harmful substances carried in waste water, from consumers and urban runoff, such as heavy metals, organic compounds, pharmaceuticals and pathogens.

4.3.2 Sludge treatment and fate

In Sewage Treatment Works, sludge is treated to increase its stability and reduce its water content. A reduction in water content can be achieved through thickening, dewatering (dry matter content up to 30%) and drying the sludge (dry matter content 35-90%). Drying is an energy intensive process and it often takes place after dewatering to reduce costs. The most common sludge stabilisation[66] methods used in EU27 are: anaerobic digestion, aerobic stabilisation, lime stabilization and composting. Upon treatment, sludge becomes **treated sludge** defined by the Directive 86/278/EC as: "*sludge which has undergone biological, chemical or heat treatment, long-term storage or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting from its use*". **Anaerobic digestion** is the most common treatment for sludge that is later applied to land. Anaerobic digestion stabilises the organic compounds in sludge and reduces the odour. In addition, anaerobic digestion leads to the production of biogas, which can be used internally in the plant or used to produce electricity.

After treatment, sludge is currently applied to agricultural land, incinerated, disposed in landfills, composted or follows other disposal routes according to EU legislation limits and regulations. Incineration, composting and landfilling are regulated by general EU waste legislation. Agricultural application of sludge has its own Directive[67]. Figure 13 shows that the choice amongst these disposal processes varies widely between the Member States (Eurostat 2015, Milieu *et al* 2010). Further processing of sludge and conversion into mineral fertiliser is currently considered negligible.

FIGURE 13. Sewage sludge disposal in 2013 in the EU27 by type of treatment



(*) Belgium, Denmark, Greece, Spain, Cyprus, Lithuania, Luxembourg, the Netherlands, Austria, Portugal, Finland, Sweden and the United Kingdom: 2012.
Italy: 2010. Croatia: not available.
Source: Eurostat (online data code: env_ww_spd)

(Source: Eurostat 2015a)

- Land application. Sludge is used in agriculture as a source of nutrients (N and P) for plants and also a way to replace organic matter back into the soil. On average, 42% of the sludge in the EU27 was disposed on agricultural land in 2013 but the percentage among Member States varied from 0% to 90% with Portugal, Ireland, UK, Luxembourg and Spain at the high end applying over 70% of the sludge on land (Figure 13, Table 8). Treated sludge is mainly applied to agricultural land but can also be applied to land reclamation

[66] *Stabilisation processes aim at reducing the fraction of biodegradable matter and pathogen concentrations in sludge to decrease environmental and health risks.*

[67] *Directive 86/278/ EEC*

and revegetation areas, green areas and forest plantations. National regulations are often very specific in terms of sludge application to agricultural land but its use in land reclamation, green areas and forest plantations is not addressed in most member states. This study focuses on sludge application to agricultural land only.

Data from EU27 member states dating between 2002 and 2007 shows that, on average, around **4 Mt of dry** treated sludge were applied to agricultural land in the EU27 on an area covering less than 5% of agricultural land in the EU. Most of this, 3.7 Mt of sludge were returned to land in the EU15 while the contribution of the EU12 was minor (0.3 Mt) (ESWI 2012; Evans 2012; Kelessedis and Stasinakis 2012). Overall, the range varies widely between members states (from 0 to 70%). High sludge returns to soil (> 60%) are found in countries such as the UK, France, Ireland, Spain, Hungary and Luxembourg. Despite increased sludge production and return to soil, public perception issues, investment in storage facilities in farms and the legislative controls imposed still limit its use (Milieu *et al* 2010).

Sludge application to agricultural land is framed by the **directive on the use of sludge in agriculture (86/278/EEC)**. This Directive dates back thirty years, and member states have asked for more stringent limits on the allowed concentration of hazardous substances in sludge and soil. The implementation of the directive in member states varies considerably, especially in terms of maximum allowed levels of heavy metals and organic compounds. Finland applies the stricter heavy metal contents, while in Flanders (Belgium) the use of sewage sludge on agricultural land is forbidden since 1999 unless sludge is treated to reduce N and P by 85% (Table 8) shows the percentage of sewage sludge applied to agricultural land, and some of the restrictions in place for four EU Member States. In the other 23 Member States the percentage of sludge applied to agricultural land ranged between less than 3% in Finland, Netherlands, Slovenia and Romania, and over sixty percent in the UK, France, Spain, Ireland and Slovakia. In twelve Member States the proportion of sludge applied to farm land is less than a third. The variation in practice is thus very wide and it would be revealing to understand in depth the reasons for the reluctance of so many Member States to engage in this aspect of recycling.

Besides the Sludge Directive, sludge applications in agriculture must also comply with limits set by other EU legislation on nutrients in the environment, such as the **Nitrates Directive (91/676/EEC)** that limits the amounts of nitrates in water. In 2006, the **Thematic Strategy for Soil Protection (COM/2006/0231)** mentioned the use of sewage sludge in agriculture as a means of combating reduction in soil organic matter and called for a revision of the sludge directive in order to maximise the reintroduction of nutrients into soil while reducing the release of dangerous substances. This strategy has not yet been translated into a soils directive because there was political disagreement on the necessity for EU legislation on soils. In addition, sludge application must follow certain requirements and conditions. As the Commission Decision 98/433/EC clearly states, it cannot be part of eco-labelled soil improvers. Producer and receiver both have to provide information on the sludge: treatment, composition and properties for the first and land information and history of agrochemicals and previous manure/sludge use for the second.

TABLE 8. Sewage sludge application to agricultural land among EU Member States and restrictions

Country	Year	To agriculture (%)	Restrictions to sludge application on agricultural land
Austria	2006	16	Sludge cannot be spread on: pastures, vegetable crops, berries, waterlogged or frozen soil, or on inclined land
Belgium -Flanders	2006	0	Use of urban sewage sludge on agricultural land is prohibited (1999) unless treated to reduce N and P contents by 85%.
Belgium - Wallonia	2007	35	Prohibited on grassland and forage crops; in soils in which fruit or vegetable crops are growing (except fruit trees after harvesting and before flowering); ground indented for cultivation of fruit or vegetables (at least 10 months before harvest), frozen soils.
Denmark	2002	59	Max. 10 Tn/ha/yr; limit values for organic compounds. Not allowed on edible crops or gardening. Only allowed in areas growing cereal, seed crops, grass or fodder. Must be worked into soil 12h following application.
Finland	2005	3	Most strict heavy metal content values in Europe. Allowed on soils where grain, sugarbeet, oil-bearing crops or crops not used for human food and animal feed are cultivated. Samples of cultivated soil to be taken at short intervals.

(Source: based on data from Milieu et al and European Commission 2001). All countries have restrictions on heavy metals.

- Incineration. On average, 27% of the sewage sludge produced was incinerated in the EU27 in 2005, making it the second choice of sludge disposal behind agricultural application. The Netherlands, Belgium, Germany and Austria incinerate more than half of the sludge they produce. Incineration takes place mostly in the EU15 while in the EU12 it still represents a very marginal or non-existent practice (Milieu *et al* 2010). The percentage of sludge that is incinerated varies widely across the EU member states (0-76%). Incineration of sludge is projected to increase by 2020 reaching a share of 90% or above in countries such as Belgium and the Netherlands, but remain at very low levels (10% or less) in Finland, Sweden and several EU12 countries (Bulgaria, Cyprus, Poland and Romania) (Milieu *et al* 2010). An interesting case is that of Switzerland, a country that currently incinerates 100% of its sludge but that recently passed a federal decree obliging phosphorus recovery (rates and conditions to be defined). Other countries may follow this lead.

  Two incineration methods are used: mono-incineration and co-incineration. **Mono-incineration** is a high temperature incineration of dewatered sewage sludge in dedicated incineration plants. The incineration processes produces steam (that can be reused in the incineration plant) and residues (**fly ash**) with high phosphorus contents (2-6%) that can be used as a substrate for P recovery. Alternatively, sludge can also be **co-incinerated** together with municipal solid waste or industrial waste in existing general purpose incineration plants that produce energy. This route is becoming increasingly popular in the EU. While co-incineration may be an interesting alternative in terms of carbon balance - it could be considered as neutral (0 balance) energy production system according to the IPCC – the ash produced has a lower P concentration than that obtained through mono-incineration and is mixed with other substances, increasing the difficulty for nutrient recovery. There are several environmental impacts derived from sludge incineration such as emissions of pollutants (NO_x, SO_2) and GHG gases to air (Milieu *et al* 2010).

- Landfilling. In 1998, 25% of the produced sewage sludge ended-up in landfill in the EU27. This percentage, however, has decreased over time due to the restrictions on the disposal of organic matter in landfill introduced through the **Directive on Landfill** (**99/31/EC**). This requires Member States to reduce the disposal of biodegradable waste in landfills to 35% of the biodegradable waste produced in 1995. In 2010, the percentage of sewage sludge going to landfill in the EU27 was reduced to 14% and is expected to further decrease by half by 2020 (Milieu *et al* 2010). The decrease was mainly led by the EU15, which has only 15% of sludge disposed in landfill, and several countries which have banned the landfilling of biodegradable matter (e.g. Austria, Belgium, Denmark, Netherlands, Norway and Sweden). However, the percentage of sewage sludge that ends up in landfill is still high in the EU12, at 28%. Despite landfill limitations and the fact that landfilling is currently the most common sludge disposal method in some EU12 Member States, sludge landfilling rates could still increase in the EU12 due to the full implementation of directive 91/271/EEC on Urban Waste Water Treatment. This is expected to increase sludge production in the EU12 by 100% by 2020 (Kelessedis *and* Stasinakis 2012) and it not clear if alternative processing routes will be available. How this develops in the EU12 remains to be seen since increasing landfilling and incineration taxes could make agricultural application of treated sludge a cheaper alternative.

- Composting. Although composting sludge is a minor practice in the EU (it applies to about 7.5% of total sludge) it represents the main disposal route for sludge in Eastern European and Baltic countries (>60%). The composted sludge is often returned to agricultural land.

4.3.3 Nutrient recovery from sewage

Currently, almost half of the nutrients in sludge are already being recycled back to agricultural soils through direct land application and composting. Yet, these nutrient recycling paths are questioned for two main reasons. First, there is still insufficient knowledge and confidence by farmers about the consistency, content and plant-availability of the nutrients present in the land applied sludge. Second, although the concentration of heavy metals in sludge has been reduced, there is not full confidence that the presence of pathogens, pharmaceuticals and complex organic compounds is sufficiently well monitored and controlled, and that the application of sludge to agricultural land is well enough regulated. This route for NRR is therefore still regarded in many countries as a threat to plant and human health. Current development of new technologies could contribute to increasing nutrient and energy recovery while diminishing its currently negative perceptions.

The new technologies for increased nutrient (and energy) recovery from sludge are appearing, partly as a response to these challenges. Developers of these technologies aim to recover materials or fertiliser products that can have a market value by developing safe products with proven fertilising effect. These are not the only factors/motivations that make nutrient recovery from sewage sludge an interesting route to explore. According to the FAO[68], sewage sludge treatment and disposal costs represent about **one half** of the operating costs of secondary sewage treatment plants in Europe. Therefore, increased recovery of nutrients from sludge offers a way of reducing the cost of sludge disposal – as well as offering value to the farmer.

An important advantage of nutrient recovery from Sewage Treatment Works, in the case of phosphorus, is to reduce the rate at which the pipe work is obstructed and

[68] *FAO website on agricultural use of sewage sludge: http://www.fao.org/docrep/t0551e/t0551e08.htm*

valves damaged due to the precipitation of struvite in the presence of ammonium. Struvite is the common name of a magnesium ammonium phosphate mineral ($NH_4MgPO_4 \cdot 6H_2O$). It was discovered in the 19th century. Sewage treatment companies have developed various processes to control this precipitation of phosphorus, mostly by adding ferric, aluminium or magnesium ions, and more recently, using ultrasonic technology. Finding ways to recover this phosphorus would reduce maintenance costs in these plants. It is estimated that recovered phosphorus from sewage could cover up to 15% of current phosphorus demand (P-Rex 2015) and up to 3% of mineral nitrogen fertiliser inputs (Sutton *et al* 2011).

Sewage Treatment Works are often confronted with the problem of reducing nitrogen loadings. Nitrification and denitrification processes are the most commonly used practice to reduce reactive nitrogen concentrations. However, these techniques do not allow for nutrient recovery, since nitrogen is emitted to air in the form of N_2, and a large surface area is required to place the tanks where this biological nitrogen removal process takes place. An alternative option is **ammonia stripping** (Box 4), which can produce nitrogen fertiliser with a market value in the form of ammonium sulphate or ammonium nitrate depending on the acid used to convert the gas into a salt.

BOX 4. Case Study: Nitrogen recovery from wastewater. The VEAS-Yara business case (Oslo, Norway)

This is a working example of the circular economy in action. It has been developed by VEAS, a waste water treatment plant (WWTP) serving a large part of Oslo municipality (~ 650,000 pe) , and Yara International ASA, a mineral fertilizer and environmental solutions company. The model is based on recovering nitrogen from effluent water from a WWTP. This is done after anaerobic digestion and filter pressing stages, by means of ammonia stripping and its subsequent recovery and reuse.

Ammonia stripping is a well-established industrial process that allows nitrogen recovery from a liquid waste stream containing high levels of dissolved ammonium (NH_4^+). The ammonia gas (NH_3) produced in this way is subsequently captured in an acidic medium, thereby producing an ammonium salt liquid side stream.

Initially VEAS used sulphuric acid (H_2SO_4) for ammonia capture, resulting in an ammonium sulphate $(NH_4)_2SO_4$ "slurry". Ammonium sulphate is a widely-used fertilizer commodity, but has relatively low market value. Moreover, the physical properties of the ammonium sulphate slurry hamper handling and reuse, making it rather difficult to market this material. In 1998 VEAS switched from sulphuric acid use to nitric acid (HNO_3) use for ammonia capture, thereby producing a 54% ammonium nitrate (NH_4NO_3) solution which meets market-quality specifications (low levels of metals, chlorides and TOC).

Yara supplies the nitric acid, recovers the ammonium nitrate solution, and provides logistic and safe-handling support. The bulk of the ammonium nitrate solution is sold directly to industrial users, any surpluses are recycled in Yara's fertilizer plant in Porsgrunn. Based on this air stripping technology and the associated business model, VEAS produces approximately 4,000 Mt of ammonium nitrate solution per annum, thereby recovering about 750 Mt of nitrogen, or some 15-20% of the total nitrogen load entering the WWTP facility.

Picture (Courtesy of VEAS). Nitrogen recovery at VEAS wastewater treatment plant in Oslo (Norway). Right is the ammonia stripping tower, and left the acid absorption tower.

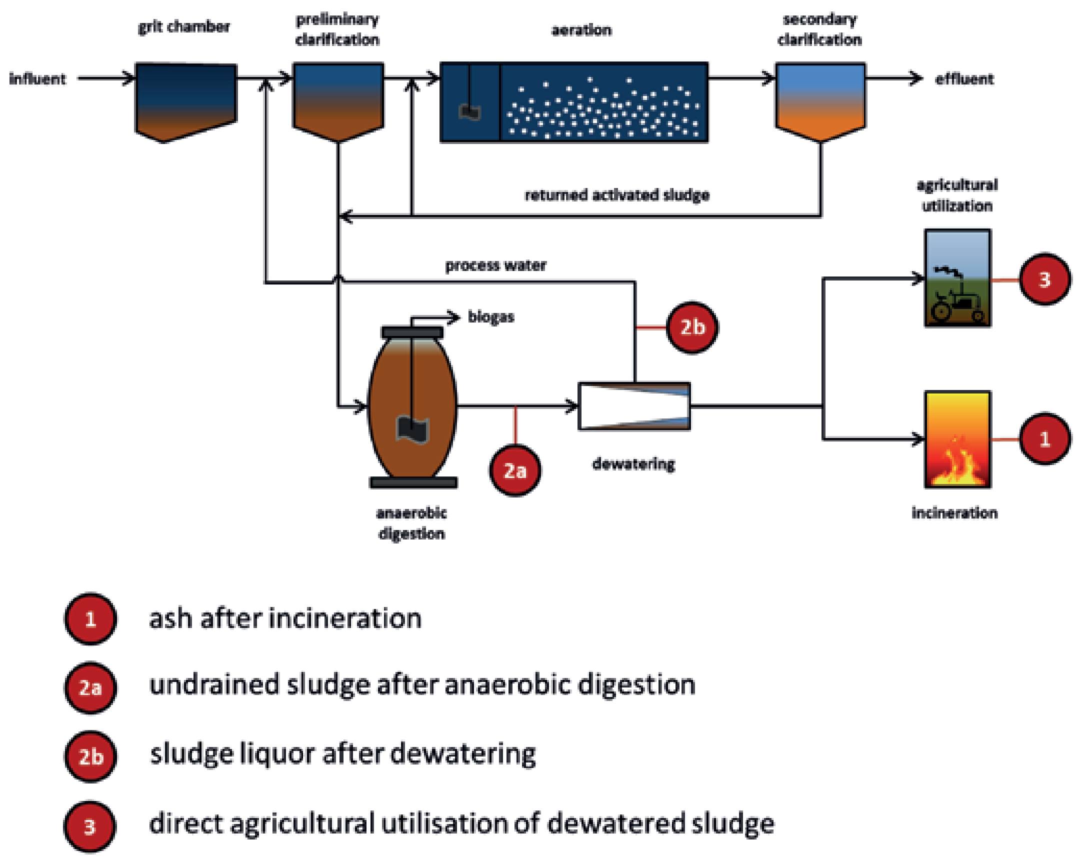
(Based on: Sagberg et al 2006)

Over the last two decades, the number of processes available to technically recover phosphorus from sewage (in a mineral form) has multiplied. Today in Europe there are **over 20 sites** currently planning or operating technical phosphorus recovery. Details on the specific technologies have been summarised in several publications such as those by Desmidt *et al* 2015 and Kabbe *et al* 2015, and here only the main pathways are summarised. The European Commission published in 2015 "Circular approaches to phosphorus, research to implementation" that presents conclusions of the ESPP – P-REX – EU Commission Berlin workshop on P-recycling held in March 2015. This report identified processes that are already at the commercial production scale. It underlined the need for policy support for phosphorus recycling and identified R&D needs to support implementation.

Phosphorus can be recovered from sewage sludge dewatering liquor or sewage works process side-streams, mainly in sewage works operating enhanced biological nutrient removal (Figure 14). These plants show recovery rates generally between 15-30% of total sewage works inflow of P (some of the P is not accessible because in the sludge solids). Alternatively recovery from sludge or sludge incineration ashes produce recovery rates up to 90% (Desmit *et al* 2015, Egle *et al* 2015, Kabbe *et al* 2015) (see Table A2 in Annex III for more detailed information on P recovery from sludge and ashes).

The most common P recovery processes operating today in Europe are struvite (magnesium ammonium phosphate) recovery in sewage sludge dewatering reject streams or liquid sludge before dewatering. The struvite produced is a fertiliser, which can be used in agriculture or specialist applications (e.g. nurseries, public gardens, sports fields). Depending on the process, where in the sewage works it is operated and what washing product is applied, the organic content can be up to 25% or below 0.5%. However, struvite recovery is in general only viable in sewage works where these are operating enhanced biological nutrient removal (bio-P or EBPR), usually with anaerobic digestion of the sludge. The main benefit of struvite recovery for these plant operators lies in the improved sludge dewaterability and/or in the cost reduction of plant operations associated to reduced pipe clogging (Egle *et al* 2015). Therefore, the value of the struvite itself currently constitutes only a small component of the total benefit.

FIGURE 14. Phosphorus recovery hotspots in sewage treatment works



(Source: Kabbe et al 2015)

Phosphorus removal in sewage works is also motivated by the need to achieve discharge consents in order to respect the Urban Wastewater Treatment Directive and Water Framework Directive obligations. These, in turn have the goal of avoiding eutrophication of surface waters. When this removal is achieved using chemical P dosed with iron or aluminium salts then the phosphorus is not available for recovery by struvite precipitation. Also, recovery using other processes (see above) can be more difficult, because the phosphorus is strongly bound to the metal even after sewage sludge incineration. There is further technical discussion as to whether this phosphorus is available to plants when treated sewage sludge is used in agriculture, or whether it is plant available within the time frame relevant for crop production. These all raise questions about the effectiveness for agricultural application of such 'bound' phosphorus.

Phosphorus can also be recovered after incineration, from **sewage sludge incineration ash** resulting from mono-incineration. Mono-incineration refers to the incineration of sewage sludge alone, not mixed with low-P industrial wastes or municipal solid refuse. The sludge ash from mono-incineration has phosphorus content ranging from 2% to 12% P. A number of technologies in development enable the recovery of P concentrated in ash. Following such incineration the phosphorus can be produced as fertiliser phosphates, chemical calcium or other phosphates, or as phosphoric acid. Ecophos are building a 60 000 tonnes / year factory in Dunkerque France which will take as input low-grade phosphate rock and sewage sludge and possibly manure incineration ashes. Kanton

Zurich has recently announced the decision to invest 5 M CHF in a wet chemical process piloting project to recover phosphate from sewage sludge incineration ash. Several other processes using ash or sludge have been or are being tested at pilot plants including Outotec/AshDec®, Recophos Thermal, and Budenheim.

Ideally, these processes should perform three tasks: to concentrate the phosphorus, render it either as fertiliser (plant available) or in a high-value form (for industrial use), and separate it from the heavy metals and other unwanted elements (e.g. iron, aluminium) present in the ash. Phosphorus recovery potential is the highest for sewage sludge ashes (70-90%) among all other technologies. Only mono-incinerated sludge is realistically compatible with phosphorus recovery. Co-incineration involves a dilution effect and can involve large amount of impurities being added (Milieu *et al* 2010) but on the other hand already existing infrastructure can be used and advantages of scale apply. It is difficult to know the fraction of sludge mono-incinerated and co-incinerated since statistics are not available (Kabbe *et al* 2015).

To summarise, increasing nutrient recovery from sewage will require: (i) increased central collection of sewage; (ii) switching from nitrification/denitrification to ammonia stripping in order to recover N from sewage; (iii) encourage anaerobic digestion to obtain a stable sludge, produce biogas and allow for further nitrogen stripping, and (iv) support research on technologies to separate P in sludge and sludge ashes from pollutants.

In addition to nutrient recovery from sewage in Sewage Treatment Works, there have been initiatives to separate human urine and faeces at source using waterless urine separating toilets. This facilitates recovery by avoiding dilution. The amount of phosphorus in urine is high and Mihelcic *et al* (2011) estimated that global collection of urine could cover up to 22% of the world´s phosphorus demand. Installing waterless urine-separating toilets has been successful in households not connected to sewage systems and in new developments in some countries. It remains to be seen if a case can be made to retrofit these in towns or cities with conventional water toilets and sewage treatment facilities.

4.4 Food chain waste

A third potential source for nutrient recovery is biodegradable waste. In the EU27, the production of biodegradable waste from municipal solid waste and the food industry ranges between **120 and 140 Mt/yr**[69] (European Environment Agency 2013c). Despite this impressive resource quantity which is four times the estimated amount of sewage sludge, the nutrients in this waste stream are more dilute, decentralised and often mixed with other types of waste which makes the recovery more difficult.

[69] *This range includes consumer waste and waste from the food industry.*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A further important characteristic of the municipal and food chain waste streams is that there are high level objectives to reduce the generation of such wastes. The EU waste hierarchy (discussed in section 2.4) assigns top priority to the reduction of waste in the first place, and recovery lower down the hierarchy. Implementation of the circular economy will further drive this set of priorities. This sets a framework which should be understood by those contemplating investment in nutrient recovery from such waste streams. They must plan on the prospect that waste reduction policies are likely to limit the growth of these waste streams and, if really successful, may reduce the flow from current levels. This is an uncertain area, the effects of following the waste hierarchy will not apply equally to all types of biodegradable materials in municipal and food industry waste. Recovery may often be the only or most effective solution to treat biodegradable waste and reduce the amounts disposed in landfill[70].

This section focuses on the biodegradable fraction of municipal solid waste and on biodegradable waste from the food industry.

4.4.1 Municipal solid waste (MSW)

Amounts. The EU27 generates on average **88 Mt/yr** of biodegradable waste from municipal solid waste, or around **177 kg/capita/yr** (Saveyn *and* Eder 2014). The biodegradable fraction represents on average 37% of all municipal solid waste although the fraction varies widely between EU countries (19-60%) (European Commission 2010). Green waste, household waste, food waste from food service and food waste from retail are all considered biodegradable wastes according to the Waste Framework Directive (2008/98/EC). Most of the waste is produced in households (43%) and in food manufacturing (38%), while catering (14%) and retail (5%) are responsible for

[70] *The goals set for biodegradable waste in the EU are currently to reducing the amount that is being landfilled to 35% of 1995 levels by 2016 (Landfill directive 1999/31/EC).*

smaller quantities (Monier 2010). In the UK, one third of the food bought by consumers becomes waste, but over half of it could be avoided (European Commission 2010). A difficulty encountered when analysing the biodegradable fraction of municipal solid waste is that the definition varies from country to country. The EU has placed emphasis on the recycling of municipal solid waste as part of the waste hierarchy. Although much progress has been made more effort has been devoted to material recycling and less to the recycling of biodegradable waste.

The nutrient content of household food waste and retail food waste is not clear. Based on a gross average nitrogen content of 2-3% and a phosphorus content of 0.5% and a dry matter content 25% it is estimated that the 88 Mt of biodegradable waste could contain around **0.55 Mt N** and **0.11 Mt P**.

Fate. Until 1995, several EU27 countries were still landfilling more than 80% of their municipal solid waste. In the following twenty years the situation has changed and although landfill still has the largest share of waste disposal (31% in 2013), recycling of materials (27%) and incineration (26%) have increased significantly. The remaining 15% corresponds to the composting and digesting of biodegradable material in MSW. On the whole, out of the average **88 Mt** of biodegradable waste produced annually in the EU27, only **24 Mt** are being collected separately. This indicates that only **30%** of the potentially recovered nutrients are being converted into digestate and compost (JRC 2014). Currently, there is no obligation at the EU level to recycle biodegradable waste, which results in large differences in its fate among EU27 countries. The cost of managing biodegradable wastes ranges between €35 and €125 per tonne. Separate collection of bio-waste followed by composting (€35-€75) and landfill of mixed waste (€55/tonne) are generally cheaper options. Separate collection followed by anerobic digestion (€80-€125 per tonne) and incineration (€90 per tonne) are more expensive options (European Commission 2008). The EU has set a target to reduce food waste by 30% by 2025. In the EU27, the capacity for separate collection of bio-waste is currently in the order of 150 kg/inhabitant/yr, but only 30% of it is being used.

Nutrient recovery. Nutrients can be recovered from biodegradable waste through composting, anaerobic digestion and incineration (in certain cases). According to the European Commission, maximizing recovery and recycling of bio-waste could potentially substitute 10% of phosphate fertilisers with compost and reduce soil degradation by 3-7% due to the addition of organic matter. However, the current situation is far from achieving these objectives. Besides the agronomic interest, there may be an economic interest in the recovery of nutrients.

Composting and anaerobic digestion allow nutrients in waste to be brought back to soils. Because of the low nutrient concentration in these substrates and their high organic carbon content, they are classed as soil improvers rather than fertilisers.

Throughout history, composting organic material has been used as a process to stabilise organic material and recover carbon and slow-release nutrients back to soils. Current production of compost in the EU27 is **11.3 Mt** (Saveyn *and* Eder 2014)[71] containing around **0.15 Mt N** and **0.03 Mt P**[72]. Given that one tonne of biodegradable waste can be converted to 350-400 kg of compost, there is a potential for the production of 35-40 Mt of compost annually.

The potential for compost derived from municipal solid waste to be used in agriculture is not very high. Even in the hypothetical case of maximum compost production only 3.2% of EU27 agricultural land could be served with an average 10 Tn/ha application rate (Saveyn *and* Eder 2014). Currently, half of the compost being produced in the EU27 from MSW is applied in agriculture. The rate ranges between 20% (Finland) and 80% (Spain).

Nutrient recovery from municipal bio-waste appears to be more constrained by legislation and consumer habits than technology. There are wide differences regionally in the use of these techniques. Composting and digestion rates in Austria, the Netherlands and Luxembourg are above 130 kg/inhabitant/yr. In the Basque Country, for instance, it is estimated that up to 49% of N and 83% of P contained in bio-waste could be recovered with existing infrastructure. However, current recovery rates are much lower (3.4% N and 7.4% P) (Zabaleta *and* Rodic 2015).

Another treatment option of the biodegradable fraction of MSW is anaerobic digestion. In the EU27, **56 Mt** of digestate are produced annually, over 80% of which are used in agriculture (Saveyn *and* Eder 2014). Part of the digestate is also composted. One of the advantages of the use of digestate over compost is that it is more homogeneous in composition (especially in terms of nitrogen content). In addition, its production allows for biogas recovery (25% of the initial substrate) and the generation of energy. Digestate is applied to agricultural soils mainly via injection or band spreading, close to production sites. The production of digestate costs about 10-30 euro per tonne (according to the European Biogas Association). Sale price for digestate is lower than for compost. Prices range from €5-€30 per dry tonne of digestate (Saveyn *and* Eder 2014). The other option for nutrient recovery from biodegradable waste is incineration. Compared to sludge incineration, residues from incinerated MSW have a lower concentration of P (0.4%) (Kalmykova *and* Fedje 2013).

4.4.2 Biodegradable waste from the food industry

The total amount of biodegradable waste produced annually by the food and drink industry in the EU27 remains highly uncertain but it has been estimated to be around

71 Data for 2005 and 2008.

72 Based on a 1.4% N and 0.23% P concentration in fresh compost (ECN).

90 Mt[73] of dry solids. This is made up of a very wide range of materials from blood, entrails, meat and bones to fruit stones, skins and peel, and a myriad of materials from brewers, bakers and diaries. Nutrient flow calculations from the ENA (Sutton *et al* 2011) and van Dijk *et al* (2016) have shown that waste flows from the food industry may carry large volumes of nutrients that could be recovered, for P a large part in slaughterhouse waste. Unfortunately, precise data on mass flows and nutrient concentrations of all parts of the food chain is not available. Table 9 shows data for four parts of the food chain for certain groups of EU countries. The rest of this section focuses on slaughterhouse waste as an example for other parts of the food chain.

TABLE 9. Amounts and characteristics of waste streams derived from food processing industries

	Total amount (Mt)	% dry solids	Characteristics	Returned to land
Slaughterhouse waste	~25		Rich in N, P	
Sludge from sugarbeet industry[(a)]	~25	50%	Rich in N, K	32%
Olive oil industry[(b)]	~11	25-60%		40%
Vegetable industry[(b)]	~30	5%		>10%
TOTAL	~30			

[(a)] *EU15*
[(b)] *Spain, Italy, Greece and Portugal*

Slaughterhouse waste

Annually, abattoirs produce **25 Mt of waste and waste water** which is disposed by land spread or injection, incineration, composting or it undergoes anaerobic digestion (Gendebien *et al* 2001). Part of it is also used to produce pet food (0.033 Mt/yr P). Concentration of N and P in slaughterhouse wastewater is 150-10000 mg N/l and 22-217 mg P/l. van Dijk *et al* (2016) estimate that residues from slaughterhouses contain **0.28 Mt P** in total.

Animal bones were one of the first materials used to produce phosphate fertilisers in the nineteenth century and were widely used in Europe to produce fertilisers, gelatine and animal feeds until the 'Mad Cow' (BSE Bovine spongiform encephalopathy) crisis in the 1990s. The EU Animal By-Products (ABP) Regulation (1774/2002) was introduced in response to this crisis, and effectively stopped much recycling of phosphorus in meat and bone meal animal byproducts. In some countries, this recycling has resumed for certain types of animal byproduct, for example SARIA in the UK (SCOPE Newsletter n° 105). In meat processing, only around 20% of the phosphorus in animals ends up in meat, the rest goes to liquid and solid wastes or by-products (Lamprecht, 2011). There is today general agreement that the ABP Regulation should be modified to facilitate phosphorus recycling, whilst still guaranteeing food and animal feed safety, and this is planned within the context of the currently underway revision of the EU Fertiliser Directive.

The majority of slaughterhouse wastes are reused and recycled and a small amount are used in biogas plants or spread to land (Gendebien *et al* 2001). About 80% of slaughterhouse waste is used to produce meat and bone meal (MBM). MBM is one of the main by-products of the slaughtering industry and is attractive for nutrient recovery. It consists of protein, ash, fat and moisture. What makes it interesting for plant nutrition is that it contains about 8% N, 6% P and 0.5% K, although these percentages can vary widely according to the mix of animal parts. Animal meat and bone meal contains 4 times more nitrogen and 10 times more phosphorus than manure. MBM can be a good fertiliser due the large amounts of phosphorus and nitrogen it contains, which is found in a form that is rapidly mineralised in soils. For the same reason, in soils that have already high contents of P, the use of MBM is not recommended to avoid its accumulation; it does not optimise the NPK ratio.

The main process of nutrient recovery from MBM is **incineration**. Incineration of MBM mainly takes place in Combined Heat and Power (CHP) plants. The resulting product is a combination of bed ash and fly ash. An example of such a process is the FLUID-PHOS technology used in an England based plant (from the SARIA group) that produces 12.000 tonnes of a calcium phosphate fertiliser (mix of bed ash and fly ash) derived from animal carcasses and those animal parts not used for human consumption. The resulting product, a mix of bed ash and fly ash, is a slow release fertiliser[74] that contains 22% P and smaller amounts of other nutrients.

P-Rex (2015) estimate that nutrient recovery from slaughterhouse waste could cover a significant share of current P demand by EU agriculrure. However, the technology to recover N and P concentrated in ashes and turn them into recovered phosphate fertliser is still not fully operational. Several processes are being tested at pilot plants with the aim to remove heavy metals from the ash, either in a liquid or gas phase, and extract the phosphorus.

[73] *According to European Commission 2008 it is 37 Mt/yr, but combining sugarbeet waste, slaughterhouse waste, vegetable waste and waste from olive oil production from a study by Gendebien et al 2001, results in a total of 91 Mt/yr.*

[74] *A fertiliser containing nutrients that are slowly released (e.g. due to slow solubilisation) or found in organic form, requiring mineralisation.*

Another possible route for the valorisation of MBM is the production of biochar through pyrolisis[75]. Biochar usually derives from plant biomass but can also be produced from animal MBM. Plant biomass derived biochar is mainly a soil improver while biochar derived from animal bone meal could also be regarded as a phosphorus fertiliser (although this remains to be tested). The main interest of biochar, however is not its nutrient content but its adsorptive capacity. There is currently only one industrial-scale pilot plant producing biochar from animal bone. The potential of biochar in large scale applications remains to be demonstrated and it has been suggested that its best use might not be a direct application to soils but rather as part of the processing of other products, for instance, as a growing medium or an adsorbent material for organic molecules in water[76].

4.5 Summary

Half of the nutrients currently applied to European croplands are already recycled from waste streams, representing around 8 Mt N and 1.8 Mt P. Manure accounts for more than 90% of this recycled flow, while a smaller percentage comes from land application of stabilised sewage sludge. Thus nutrient recycling is not a new idea. The challenge is to significantly increase the amount of recycling by recovering and reusing much more of the nutrients from waste streams while at the same time increasing the efficiency of currently recycled material.

There is certainly scope to do both. This study suggests the three key waste streams on which to focus are manure, sewage sludge and food chain waste. It is estimated that between 2.0 and 5.0 Mt N and 0.6 Mt in these three waste streams are not being recovered nor returned to land. This represents 18-46% of the 10.9 Mt of mineral N and 43% of mineral P currently being applied. In addition to these fluxes, part of the 12 Mt of N and 1 Mt P annually leaking into soil, water and air as a result of agricultural activities could also be available for recovery by implementing more effective nutrient application techniques, improving manure management to avoid leakage and increasing the fertiliser value in recovered products.

A large number of nutrient recovery techniques are currently available or under development. There are several processes used to stabilise the waste material from the three identified sources before being returned to land. Key such processes are anaerobic digestion and composting. In terms of nutrient recovery, the main technique for nitrogen is ammonia stripping, which can be implemented for manure processing and sewage treatment works. In the case of phosphorus, several processes are being tested in pilot plants and a few are already operational to recover P from digested sludge and reject streams. Further developments are expected enabling efficient extraction of P from manure and sewage sludge ashes. In short, increasing the potential of nutrient recovery and reuse requires that three parallel tasks be undertaken: (i) to increase the **total amount of recovered nutrients** from waste streams; (ii) to increase the **fertiliser equivalence value** of recovered nutrients (as formulated by Sutton *et al* 2011); and (iii) to create recovered products that are safe, easy to store, handle and use by farmers and which reduce current N and P leakage associated to nutrient recycling.

The next chapter considers the actions which will be required to develop more of the potential that has been identified to recover and reuse nutrients.

[75] *Decomposition of organic material at high temperatures in the absence of oxygen.*

[76] *http://phosphorusplatform.eu/images/scope/ScopeNewsletter117.pdf*

5. Public policy and other actions to boost nutrient recovery and reuse

5.1 Strategic approach: globally and EU level

This report commenced by juxtaposing five challenges to the way nutrients are used in the world.

1. **Food production** to feed a growing population.
2. **Farm viability**. Examine how the outstanding success in achieving goal No. 1 has resulted in agricultural systems which are all too frequently **economically precarious.**
3. **Pollution of water, air and soil and impact on the climate** due to inefficient and wasteful nutrient management with deleterious effects on biodiversity.
4. Reduction and recycling of **food chain waste.**
5. Confront the dependence of the food system on **finite, insecure, non-renewable resources**.

It turns out that focusing on nutrient flows through the food system is a graphic, tangible and practical way of characterising this complex nexus of issues. Nutrients are essential for humans and the animal and plant products they eat. Eating is a universal daily pleasure and associated with positive social interaction. Yet one-sixth of the world's population, mostly in developing countries, are under nourished, and another one-sixth, found in developed and emerging economies but also in developing countries, are malnourished, principally by over-consumption of calories and animal fats and under-consumption of fibre, and as a result are suffering disease and shortened lives. Nutritional security[77] is therefore far from assured for a third of the world population. Furthermore, the very success of providing the nutrients to the expanding food system has caused significant disturbance to natural nutrient cycles, as well as the water and carbon cycles. The result is that the sustainability of the global food system is in doubt, and may be outside the safe operating space[78].

5.1.1 Global approach to nutrient management

The issues of disturbed nutrient cycles are well recognised at global level. An important expression of this is

[77] *The European Union's Scientific Advisory Committee for the Milan 2015 World Expo on Feeding the Planet, developed the concept of Food and Nutritional Security precisely to make these points.*

[78] *This is the concept developed by Rockström (2009) and placed at the heart of the German Advisory Council on the Environment report (SRU 2015).*

the creation of the Global Partnership on Nutrient Management (GPNM)[79] and the work it is doing. Indeed this report for the RISE Foundation has been informed by the global overview of nutrient management produced by the GPNM partnership and contained in their comprehensive and accessible document "Our Nutrient World". This document justifies and explains clearly why further actions are required to contain the impacts of excessive nutrient flows. But whilst this recognition at the level of science and high-level policy makers is an essential step, it can only be a start. The challenge is to motivate national governments, and particularly businesses and citizens to be more aware of the nutrients challenge and to make necessary changes in their business practices and ultimately life styles required to restore manageable equilibrium in nutrient flows. A generally accepted global level action plan on nutrients has still to materialise and to be implemented.

At the global level the Sustainable Development Goals (SDG) implicitly address many of the actions required for better nutrient management, but regrettably neither the phrase 'nutrient management' nor 'nutrient recovery and reuse' are explicitly listed in the SDG to be achieved by 2030[80]. However, six of these goals embrace exactly the kinds of actions required to restore better balance in nutrient cycles. These are Sustainable Development Goals:

- *6.3 to improve water quality, reduce untreated water and increase recycling,*
- *12 for sustainable consumption and production, with the specific goals:*
  - *12.2 to ensure sustainable management and efficient use of natural resources,*
  - *12.3 to halve food waste,*
  - *12.4 to achieve environmentally sustainable management of all chemicals and waste, and*
  - *12.5 to substantially reduce waste generation*

These are global goals and are intended to apply to all UN members although their origins and their emphasis is on the developing countries. Their very breadth and ambition reflects a dominant idea of our times that issues such as food security are complex, multidimensional and dynamic and therefore should be considered in an integrated systems view[81]. It implies also that the solutions to address these problems are also multi-faceted. There are no simple, one-dimensional answers. Actions are required at every level from international to local, and by public bodies, private businesses, charitable and NGO groups as well as by individual families and citizens. This of course increases the challenge. Any administration finds it difficult to act simultaneously on multiple fronts. Organisations are invariably set up to address specific aspects of any issue and thus to tackle 'their' concern by whatever seem to be the most appropriate specific actions. To ensure that the sum of such actions add up to a coherent approach requires constant monitoring of the whole system behaviour so that undesirable trade-offs – for example reduced greenhouse gas at the expense of more wastage, water pollution or biodiversity loss – can be spotted early and corrected. This will never be easy.

5.1.2 EU approaches to nutrient management

The European Union and its Member States have been active participants in developing the SDGs and the issue of disturbed nutrient cycles are also well understood and acknowledged at EU level. This is exemplified in three ways: (i) the regulatory framework in the EU currently in place, (ii) the initiative to recognise the distinctive nature of the bioeconomy in Europe, and (iii) the more recent initiative to promote the virtues of the circular economy.

EU regulatory framework influencing nutrient flows and management

The European Union has created a significant assembly of regulation impacting on nutrient use. The main elements of this: regulate nutrients on the market, their use in crop and livestock farming, the consequential treatment of animal manure and other organic waste, the pollution of water and air, the treatment of food waste, the operation of waste water treatment plants and the fate of waste and secondary raw materials arising from this complex chain. The sheer number and breadth of this regulatory structure is summarised in Table 10.

The very fact that there is a substantial set of regulation bearing on nutrient management in Europe is both reassuring and alarming. Reassuring, because it says 'we are on the case'. It demonstrates that European society is well aware of the problems it is creating with nutrient use and is trying to deal with them through this collective legislative action. But at the same time it is alarming because the problems have patently not been resolved despite this collection of attempts to deal with them. It is instructive to ask whether this is because we have the wrong regulation, gaps in regulation, poor implementation, or that we require patience because these matters are not susceptible to quick resolution. It is perhaps most likely that there is truth in all four explanations. Indications from the Fitness Check of EU nature regulation seem to indicate that poor implementation in the Member States is a dominant concern[82].

[79] This global partnership is one of the actions under the United Nations Environment Programme (UNEP) Global Programme of Action (GPA) for the protection of the marine environment from land-based activities. The GPNM includes Governments, Industry, Scientists, NGOs, UN agencies and several international and regional organisations. http://unep.org/gpa/gpnm/gpnm.asp

[80] See https://sustainabledevelopment.un.org/?menu=1300 For a list of the SDGs agreed in 2015

[81] The report of the Expo 2015 EU Scientific Steering Committee summarises this very well, Benton T et al (2015) New ways of providing knowledge to tackle Food and Nutrition Security. What should the EU do? European Union, Brussels. http://europa.eu/expo2015/sites/default/files/files/Expo-Document_1115_BD.pdf See also Ingram J (2011) A food Systems approach to research interactions between food security and environmental change, Food Security 3, 417-431.

[82] Milieu, IEEP, ICF & Ecosystems Ltd (2015) Evaluation Study to Support the Fitness Check of the Birds and Habitats Directives. Draft Emerging Findings. http://ec.europa.eu/environment/nature/legislation/fitness_check/docs/consultation/Fitness%20Check%20final%20draft%20emerging%20findings%20report.pdf

TABLE 10. EU legislation and guidance impacting on nutrient flows and management in the EU

Category	Main EU legislation and guidance	Date
Fertiliser Manufacture & trade	**Critical raw materials list** (CRM). List of 20 raw materials for which "supply security is at risk and economic importance is high". Phosphate rock was added to the list in 2014.	2014
	Fertiliser regulation EC (2003/2003) (under revision) – The current version defines and lists inorganic fertilisers and micro-nutrients and regulates their market placement.	2003
Nutrient use and management in crop and livestock production	**CAP**: DP (indirectly through greening), RD (indirectly through agri-env-climate measures and directly through WFD measure), and Cross Compliance (area "environment, climate change, good agricultural condition of land)	2013
	Nitrates Directive (91/676/EEC) – limit of 170 kg N/ha/yr from livestock manure in NVZ ,	1991
	Sludge Directive (86/278/ EEC) – regulates the use of sewage sludge in agriculture	1986
Biodiversity	**Habitats Directive** (92/43/EEC)	1992
	Birds Directive (79/404/EEC)	
Treatment of animal manure and organic wastes	Animal by-product regulation (1069/2009/EU) implemented by the 142/2011/EU regulation – regulates the disposal of animal-by-products.	2009
Containment of water pollution	**Nitrates Directive** (91/676/EEC) – limits nitrates in water to 50 mg/l	1991
	Water framework Directive (2000/60/EC) – establishes a framework for the protection of surface and groundwater in the EU	2000
	Urban Waste Water Directive (91/271/EEC) – requires the collection of waste water and the implementation of secondary treatment for agglomerations with more than 2000 person equivalents. More advanced treatments for populations > 10000 person equivalents	1991
	Groundwater Directive (2006/118/EC) – sets a quality standard of 50 mg/l of nitrates	2006
	Surface Water Directive (75/440/EEC)	
	Drinking Water Directive (98/83/EC) – maximum allowed concentration of nitrates in water of 50 mg/l and guide level of 25 mg/l	1998
	Bathing Water Directive 76/160/EEC amended by 2006/7/EC	2006
	Directive on Dangerous Substances 76/464/EEC = 2006/11/EC	2006
	Marine Strategy Framework Directive 2008/56/EC	2008
	Air Quality Directive (2008/50/EC)	2008
Containment of air pollution	**Industrial Emissions Directive** (2010/75/EU) - (replaces IPPC Directive 96/61/EC) best available practices for intensive rearing of poultry and pigs	2010
	EU National Emissions Ceilings Directive (2001/81/EC) (under revision) – sets emissions ceilings for several air pollutants including NH_3 and NO_x	2001
Waste and food waste	**Hazardous waste directive** (91/689/EEC)	1991
	Waste Framework Directive (2008/98/EC)	2008
	Landfill Directive (1999//31/EC)	1999
	Waste Shipment regulation (96/61/EC)	1996
Non-regulatory nutrient management	EMAS – Eco-management and Audit Scheme (voluntary)	
	Stockholm convention on persistent organic pollutants	2004
	Eco-labels	
	Best Environmental Management Practices	
General Initiatives	Bioeconomy communication	2012
	Circular Economy Package	2015

Inconsistent progress in implementing these aspects of environmental legislation illustrates the classic challenge of trying to internalise environmental externalities. Society acknowledges the problem and need for action, passes laws to change behaviour, but **businesses and citizens are reluctant to accept the higher costs of behaving in a more responsible and sustainable way**. Converting societal or collective acceptance (as expressed by willingness to pass laws) into individual acceptance (as expressed by individual action) is the real challenge. Information and awareness raising is an important early step in this process.

In addition to these EU regulations with relevance to nutrient management, there is an equally long and diverse list of Member State regulation on these matters. An example is provided by the survey conducted by Amery and Schoumans (2014) of national level regulations concerning the use of phosphorus in agriculture. Their findings are shown in Table 11. The table shows that thresholds for phosphorus application do not exist in many EU countries and even among those where they are specified, differences in the regulatory systems make comparisons difficult. Often, P status in soil is not well established and recommendations of appropriate P application rates are difficult to define.

TABLE 11. Member State regulation of phosphorus use on farmland

Country / region	P application limits?	Regulation system	P type regulated	Limits (kg P/ha/yr)	Limits depend upon
Austria	No	-	-	-	-
Belgium-Flanders	Yes	Max. rates	Total P	17-41	Crop type, phosphate saturated soil or not
Belgium-Wallonia	No	-	-	-	-
Czech Republic	No	-	-	-	-
Denmark	No	-	-	-	-
England, Scotland and Wales	No	-	-	-	-
Estonia	Yes	Max. Rates	Manure P Extra chemical P	25 2-98	Crop type, yield and soil P
Finland	AEP	Max. Rates	Total P	0-110	Soil P, crop type and yield
France-Brittany	Yes	Max. Rates or balance	Total P	35-41 or export + 10%	Farm type and water basin, or crop export
Germany	Yes	Balance	Total P	Export + 9	Balance (crop yield and export) and soil P
Greece	No	-	-	-	-
Hungary	No	-	-	-	-
Ireland	Yes	Max. Rates	Total P	0-125	Crop type and soil P (and yield for cereals)
Luxembourg	AEP	Max. Rates	Total P	0-81	Soil P, crop type and yield
Northern Ireland	Yes	Max. Rates	Chemical fertiliser P	0-109	Advice (soil P, crop type and yield)
Poland	No	-	-	-	-
Spain	No	-	-	-	-
Sweden	Yes	Max. Rates	Manure P	22	-
The Netherlands	Yes	Max. rates	Total P	24-52	Soil P (and crop: grass or arable crop)

(Source: Adapted from Amery and Schoumans 2014)

There is likely to be similar diversity of practices for other aspects of manure, food waste and sewage sludge treatment and valorisation in the Member States. This diversity is not necessarily a problem for nutrient recovery and reuse taking place within Member States. However, as this activity grows, and international trade develops in waste materials and recovered nutrients between Member States then smooth operation of the single market will require some harmonisation of product and possibly also process standards.

An issue already identified which can be a barrier to the development of Nutrient Recovery and Reuse relates to **end-of-waste criteria** and the treatment of recovered products under legislation such as REACH, Water Framework Directive, Nitrates Directive, Waste Treatment Directive or the Common Agricultural Policy. It is clear that all the while recovered products from waste do not cease to be considered as waste they will be subjected to additional legislation. This not only constrains the use of these products in agriculture but may also discourage investment that would otherwise lead to increased nutrient recovery. New terms for recovered products may be organic fertilisers or soil improvers. In the case of manure, there are ongoing discussions on how to interpret the constraints set by the Nitrates Directive.

One of the claims of the recovered organic fertiliser sector is that in the EU legislation, there is currently perceived to be no added value in the application of organic matter to soil which would help to stimulate an organic products market. Another important issue is the certification of organic soil amendments/fertilisers. Permits, labels and certificates are issued at national scales, representing an economic burden for farmers wishing to export their products in other EU countries. The revisions to the fertiliser regulation should help deal with this at least for biochar, struvite and ashes, which are expected to be covered in the new regulation. In principle, the legislation applying to each product will in future depend not on its source (waste streams) but rather on the qualities and performance that the producers claim that it has.

The coherence and coverage of this set of regulation for better nutrient management is indeed now under review. It is clear that this is an important further analytical step necessary to ensure that there is coherence within and between Member States in the myriad of policies affecting nutrient management.

EU support for the Bioeconomy

Second the EU has recognised the important particular characteristics of the bioeconomy in its 2012 communication, Commission (2012)[83]. This document explains that: "The bioeconomy . . . encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy." It suggested that "Establishing a bioeconomy in Europe holds a great potential: it can maintain and create economic growth and jobs in rural, coastal and industrial areas, reduce fossil fuel dependence and improve the economic and environmental sustainability of primary production and processing industries." However it also warned that "Europe is confronted with an unprecedented and unsustainable exploitation of its natural resources, significant and potentially irreversible changes to its climate and a continued loss in biodiversity that threaten the stability of the living systems on which it depends". The principal proposed actions were general, but pertinent and consistent with those required to push nutrient recovery and reuse to the next level, viz: coherent policy, investment in knowledge, innovation and skills, participative governance and informed dialogue with society, and it recognized there may be the need for new infrastructures and instruments.

EU Action Plan for the Circular Economy

A third step in the EU recognition of the need for new initiatives to push ideas like nutrient recovery and reuse is in the more recent Circular Economy package entitled 'Closing the loop: an action plan for the circular economy'[84]. The package comprises the action plan and associated timelines, and four proposed directives on waste, packaging waste, landfill and on electrical and electronic waste and connected matters. These will now proceed to debate and discussion in the Parliament and Council and will in due course be amended and adopted for implementation over the coming years. As with the bioeconomy communication the objectives of moving to a circular economy are broad (p2). "The circular economy will boost the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices, helping to create new business opportunities and innovative, more efficient ways of producing and consuming. It will create local jobs at all skills levels and opportunities for social integration and cohesion. At the same time, it will save energy and help avoid the irreversible damage caused by using up resources at a rate that exceeds the Earth's capacity to renew them in terms of climate and biodiversity, air, soil and water pollution." It talks specifically of "targeted action in areas such as . . . food waste . . . critical raw materials . . . and consumption " and it signals that key legislative proposals will follow on fertilisers and water reuse". It flags that turning the circular economy into reality will require "involvement at all levels, from Member State, regions, cities to businesses and citizens".

There are many proposals in 'Closing the loop' which have relevance to actions for nutrient recovery and reuse. One example is promoting best practice through '*best available technique reference documents' (BREFs,* p5[85]*)* which could usefully be developed for a range of the nutrient recovery technologies discussed in chapter 4. There is recognition of the need to help *Small and Medium sized Enterprises (SMEs*). This is highly pertinent to the nutrient sector because of the geographic dispersion of the generation of the substrate materials for NRR, and the equally dispersed market for recovered products, both are dominated by SMEs. The intention is to create *European Resource Efficiency Centres*, and a pilot programme on *environmental technology verification*. These could be highly relevant for the further development and standardization of nutrient recovery processes.

The broad statement on waste management has direct applicability to nutrients and their recovery and reuse (p8). "The way we collect and manage our waste can lead either to high rates of recycling and to valuable materials finding their way back into the economy, or to an inefficient system where most recyclable waste ends in landfills or is incinerated, with potentially harmful environmental impacts and significant economic losses. To achieve high levels of material recovery, it is essential to send long-term signals to public authorities, businesses and investors, and to establish the right enabling conditions at EU level, including consistent enforcement of existing obligations." It is explicit that the principal aim of proposed actions is to deliver 'best overall environmental

[83] *Commission (2012) Innovating for Sustainable Growth: A bioeconomy for Europe, Communication from the Commission to the parliament and Council, COM(2012)60 final 13/2/2012*

[84] *European Commission (2015a). This communication replaces an earlier version published in July 2014 but withdrawn for reconsideration by the new Commission in 2015.*

[85] *These page numbers refer to the document 'Closing the loop'.*

outcome'. It is therefore driven by environmental concerns. This seems realistic. If in the process it brings about innovative new economic activity to recover, process and reuse waste materials, and if much of this NRR activity is decentralised it could well provide welcome jobs and economic growth in rural areas. These would be important co-benefits of this aspect of the circular economy, but not the primary aim.

It is sensible to get this priority clear at the outset because, as will be discussed at greater length below, this raises the question of who will pay any costs involved in delivering the desired environmental outcomes. The approach on waste is through four actions: to set long-term recycling and reduction targets, to promote greater use of economic instruments, to create a general requirement for extended producer responsibility schemes, and simplification and harmonization of definitions and calculation methods. All of these are potentially relevant to nutrient recovery and reuse. The key targets proposed are to recycle 65% of municipal waste by 2030, 75% of packaging waste by 2030, to reduce landfill to a maximum of 10% by 2030 and to halve food waste by 2030. Their applicability to nutrients is discussed further below.

One of the key principles to give effect to more intelligent use of waste flows is to define a new category of resource, 'secondary raw materials' which can then be traded and used just like primary raw materials. In turn, to encourage the uptake of secondary raw materials the communication recognizes that establishing trust in putative buyers of these materials of their quality, consistency and efficacy will be critical to success. This is certainly a key question to be addressed for recovered phosphorus. It requires the establishment and harmonization of, preferably EU-wide, quality standards. The communication acknowledges this explicitly (p11): "Recycled nutrients are a distinct and important category of secondary raw materials, for which the development of quality standards is necessary. They are present in organic waste material, for example, and can be returned to soils as fertilisers. Their sustainable use in agriculture reduces the need for mineral-based fertilisers, the production of which has negative environmental impacts, and depends on imports of phosphate rock, a limited resource. However, the circulation of fertilisers based on recycled nutrients is currently hampered by the fact that rules as well as quality and environmental standards differ across Member States. In order to address this situation, the Commission will propose a **revision of the EU regulation on fertilisers**. This will involve new measures to facilitate the EU wide recognition of organic and waste-based fertilisers, thus stimulating the sustainable development of an EU-wide market." Thus the pledge on nutrient recovery and reuse is that: "The Commission will propose a revised EU regulation on fertilisers, so as to facilitate recognition of organic and waste-based fertilisers in the single market and thus support the role of bio-nutrients in the circular economy".

Another reference directly relevant to NRR is presented in 'Closing the loop' under the heading of Priority areas. The second Priority area is food waste. It is acknowledged that progress in practical actions, for example setting meaningful targets for food waste, are currently bedevilled by the absence of a harmonized, reliable method of measuring it. The proposed, and highly necessary, actions therefore are (p15): "In order to support the achievement of the Sustainable Development Goal target on food waste and to maximise the contribution of actors in the food supply chain, the Commission will:

- Develop a common EU methodology to measure food waste and define relevant indicators. It will create a platform involving Member States and stakeholders in order to support the achievement of the SDG targets on food waste, through the sharing of best practice and the evaluation of progress made over time.
- Take measures to clarify EU legislation relating to waste, food and feed and facilitate food donation and the use of former foodstuff and by-products from the food chain in feed production without compromising food and feed safety; and
- Examine ways to improve the use of date marking by actors in the food chain and its understanding by consumers, in particular the "best before" label".

The issue of critical raw materials is listed as Priority area 3. However, the actions make no specific reference to phosphorus, even though it is on the list of such substances. The presumption must be that the recovery of phosphorus is already covered by the above references to wastes, waste water and food waste.

Interestingly, Priority area 5 is biomass and bio-based products. The Bioeconomy communication is therefore cross referenced. Evidently, however, no new principles have been uncovered to steer development of this sector. The document simply offers a statement of the complexity and care that has to be exercised in handling this area which offers promise, yet if badly done has the capability of worsening environmental impacts rather than reducing them[86]. "The bioeconomy hence provides alternatives to fossil-based products and energy, and can contribute to the circular economy. Bio-based materials can also present advantages linked to their renewability, biodegradability or compostibility. On the other hand, using biological resources requires attention to their lifecycle environmental impacts and sustainable sourcing. The multiple possibilities for their use can also generate competition for them and create pressure on land-use. (p17).

The Circular Economy Action Plan concludes with horizontal measures, a most important one of which with relevance to nutrients is the need to support research, innovation and investment. The funds to support research are of course those already voted for under the EU's Horizon 2020 programme and there are already many projects included of relevance to the circular economy, no doubt with more to come. Research and innovation is may also

[86] *An unfortunate example of just this is the over-expansion of certain biofuels before adequate sustainability criteria had been established.*

be funded through the Cohesion Policy structural funds, e.g. Interreg. SMEs may be supported through the 2014 Green Action Plan for SMEs. Also, it might be possible for assistance with certain nutrient recovery and reuse project to find assistance through rural development programmes. NRR innovators are certainly advised to investigate the programmes and funds indicated in this penultimate section of the communication.

The combination of existing environmental regulations, and the communications on bioeconomy and circular economy, offer a clear demonstration of high level political awareness in the EU that there are problems to be grasped with nutrient management. These policy measures offer a comprehensive set of mechanisms to tackle them, and there is certainly a challenge to be overcome. The scientific assessment concludes that "the World's N and P cycles are now out of balance causing major environmental, health and economic problems that have received far too little attention"[87]. Why is this and what more can and should be done?

5.2 Challenges of NRR and justifications for collective action

Section 3.3 demonstrated the invaluable work the scientific community has done in quantifying the flows of nutrients through the food chain and demonstrating the enormous wastage and damaging leakage into the environment. Building on this, the analysis of Chapter 4 led to the conclusion that there is scope for nutrient recovery and reuse to make a significant contribution to reduce reliance on mineral fertilisers in the EU and therefore on the imports of finite phosphate rock, and use of natural gas to produce nitrogenous fertilizer. Section 5.1 has summarized the considerable steps the international policy community and the European Union have already taken to make the case for concrete actions to stimulate a step-up in nutrient recovery and reuse. This section looks more closely at the characteristics of the nutrient flows which help explain the scale of the challenge to deal with them. It then discusses whether nutrient recovery is likely to spontaneously to develop or whether further purposive positive or negative incentives will have to be put into place to stimulate this development.

5.2.1 Characteristics of material flows of nutrients

Nutrient waste flows generally comprise very large masses and volumes of material, many are highly dilute and heterogeneous especially the outputs from livestock and humans; they arise in continuous daily flows, widely spatially dispersed in multiple sources over all human-occupied territory; and whilst nutrients *per se* are welcome, many of the output flows are considered wastes and distasteful. They are associated with substantial soil, water and air pollution risks some of which also risk harm to human health; and they are destined to be added to the soil where there is potential for long-run accumulation of any undesirable substance present even in very low concentration. With these characteristics, this is never going to be an easy sector to manage.

The sheer scale of the flows involved and their nutrient concentrations are illustrated in Table 12. The quantities in Table 12 are based on the nutrient flow calculations discussed in section 3.3 above. The point of the table is to show the contrasting volumes of inputs and outputs of nutrients at each stage. It can immediately be seen that the volumes of inputs of nutrients – fertilisers to crops and feed to livestock – are significantly smaller than the volume of output flows – especially animal and human excreta. This means that nutrients in the output flows leave the system much more diluted than when they enter. The input products are purposively manufactured or processed for their role, the outputs are biological wastes. The number of different types and brands of fertilizer is relatively small; the number of different animal nutrient products is much greater, and the number of specific human nutrient products (foods and drinks) is of an even higher order of magnitude. However, the nutrient specification of each such product will be relatively well-defined, measurable and measured, and homogeneous and consistent.

The output flows from which nutrient recovery must operate are of quite different character. They are much more dilute and therefore voluminous. They are highly variable in their composition, especially their dry matter content, but also their nutrient content. Typical nutrient concentration ratios for mineral fertilisers and the waste stream substrates for NRR are shown in Table 13. A further aspect of these substrates is the presence of any other potentially undesirable materials – for example, pathogens, pharmaceuticals and heavy metals.

TABLE 12. Illustrative orders of magnitude of annual nutrient flows in the EU

Nutrient flow per annum EU28	Total mass Mt/yr	Typical - Ranges		
		dry matter %	N content Mt	P content Mt
Nutrient input flows				
Mineral fertilisers - domestically utilised	45[a]	X-100	10.9	1.4
Animal feed – domestically utilised[b]	478	?	10.1	0.4
Recoverable nutrient output flows				
Animal manures	1400	15-60	8.8	1.8
Food chain wastes	120-160	30%	>0.5	>0.4
Sewage sludge (dry)	9.5[c]	>65%	0.32	0.10

(Source: Total mass values are taken from Table 4).

[a] *Brought to field during the 2013/2014 season (Fertilizers Europe, unpublished data based on consumption statistics for EU-28).*
[b] *From FEFAC, Leip et al 2014 and van Dijk et al 2016.*
[c] *Note that total sewage volume is much larger (aprox. 9500 Mt if we take a 0.1% solids concentration).*

[87] *Our Nutrient World (Sutton et al 2013), Executive summary, second paragraph.*

This is a technical challenge, and one that technology can, and must, overcome. However, it may be more difficult to persuade society that it has been overcome. Most of the substrate flows are comprised of water, therefore the value of these materials per tonne is low, and all the while they are thought of as waste, their value is often seen as negative, something that is a nuisance which has to be disposed at cost to the business. There are clearly limitations on how far it is worth transporting these dilute materials. The substrates and processes with which the NRR sector will work are therefore qualitatively different to the mineral fertilizer industry. The latter is essentially concerned with physical and chemical engineering of chemical inputs and outputs. Much of the NRR processing sector will be concerned with biological inputs and biological processes.

The periodicity of these flows also differs greatly. Nutrient input to crop production is highly seasonal. In Europe it is mostly in late summer/autumn and in spring. There is reasonably pronounced seasonality in some livestock production (e.g. autumn or spring calving dairy cows), but others, especially pigs and poultry are year round. This affects both the rate of feed input flows and consequently the manure output flows. Of course, all animals require feed inputs and produce waste outputs daily. Where there is seasonality (i.e. departure from more or less uniform flows year round) then the materials input or output have to be stored. Again this is expensive for the more dilute, and more biologically active wastes. The timing of distribution of animal manure is certainly seasonal if it is to accurately match crop nutritional requirements and prevent losses. Many of these flows will also be sensitive to, and impacted, by uncontrollable influences such as weather.

TABLE 13. Nutrient concentration of typical products – inputs and outputs

Product	N-P-K %
Mineral	
Urea	46-0-0
Calcium Nitrate	15-0-0
Ammonium Nitrate	34-0-0
Calcium Ammonium Nitrate	26-0-0
UAN	28-0-0
Mono-ammonium phosphate	11-52-0
Di-ammonium phosphate	18-46-0
Triple Superphosphate	0-45-0
Single superphosphate	0-18-0
Organic	
Cattle manure	1-0.5-0.5
Poultry manure	3-1-1/3-2-2
Dairy manure	1-0-0
Meat and bone meal	4-12-0 / 3-15-0
Compost	2-1-1
Bird guano	18-8-2/16-12-03

In order to impact on these flows and how they are managed, perhaps just as important as the scale and character of the flows themselves, is the number of enterprises, and ultimately people, whose behaviour has to be influenced. The number of fertilizer manufacturers in Europe is measured in the tens, although there are probably thousands of fertilizer distributing enterprises. The numbers of animal feed producers and distributors in the EU is likely to be measured in the thousands. At the next stage, human nutrition, not only is there a much larger number of products, but the number of enterprises engaged is considerably higher. There are 6 million farm holdings in the EU, and off-farm enterprises in the EU food chain will be measured in hundreds of thousands. The number of sewage treatment works in the EU presumably broadly matches (as an order of magnitude) the number of human settlements over 2000 inhabitants and again is measured in the tens of thousands. Because we are dealing with human nutrition the ultimate number of hearts and minds which may have to be engaged to improve nutrition management is the human population of the EU, 504 million, although perhaps only a quarter of these, are actively managing family nutrition. The very different economic structures in fertiliser and animal feed manufacturing and the likely NRR sector will have strong implications on cots of production. The implications of this are taken up below.

These characteristics will have important implications for the structure and the economics of businesses engaged in nutrient recovery and therefore their competitive position vis a vis the mineral fertilizer industry. In particular the large volume, low concentration of nutrient and spatial dispersion of generation of the material, suggests that the nutrient recovery sector will be a relatively decentralized activity to deal with reasonably local flows of substrate. In turn this will limit the achievable scale economies. It is perhaps only for sewage treatment, and possibly food waste associated with cities that larger scale processing opportunities will present themselves. This is a very different situation compared to fertilizer manufacture. Likewise, growth in manure processing as a means of recovering nutrients and reducing regional nutrient imbalances will be a decentralized activity located in the zones of high livestock populations. Poultry numbers per enterprise are usually large and the manure relatively high in dry matter so this may be transported further. Cattle are more dispersed, the manure is least concentrated and voluminous and is unlikely to be economically transported over large distances (>10 Km) in the majority of EU Member States. Rural transport by large articulated vehicles will also generally be unwelcome, and often impracticable on small rural roads. These aspects will determine the optimal radii served by nutrient recovery and processing facilities. A particular challenge confronting development of the sector dealing with food chain waste is the dependability of future supplies given that it is policy to encourage wholesale reduction in the creation of waste. This has to be factored into investment decisions.

5.2.2 Justifications for collective action to stimulate NRR

This section considers whether policy actions are needed to stimulate the nutrient recovery sector. It explains why the answer is yes. Discussion of the most appropriate kinds of collective actions is offered in the following Section 5.3.

BOX 5. Nutrient Platforms in Europe

- **European Sustainable Phosphorus Platform (ESPP)** (http://phosphorusplatform.eu/)

  150 members covering actors across the whole value chain of phosphorus stewardship. It aims to promote a long-term vision for phosphorus sustainability in Europe through its activities which include, but are not limited to: knowledge sharing, experience transfer and networking for opportunities in the field of phosphorus management, facilitates discussion between the market, stakeholders and regulators, addresses regulatory obstacles.

- **Dutch Nutrient Platform (Nutrient Platform NL)** (http://www.nutrientplatform.org/)

  The Nutrient Platform NL consists of more than 35 Dutch businesses, knowledge institutes, government organisations and NGOs whose joint ambition is to create a market for recycled nutrients.

- **German Phosphorus Platform (Deutsche phosphor Platform)** (http://www.deutsche-phosphor-plattform.de/)

  This platform brings together the knowledge and experience of stakeholders from the relevant public and private sectors and research and development institutions to promote the sustainable use of phosphorus.

- **UK Nutrient Platform (**Currently no website)

  Its aim is to establish a cross-sector UK Nutrient Platform for all stakeholders with interests in sustainable nutrient use and recycling, nutrient management and security and environmental impact.

  Funding: Has received funds from the European Regional Development Fund

- **The Flemish Nutrient Platform (Vlaams Nutrienten Platform) (**Currently no website)

  Connects entrepreneurs, governments and researchers with the objective to close the nutrient cycle in an economically efficient way.

From the story to this point, it appears that conditions are good for the growth and development of an active nutrient recovery and reuse sector in Europe. It has been demonstrated that: suitable substrates and technical processes are available; there is growing awareness of opportunities and information systems; and the societal and political climate is strongly encouraging development of the circular economy, especially in this sector. There already is encouraging activity and a strong, creative and positive 'buzz' at events convened under the numerous sustainable nutrients platforms which have sprung into life in recent years (Box 5). These organisations are self-help groups exchanging information, ideas, research findings about processes and products for NRR, and coordinating actions to influence policy. There is indeed a great deal of innovation already taking place, and many signs of new business activity already engaging on the ground in nutrient recovery[88]. However, the quantification of nutrient flows has demonstrated that this sector is in its infancy and has a long way to grow. There are several reasons to suppose that NRR will not spontaneously bloom and develop into full maturity without some further collective or societal action, or 'Policy'. These are first to overcome the structural features of the nutrients markets, and second to help unblock and overcome a variety of impediments and challenges to nutrient recovery and reuse. The next two sections look, in turn first at these structural features and then the impediments to NRR development. These issues arise from the very character of the of the nutrient flows which demand careful management of the set of concerns often bracketed together under the acronym HESQ – health, environment, safety and quality. Each will be dealt with in the next two sections.

Market structure reasons for collective actions

The first structural reason for expecting the need for collective action is the existence of widespread **market failure**. As explained in chapter 2 above, one of the strong motivating forces for focusing on nutrient management is that the imbalance of nutrient use to feed the human population is causing substantial negative impact on the **environment**. The overloading of nutrients in soils is leading to pollution of waters, air and atmosphere. In economic terms these are classic examples of negative externalities. The term is used by economists to suggest that many activities are associated with unintended side effects whose costs are not borne by the enterprises concerned, but are externalized outside the business, and therefore borne by society at large. Applying these concepts to nutrient management it is observed that crop and livestock farming do not take sufficient account of the pollution they are causing. This damages water quality and imposes costs on water companies, and thence their customers, to purify the water to standards fit to drink. Nutrient use in farming also damages the air through emissions of nitrogen oxides and the substantial costs show up in human health costs and premature deaths. As some of the emissions are also greenhouse gases leakages are altering the climate with costs borne by everyone[89]. Because the enterprises immediately causing the pollution are not bearing the full costs of their activities, the products they sell do not embody these costs either. This means that production and consumption of such products will be higher than would be the case if the costs were fully internalized in the food chain. The resulting misallocation of resources described is a significant

[88] *These are evidenced for example in the newsletters and websites of the sustainable nutrient platforms e.g. http://phosphorusplatform.eu*

[89] *Nutrient flows, and especially livestock, are associated with significant greenhouse gas emissions causing climate change about which Nicolas Stern, ex Chief Economist at the World Bank, said that "climate change is the greatest and widest-ranging market failure ever seen". Stern N (2007) Economics of climate change, Cambridge Univ Press.*

example of market failure. It is evidently not in the private interest of firms involved to rectify these failures therefore some kind of collective action is necessary.

The usual remedy suggested to deal with these negative externalities is to apply the polluter pays principle, that is, to find ways to reflect external costs on the enterprises causing them. However, in the case of diffuse pollution when the immediate polluters are farmers, and they are numerous, small and financially precarious it proves a substantial challenge to impose the polluter pays principle.[90] There are very high transaction costs of applying this principle to agriculture. This is why, in the EU, adherence to the nitrates directive (for example) is part of the statutory management requirements (cross compliance regulations) for farmers claiming direct payments under the Common Agricultural Policy. These arrangements have been in place since 2004 and yet the EU is still far from achieving full compliance with the directive. Other actions therefore are required.

The externality concept can be more directly applied to nutrient recovery and reuse itself. By managing waste streams so that the nutrient content of these streams is captured and does not reach the environment is a beneficial action. It could be seen as a positive externality. To the extent that it also displaces some mineral fertilizer, and the pollution associated with its manufacture, is a second external benefit. The question is whether any business set up to conduct the nutrient recovery and reuse can capture the full value of these social benefits. If they cannot then it must be anticipated that the development of this activity is likely to lag behind the level that society would ideally like.

Market failure is a classic indicator that some kind of collective action is needed to bring about a desired result. It does not tell us what kind of collective action should be deployed, nor indeed whether and to what extent, the action will work. The very persistence of environmental externalities despite decades of 'taking collective action' through environmental policy and creating regulations, incentives for positive actions and penalties for undesirable actions is testament to the fact that both market and governance failures are not always easy to resolve.

A second reason for possibly requiring collective or policy action to encourage nutrient recovery and reuse is **market imperfection**[91]. It has been argued that the fundamental characteristics of NRR, and the materials it will work with, suggest that this will be a sector of small and medium size enterprises. They will be geographically dispersed, and deploying a wide range of processes and products. Yet at the end of the day this sector will be supplying chemical elements, nutrients, to farmers, viz. nitrogen and phosphorus (amongst others). These ultimate customers for the recovered nutrient, the farmers themselves, operate as competitive low margin businesses. They will be highly sensitive to price and of course quality, especially reliability and consistency of the recovered nutrient. It can be anticipated that a new, fragmented, smaller-scale NRR sector producing new more environmentally-friendly products will have to work extremely hard to compete with the established, mature, concentrated mineral fertilizer sector which has a century of accumulated experience in manufacturing, formulating and selling fertilisers to farmers.

A further aspect of the imperfect market structure which complicates actions to deal with externalities concerns the inability of farmers to pass on higher costs to their customers. The contrast with water companies helps make the point. Piped water is not generally an internationally traded good, and water companies often operate as regulated local monopolies (sometimes publicly owned). In such a structure, there is in principle no difficulty for water companies to pass on the cost of cleaning up pollution to water consumers (subject to consent from the regulator). For food and farmers the situation is quite different. Food is an internationally traded good, and farmers have little or no market power. If they are required to absorb new costs to reduce their pollution, they are generally unable to pass these costs on to their customers the food processors and retailers who will source internationally from the cheapest suppliers of the products they require.

These market failure and imperfection arguments provide a basis to justify some **'infant industry' encouragement** and help and to get the NRR sector established in order to discover its socially correct contribution to the market for nutrients. Without such help it is likely that Europe will find it is still discussing the potential for nutrient recovery and reuse in one or two decade's time. What kind of help is the critical, and possibly controversial, question. This is the subject of section 5.3.

Other impediments facing nutrient recovery

- *Attitudes & culture and safety*

Perhaps unsurprisingly, people have some quite deep-seated cultural attitudes and beliefs about the management of animal and human waste, and a natural reticence to even consider them in relation to food. This is especially the case in developed, urbanised, countries where most citizens are now several generations, and usually many kilometres, removed from primary food production and its reliance on manure. This can create obstacles to further implementation of nutrient recovery and reuse in the EU. These perceptions and attitudes can apply to the separation and collection of wastes, the recovery processes, and certainly to the application of the recovered nutrients to agricultural land.

On the collection side, it is likely that increased efforts be required from citizens, both in urban and rural areas, to

90 This difficulty has at least two elements: the absence of willingness to do it, and the sheer costs and practicality of doing it where the enforcement costs are high.

91 The word imperfection is being used in its normal economics sense. A perfect market is exhibited where there are large numbers of sellers and buyers, in which there is good information available to all, no barriers to entry and thus each market participant is a price taker with no market power. An imperfect market is one where these conditions do not apply, and buyers or sellers acquire some market power.

contribute to further waste separation. In urban areas, the large increase in material recycling indicates that EU citizens can be mobilised to change their habits about waste generated at home and at work. It shows they are willing to contribute to waste recycling. However, it seems that less progress has been made with biodegradable waste. The fact that some countries are now achieving substantial collection of this waste shows that just as with material recycling, the importance of separating organic waste from the rest can be made. This is partly a matter of social acceptability and conditioning. There are many actions that can be taken to build such social acceptance such as door-to-door information campaigns, but they must be put into practice and maintained for many years. Awareness raising about the consequences of leakage of nutrients into the environment, and the ill-health effects of nutrient mismanagement must, of course, be an important aspect of such information campaigns[92]. The story can also be cast in a positive way too. It can explain how waste separation and collection can reduce our reliance on important non-renewable resources often from unstable parts of the world. It can document how new waste processing can contribute to local jobs and growth, and some energy capture and also enable the return of organic material to soils. These are good news stories which can help overcome resistance to use of certain waste flows in nutrient recovery and reuse in food production, and help motivate behaviour change.

A second kind of separation which may be helpful in the longer run, but costly in infrastructure and logistics, is the separation of urine and faeces in toilets. Vacuum-based technology to do this is available, and some new developments in Sweden and China are demonstrating its value. Two principal advantages are that urine represents only 1% of the total wastewater volume but contains 80% of the N and 55% of the P in domestic wastewater[93], and second that such toilets use far less water, a strong benefit in itself, and it also means that the collected waste material is less dilute.

A particular fear, sometimes based on uninformed opinion, concerns the use for food crops of recovered nutrients from sewage waste and in particular the **health and safety** of use of such material. There are of course legitimate concerns about potential contaminants in sewage and their impacts on health if used in food production. Similarly, given the type and origin of the biological materials, there are concerns about the safety of handling and storage, for example of manures with their potential to create gaseous leakage. In all countries already processing sewage sludge for return to the land these matters are of course regulated. However, the willingness to do this varies widely around the EU. Table 8 illustrated the highly variable extent to which sewage sludge is applied to agricultural land around the EU and indicated some of the restrictions in place in some Member States. For some, the use of any human waste in food production is taboo. Such beliefs might well be beyond the reach of rational argument and empirical evidence and scientific reassurance about safety standards, testing and monitoring. Others will be more amenable to such information. It is entirely reasonable to have concerns about the use for food production of recovered nutrients from any waste stream which is contaminated by hazardous substances. This could apply to animal manure and food waste, but there are especial concerns about sewage waste. The prime concerns are the presence of heavy metals, biological pathogens or pharmaceutical products. But of course because domestic sewage can be inter-mixed with general municipal waste water, industrial waste water and surface run-off, then in principle there could be contamination of almost any type.

Technology has advanced in detecting and avoiding the presence of these harmful substances and treating and removing them when they are found. However, consumers will not generally be well informed about the steps which have been taken to eliminate these risks. One of the difficulties in doing this is that each waste stream carriers its own load of hazardous substances and the identification and treatment will be case specific. The safety standards dealing with these issues come under the Sewage Sludge Directive. The source of heavy metals in sewage came mainly from industrial processes, and now point-source industrial pollution of this kind is well regulated. However, pathogens and pharmaceutical substances may only be partially decomposed in digesters and remain in the treated sludge in significant levels.

These are complex and serious matters which merit detailed, independent scientific investigation to establish appropriate testing protocols and safety margins. Addressing this issue will require the development of technological solutions and adequate legislation. These actions are prerequisites to calm legitimate consumer concerns. Citizens' confidence can only be built by strict, evidenced-backed certification of the processes and products involved in NRR, and then by appropriate monitoring and regulation of the processes in the field. In short, building confidence in the **quality** assurance of recovered nutrients whether organic or inorganic has still some way to go, and this is a task acknowledged by the revised fertiliser regulation expected in early 2016. Given the variety of substrates and their contaminants, the processes and likely end products it may take some time before they can all be certified. Food safety standards of course cannot be compromised. Also, because the products of NRR are destined to be added yearly to agricultural soils, potential dangers of accumulation of any contaminants themselves, or metabolic breakdown products of contaminants, have also to be considered. This requires sensitive and thorough risk assessment.

In addition to the citizen and consumer acceptability of the NRR processes and products, there has also to be social acceptance of the distribution of the recovered nutrients and their storage and spreading on fields. Prime concerns here are the traffic movements on narrow rural

[92] *Publications like Our Nutrients World and Nitrogen on the Table are an important part of such campaigns as these comprehensive, high-level reports can provide the material for numerous messages to consumers and businesses.*

[93] *Data for Sweden from Höglund 2001.*

lanes of often very large contractor vehicles, the strong unpleasant odour, and the ammonia pollution associated with piles of material stored on open land awaiting application at the right time for crop uptake or associated with the spreading itself. There are technologies to minimise odour by injecting or incorporating the material into the soil immediately before it can volatilise. Good neighbourly relations providing warnings and notice of spreading can be appreciated too.

- *Business challenges*

Four aspects of the business economics of Nutrient Recovery and Reuse will be treated here: (i) economic characteristics of the processes and products, (ii) data and benchmarking, (iii) investment costs and risks, (iv) the demand for recovered nutrients.

The **economic characteristics of the processes and products** stem directly from their physical characteristics discussed above. NRR has to work from dispersed, dilute, heterogeneous and thus variable, sometimes contaminated, biological substrate materials and it has to distribute its products, which will be less dilute and more homogeneous but still relatively high bulk and low value, to equally dispersed customers, farmers. Whilst the nature of the processes and materials suggest there could be significant scale economies, the economics of transportation of bulky low-value materials into and out of processing and storage may be a determining factor on the optimal scale of operation. Clearly the location of the processing unit will depend on the substrate mix the plant is designed for and the capacity for distributing the product to farmers. Many of the processes will be specific to the substrate, so for example struvite manufacture, and other phosphorus recovery will be done on the site of waste water treatment plants, and certain food industry waste processing will be on site of the food processor. Other plants which take a mixture of sewage sludge, farm and food waste will generally locate between the sources of these substrates and the farms to which the nutrient products will be distributed.

It was hoped at the outset of this project that there were enough NRR plants up and running that it might be possible to assemble some **data to help benchmarking** the likely economic performance of this activity. In the event it was discovered that NRR development is at too early a stage to enable this to be done. There are not many full-scale, commercial plants in operation, many have only been in operation for a few years. Many plants are operated at pilot or experimental scale. There is longer experience in some other countries outside Europe, for example Struvite recovery has been in commercial operation in Japan for many years[94]. But the newness of these activities in Europe, plus the lack of research resource and an element of commercial confidentiality has prevented the assembly of even indicative figures of the likely operating costs and plant scale economics in this domain. Likewise there is little experience yet in establishing the need and cost of any new infrastructure for handling, transport and distribution of new fertiliser products. Accumulating this evidence is work to be done in future and will take more time and resource.

As a relatively new area, **NRR investment certainly comes with risk**. It is a relatively new set of developing technologies, and the inherent material and process characteristics are tricky as described above. In addition at all three stages in the recovered nutrient chain there are uncertainties. First there may be hesitations about the quality of the NRR product to the immediate customer the farmer. These are elaborated below. Second, the farmer has to sell his agricultural products to food and feed processors and food retailers. They may have their own cautions about using ingredients sourced from farmers who use fertiliser based on sewage. They might decide on behalf of their customers without even consulting them and thereby raising their fears, that it is a risk they are reluctant to take. Third, are the risks surrounding the attitude of the final food consumers themselves, these were discussed above. It may take many years of accumulated experience, and absence of 'accidents' or scares from regions where NRR is underway to assess these risks objectively and calm fears and concerns by providing thorough independent assessments of safety and evidence of the benefits of the investments.

In addition, there is another aspect of the long-run development of nutrient recovery from food waste and possibly in the longer run from wastes from the livestock sector that investors might consider in their business plans. NRR based on food waste will be dealing with material flows which are subject to well-established societal goals to substantially diminish if not eliminate. This is explicit in the Circular Economy proposals. If these plans are achieved then the volume of this substrate material for NRR will fall, or at least grow less in future than the past. There is no contradiction at all in simultaneously setting an ambition to reduce waste, and at the same time trying to establish an industry which extracts useful resource out of the remaining waste flows. But it does add an extra element of uncertainty for investors. A similar consideration could apply to the long run future for waste arising from the livestock sector. This applies to two of the major substrate flows identified in this report, manure and meat and bone meal slaughterhouse waste. Proposals to set targets and encouragement to substantially reduce livestock product consumption, could, if they materialised, significantly reduce nutrient flows. This is clearly a long-run consideration, especially in the context of a still growing population, and growth in livestock product consumption. But it suggests that if both food waste reduction and livestock product consumption were both curtailed, then the long-run potential volume of NRR in Europe might be lower than suggested by flows based on current observation.

The fourth critical economic consideration is **the demand for the recovered nutrients**. At this point, the issue of whether farmers' customers have any concerns regarding the use of fertilisers based on sewage is put on

[94] *See Ohchi S et al (2015), and Hosho F (2015) for information about Japanese activity in phosphorus recovery.*

one side. From a purely farming perspective it is suggested that the demand for recovered nutrient is simply the demand for a commodity. Many farmers may care little whether NRR products are highly desirable socially as contributing to the circular economy and helping reduce pollution. They will be making a hard-nosed commercial decision to purchase nutrients for their crops. They will be concerned about its price, nutrient composition and consistency, its physical properties such as ease and cost of handling and storage, but most of all the performance and cost-effectiveness of the product as a plant nutrient. Once again this is a matter of the quality of the recovered product. Farmers have a readymade comparator, mineral fertilisers, whose price, consistency and performance qualities they know well. Do the crops take the NRR product up and thrive? Is the product harder to handle, and store? Does it require special new investment for application? Is it less concentrated or slower release? If there are doubts about any of these aspects, then the price of the recovered nutrient will have to reflect this to attract purchasers. There seem to be two broad options here, either recovered nutrients aim to match current specifications of mineral fertilisers and to be priced accordingly, or they create a new market by offering complementary benefits. This could certainly include soil organic carbon. For the latter to happen, knowledge dissemination and acceptance is needed to understand the importance of soil carbon and soil organic matter to fertility and soil health.

In some business models for NRR the recovered nutrient may be offered to the farmer free. This may occur where, for example, the processor is paid to take away municipal bio-waste or food chain waste. It can happen when the alternative waste disposal route facing water treatment plants or food processors is land fill with high and rising gate fees, or incineration costs. In such circumstances the NRR operator is able to give away the recovered nutrient to the farmer free of charge. He may even deliver and inject it for him in his fields, saving the farmer these costs of fertiliser spreading. In such cases, the farmer will still compare the costs and crop performance using NRR nutrient with performance using conventional mineral fertiliser in deciding whether to accept the free, or discounted-price, product.

The effectiveness of the recovered products as fertilisers is still under investigation. Trials have been mostly conducted on laboratory plots for short periods of time but evidence of their effectiveness is needed at larger temporal and spatial scales. Unless there is a market interest in the recovered products, motivation for recovery may be low despite gains in operational benefits, such as in phosphorus recovery from Sewage Treatment Works. There may be additional benefits of some recovered nutrients such as the presence of organic matter. Although it is increasingly appreciated by farmers that soil organic matter has declined in many EU arable cropping areas, this awareness has yet to materialise as a thriving market exhibiting willingness to pay for organic matter *per se*. However suitably marketed a recovered nutrient which conferred such benefit might become an attractive proposition.

5.3 Policy measures to upscale Nutrient Recovery and Reuse

It will be clear by this point that there are multiple actions by different stakeholders required to improve nutrient management, and to further pursue nutrient recovery and reuse. Each Member State will have to choose the appropriate combination of actions suitable for its own circumstances. However, a **specific action plan for NRR established at the EU level** could provide a most useful analytical framework as well as practical check lists of potential actions. This could perhaps be an early practical product from the implementation of the Circular Economy action plan.

Amongst the potential collective actions, there are a number which command general and full support. These will be considered first, and indeed many are already underway or have been proposed as part of the circular economy action plan. Probably highest priority amongst these is to make rapid progress with the clear delineation, and establishing standards and certification procedures for recovered nutrient products. This has been referred to several times in the forgoing and is an identified element of the Circular economy action plan.

5.3.1 Information, research and development

The creation of **information exchange** on nutrient recovery and reuse is already well launched. It is, and can remain, largely a private sector activity channelled through the nutrient platforms[95]. These bring together the major private and public stakeholders including researchers, engineers and process developers, fertiliser industry, farmers, water treatment and food industry representatives as well as public officials and politicians. The concrete signs of this activity are conferences and other events, websites, newsletters and publications. A further development of this approach could be through a more formal establishment of Best Available Technologies for nutrient recovery and reuse, and then their promotion through the information exchanges. This type of activity is one which can benefit from EU support to ensure that the best techniques and practices amongst the 28 Member States are discovered and shared. Few national governments can manage the breath of effort required to do this.

Similarly, **research, teaching, skills development and training** are all activities which are already well-established at EU and Member State level with the necessary mechanisms to detect the need for, and to develop the necessary materials and tools to equip an expansion of the NRR sector. Through its 7th research framework programme, the EU has invested over 15 million Euros on the

[95] *The European Sustainable Phosphorus Platform recently launched an initiative called "Data on Nutrients to Support Stewardship (DONUTSS)" to identify what data on nutrients is needed by different stakeholders and how it would be monitored to support decisions.*

development of new technologies to recover nutrients from waste streams. The most explored lines have been waste water and sewage sludge in Sewage Treatment works, livestock manures, food waste and biofuels production. Examples of projects can be seen in Box 6 such as P-Rex, RecoPhos, BioEcoSim, ROUTES and PHORWater. Similarly in the current research call under the 2014-20 framework programme for EU research, Horizon 2020, two calls are relevant to nutrient recycling. One is on 'Water in the context of the circular economy, to demonstrate the potential of efficient nutrient recovery from water', and the other is on 'Unlocking the potential of urban organic waste'[96]. This group of actions are seen as public good activities for which public financial support is made available and well justified to provide the knowledge and skills required to help tackle the market failures surrounding nutrient management. Whilst there is always scope for more research, it does not appear that there is a lack of public support to identify and pilot nutrient recovery technologies.

As new processes move from the research laboratory towards commercial application, there is often a pilot plant stage where the technology, the logistics of substrate supply and management, and quality measurement and monitoring of the output product whether it is a fertilizer, digestate or compost material are all tested. It is reasonable that some public funds can be devoted to support such development activity. There might even be a further stage when the pilot process is up-scaled to a commercial basis and the enterprise provided with some assistance in return for acting as a demonstration plant actively encouraging visits and sharing of the operational details and how problems are overcome.

BOX 6. FP-7 projects focusing on nutrient recovery

- **FERTIPLUS** Period: **2011-2015** Budget: **€4,035,827** (74% EU contribution)

  "FERTIPLUS will identify urban and farm organic wastes that can be used to recycle nutrients into agriculture as biochar, compost or combinations of them."

- **REFERTIL** Period: **2011-2015** Budget: **€4,157,112** (72% EU contribution)

  "The aim of REFERTIL is to improve the currently used compost and biochar treatment systems, towards advanced, efficient and comprehensive bio-waste treatment and nutrient recovery process with zero emission performance. The improved output products are safe, economical, ecological and standardized compost and bio-char combined natural fertilizers and soil amendment agricultural products used by farmers."

- **P-REX** Period: **2012-2015** Budget: **€4,359,683** (66% EU contribution)

  "The P-REX project builds on the outputs of previous European research projects and will perform the first holistic full-scale evaluation of technical phosphorus recovery techniques using municipal sludge or ashes in comparison with phosphorus recycling by land application of sewage sludge."

- **PHOSFARM** Period: **2013-2015** Budget: **€1,471,858** (71% EU contribution)

  "PhosFarm addresses the increasing market for a sustainable and economically phosphorus (P) recovery from agricultural residues to meet growing demand for food, bio-fuels and bio-materials. Key innovation will be the advanced phosphate recovery through a controlled enzymatic release of more than 90% of the organic P."

- **RECOPHOS** Period: **2012-2015** Budget: **€4,035,827** (75% EU contribution)

  "The RecoPhos process is a thermal process using ash from sludge mono-incineration."

- **BIOECOSIM** Period: **2012-2016** Budget: **€4,035,827** (73% EU contribution)

  "This project targets to produce sustainable soil improving products that can be easily handled, transported, and applied. BioEcoSIM will valorise livestock manure as an important example of valuable bio-waste into 1) pathogen-free, P-rich organic soil amendment (P-rich biochar), 2) slow releasing mineral fertilisers and 3) reclaimed water."

- **VALUEFROMURINE** Period: **2012-2016** Budget: **€4,035,827** (76% EU contribution)

  "The bio-electrochemically-assisted recovery of valuable resources from urine (ValueFromUrine) project will develop, optimize and evaluate an innovative bio-electrochemical system that allows for the recovery of phosphorus (P), ammonia (NH3) and electricity (E) or hydrogen from urine."

- **Poul-AR** Period: **2014-2015** Budget: **€4,035,827** (70% EU contribution)

  "The project proposes an integrated biological approach for the pre-treatment and valorisation of poultry manure. The liberation and fixation of nitrogen as nutrient is optimized and the product consists of a valuable ammonium salt directly applicable as fertilizer. The residue of the de-ammonification allows for a variety of post treatment methods."

- **EFFICIENTHEAT** Period: **2011-2013** Budget: **€4,035,827** (79% EU contribution)

  "The aims of EfficientHeat is to develop an affordable technology for all types of farmers which reduces the transportation cost, currently accountings for almost 60% of the total processing costs. EfficientHeat will also permit an increase of the energy efficiency up to 20% and the abatement of emissions (N-compounds) reducing foul odours. Additionally, EfficientHeat will also provide for nutrient recovery for recycling and reuse."

(Source: http://cordis.europa.eu)

Precisely these kinds of development issues are being examined and debated in the Biorefine cluster. This initiative bridges multiple projects in the domain of nutrient and energy cycling. It emerged to provide a long-term, wider-scale vision of the developments being made on nutrient recovery. The Biorefine cluster was born from a

[96] *https://ec.europa.eu/programmes/horizon2020/. Calls: CIRC-02-2016-2017 and CIRC-05-2016*

NWE INTERREG[97] project and facilitates synergies and networking and, consequently, knowledge sharing and its impact on policies and market development. The cluster also receives funds from the European Union through the INTERREG IV B programme.

There are three areas where more research and information collection, collation and analysis are required. Two of these were summarized in the declaration of the second European Sustainable Phosphorus Conference (Berlin March 2015). They are to:

- Implement coherent, annually updated data monitoring of phosphorus mass-flows, concentrations and sinks at regional and national levels in EEA (European Environment Agency) reporting.

- Assess phosphorus in general and other specific forms of phosphorus as critical raw materials, in addition to phosphate rock.

The European Nitrogen Assessment and comparable (though less generously funded) work on phosphorus have been very important in understanding the scale and nature of the nutrient management challenge faced in Europe. This work could certainly be built upon and developed further. It is important to assess the flows at regional or national level, investigate further the balance between domestically sourced and imported nutrient, and to look more closely at the components of the flows through the food chain to better assess where the real scope for recovery is. It is also important to investigate the annual variability in these flows by repeating analysis at suitable intervals. These efforts were no doubt resource intensive especially to establish the methodologies and assemble the data required, but it is to be expected that now that the conceptual framework for calculating these balanced material flows has been established, subsequent analyses and breakdown of data by Member State should be less demanding tasks. A further line of investigation is then to consider how the concepts of nutrient flows might be calculated for, and communicated to, farmers in a much more localised area, e.g. a water catchment, or flood plain.

A third information challenge is correctly identified by the circular economy action plan and explained above, this is to develop a common EU methodology to measure food waste and define relevant indicators.

5.3.2 More active stimulation of NRR market development

For some, the above actions define the full scope of what the public sector should consider doing. This liberal market view suggests that it is for private investors to spot and seize the opportunities to process waste streams and produce commercially marketable secondary raw materials or finished organic fertilisers and soil improvers. The unhappy experience of strong measures to encourage bio-fuels before the evidence was available to demonstrate climate benefits from such measures should induce caution, and a clear evidence base before embarking on stronger incentives for NRR. Whilst it is clear that there are substantial market failures and imperfection surrounding NRR, close analysis of potential measures and their potential impacts should be assembled before more interventionist policies than the above measures are justified.

These could take the form of measures to more purposefully and actively intervene either by offering various ***positive approaches or stimulants*** to propel specific desirable NRR activities or by taking a **negative approach of imposing *penalties or restrictions*** to repress undesirable nutrient use activities. Many of these are referred to in 'Closing the Loop' as economic instruments. Using them either positively or negatively will be more controversial with one or other stakeholder group. If, essentially these actions are seeking to internalize environmental costs then the burden will fall on some group. It is a political choice to decide which group bears the costs. For the positive measures, the incentives, these will essentially internalize some of the costs onto either nutrient users (farmers and food consumers), perhaps water users, or onto the taxpayer (if public funds are deployed). Depending on which negative measures are used the costs are likely to be borne by farmers, and then potentially food consumers.

Five kinds of market stimulants

There are five kinds of ***stimulants*** which could be deployed to get the desirable NRR projects or processes going: obligations, targets, investment grants, subsidies, fiscal reliefs.

1. *Obligations.* The most direct way to show to the public and all affected businesses that it has been politically decided that a certain aim will be achieved, is to set out some obligations on the relevant businesses to comply with a new, socially mandated, goal. There are a number of ways this could be achieved in the context of NRR.

   i. The Swiss took the bold approach to ban direct use of sewage sludge on land in 2006, and in the succeeding decade they have been getting ready for the implementation from 1/1/16 of a new regulation which obliges the technical recovery and recycling of phosphorus in the form of inorganic products from all sewage sludge and slaughterhouse waste. The immediate costs will fall on the operators of these plants, and thence ultimately on their customers.

   ii. A less ambitious approach is to mandate inclusion rates for recovered phosphorus, for example 5% of phosphorus fertilizer marketed must have been recovered from waste water or food chain waste. These are sometimes referred to as mixing quo-

[97] *http://www.biorefine.eu/cluster Interreg is the EU programme to encourage inter-regional cooperation and activity between regions of contiguous Member States of the EU. NWE refers to the regions of North West Europe in Ireland, the UK, France, Belgium, Luxembourg, Netherlands, Germany and Switzerland.*

tas. This transfers the responsibility for developing and incentivizing the nutrient recovery to the fertilizer manufacturers. Cost will then be shared with farmers. Such approaches have to be ready to deal with trade diversion. Traders may seek to source fertilizer from zones not subject to such obligation.

iii. Another less intrusive approach is to place an obligation to create a national or regional action plans for nutrient recovery, with the specified substrate targets and processes and an appropriate set of these encouragements or inducements.

2. The *public setting of voluntary targets* is a well-tried tool for increasing awareness of new challenging areas and for stimulating business to consider investing in them. At the very least the targets would be accompanied by information support, on the technicalities, markets, processes and regulations to be respected as well, perhaps, with help and advice to deal with local zoning/planning permission and dealing with local authorities and gaining acceptance by other stakeholders. More active target setting involves linking the target with a more explicit fiscal or cash incentive, such as 3, 4 and 5 below. Targets could be set for example for:

- recovery of phosphorus from waste water (P-Rex)
- processing 50% of manure and sewage sludge in eutrophication 'Sensitive Areas' by 2025 (Finnish Government)
- separation, collection and processing rates for food waste. These could be set for specific food processing sectors brewers, millers, dairies as well as slaughterhouses and meat processing facilities. They could aim at food service, especially that directed to public institutions (schools, hospitals, prisons, armed services) and restaurants. They could also focus on food retailers.

The main utility of targets, not backed-up by any other subsidies or investment assistance, is awareness raising and encouragement of investors that the Government is serious about achieving a certain goal.

3. *Investment, start-up or innovation grants*, can be direct subventions from public finances to assist the establishment of new NRR businesses. There is a variety of ways this can be done and financed, and of course they have to avoid infringing EU state aid rules. This approach could assist the NRR development process by helping establish pilot plants. It could be done through national or EU regional, cohesion, or rural development funding if it involves help to backward or disadvantaged or high unemployment areas. The argument for these kinds of assistance must be in terms of remedying local disadvantage or stimulating innovation which the market is less likely to support.

4. A very direct approach is to offer *direct subsidies* per tonne for processing certain waste streams, or for recovering specified percentages of nutrient in waste, or for including certain percentage or volumes of recovered material in marketed fertilisers. Such an overt subsidy would be the nutrient recovery equivalent of 'feed-in tariffs' paid to installers of solar PV arrays, wind turbines and certain other renewable energy investments. These are justified to stimulate the develop-

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ment of these sectors in competition with the more mature, larger scale, but heavily polluting fossil fuels. Adopting this approach for Nutrient Recovery and Reuse would first demand rigorous demonstration of the rationale and ability to contribute to higher nutrient use efficiency as well as delivering to the other objectives listed for NRR.

5. *Fiscal reliefs,* for example VAT refunds, reduced rates or reliefs on purchase of secondary raw materials.

The burden of the last three approaches falls directly on public finances. They therefore compete with all other calls on public expenditure, and would be expected to be able to demonstrate comparable value for money for other public investments. It is a separate discussion whether such support should be from EU or Member State budgets or shared.

There is an asymmetry in the burden of benefits and costs of these positive approaches to try and encourage positive NRR activity. Those generally in favour will be enterprises trying to get established in this sector. The benefits will be concentrated on this group and they have some virtue on their side because they are bravely trying to establish a new sector partly motivated by the desire to do environmental good. Opponents will be those inclined to be suspicious of subsidy in general, and unconvinced that establishing new activity on the basis of subsidy ever creates an industry capable of standing on its own feet. Those who find themselves paying for the subsidies will often not notice (unless they are farmers) if, as is likely, the costs are spread over large numbers of food consumers, water consumers or taxpayers.

Three kinds of penalties or restrictions

There are three approaches in which penalties or restrictions on 'undesirable' or polluting activities might be used to help give advantage to the development of nutrient recovery and reuse. These are taxes on mineral fertilisers, taxes or restrictions on landfill and incineration, or taxes on nitrogen surpluses.

The balance of benefits and burdens for **the negative approach using penalties or restrictions** is generally the reverse of the positive tools. This approach is essentially to find ways to impose the polluters pay principle. The intention is to directly address the activity causing the externality by taxing, restricting or banning it. This is intended to internalize the pollution cost by imposing it upon the enterprises causing the pollution and giving them the incentive to change practice or take other steps to reduce or avoid the harmful side effects. Alternatively, with higher costs they may reduce their output, and thus the pollution. The effects of such taxes or restrictions will partly be transmitted to the consumers of their products. This, in turn,

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should reduce the consumption of such products. In this way both the producer response and consumer response will tend to work together in the direction of reducing the pollution creating activity[98]. In this context a larger share of the burden of the approach is likely to be felt by the polluting enterprises, e.g. domestic farmers. They will have an incentive to fight against the imposition of the tax or restriction. The individual consumer impact will be small even undetectable because it will be shared over the large number of consumers and probably drowned by other market fluctuations. The benefit of the policy – reduced pollution may be enjoyed by all – but this too is shared, dispersed, over the entire population.

The most obvious ways that the negative approaches might be deployed in the field of nutrients is to impose **taxes on the sources of leaking nutrients**, to raise their price and incentivize much more careful use. The most obvious immediate target of the tax might seem to be mineral fertilisers. Generally, the higher the tax the greater the incentive to economise on their use, and to maximise nutrient use efficiency. Whilst raising the relative price of

[98] In economic parlance the share of the burden of the tax will be shared between producers and consumers depending on the relative elasticities of supply and demand. In extremis, if consumers can easily switch sources from domestic to foreign suppliers, then effectively the domestic producers (farmers) will absorb all the burden of the tax in reduced production and sales (and the corresponding pollution may have been moved abroad).

mineral fertiliser compared to recovered nutrient will help stimulate more use of the latter, it is not at all clear that nutrient efficiency is any higher with recovered products nor that they are themselves intrinsically less polluting. Furthermore, in the light of the new understanding of the nutrient flows in European agriculture and the relative scale of the leakages, it might be considered that the priority target for pollution taxes should instead be livestock products. This might point a finger towards taxing nutrients into that sector, e.g. livestock feed, however even if this made policy sense, too much feed is home grown and there are too many substitution possibilities to make this practicable! Taxing livestock products would be a radical step, and there are few precedents[99]. Given the variety of livestock products, the complexity of the livestock production chain, and the newness of this idea it is dealt with in a broader context in the final section of this chapter. Here, attention is confined to more specific, and perhaps more practically possible taxes or restrictions.

1. **Fertiliser taxes** are not a new idea. Their use has been analysed recently for phosphorus in a study

[99] In October 2011 The Danish Government introduced a fat tax on butter, milk, cheese, pizza, meat, oil and processed food if the item contains more than 2.3% saturated fat. However, it was abolished a year later as it apparently failed to change Danes' eating habits, had encouraged cross border trading, put Danish jobs at risk and had created costly bureaucracy for producers and retailers.

for the European Environment Agency[100]. The study found that fertilizer phosphorus has been taxed at various times in Finland, Netherlands, Austria, Norway and Sweden. Phosphorus in animal feed has been taxed in Denmark since 2005. A general conclusion is that the taxes deployed had little effect on fertilizer use rates unless the level was high, although there were benefits in greater awareness of farmers of nutrient use efficiency and in information available.

The instrument of a fertilizer tax is difficult in the context of the EU. If it imposed by an individual Member State their farmers will understandably complain that this discriminates against their production, and the pollution may be moved to other Member States which expands production and exports back to the fertilizer taxing country. Border tax adjustments within the EU single market are not allowed. Because the EU has no competence over fiscal matters, without a change of heart on this principle, the fertilizer tax cannot be imposed at EU level.

Perhaps the context of encouraging the use of recovered nutrients suggests an alternative tax-based approach. If the aim is to stimulate recovered nutrients at the expense of nutrients derived from mineral fertilisers, then consideration could be given to setting differential VAT rates, lower rate or zero-rate for recovered nutrients and normal rates for the mineral based products.

2. Some other possible ways of encouraging nutrient recovery and reuse using taxes are Landfill taxes and incineration gate fees. Alternative, stronger more direct negative approaches are straightforward bans or heavy regulatory limits imposed on defined undesirable activities. Examples are bans on land fill or incineration of certain wastes and strong limits on sewage application to agricultural land (e.g. Finland).

   These will generally be introduced with several years notice, and with other actions to help the alternatives develop.

3. The German SRU report proposes raising a **tax on nitrogen surplus** (to serve as incentive to reduce nitrogen emissions in a cost-effective way). The revenue should then be re-invested in the agricultural sector (they mention: farm advisory services, management measures in sensitive areas). This is not directly linked to recovery but could induce increased recovery at the farm level to avoid losses through runoff or air emissions.

This section has shown that there are a many actions available to stimulate further development of NRR. Some are already underway, and others are proposed in the new Circular Economy package. It remains for these proposals to be adopted by the Council and Parliament and then enthusiastically taken up by Member States. Together they could certainly unblock many of the impediments to NRR. It also appears that the research needs for NRR have been well supported at EU level to date and appear to be continuing under Horizon 2020. This suggests that attention for the future must focus on other impediments, specifically the certification of recovered nutrients to get more consistency, certainty and then critically, confidence into these markets.

However, whether unblocking these impediments is enough to then expect to see spontaneous take-off in this sector is not certain. The arguments of section 5.2 describing the nature and scale of the market failures and the challenging characteristics of the materials and processes involved in NRR were reasonably strongly suggestive that more active policy measures will be required to bring about a step change in NRR. Whether these more active measures should be the positive inducements or the penalties on polluting activities, or indeed both or a mix, cannot be answered without much more detailed analysis than is possible in this report. This indicates an important area for further research, namely to analyse the feasibility and costs and benefits of the deployment of such measures.

5.4 NRR in relation to the five challenges – especially pollution and waste

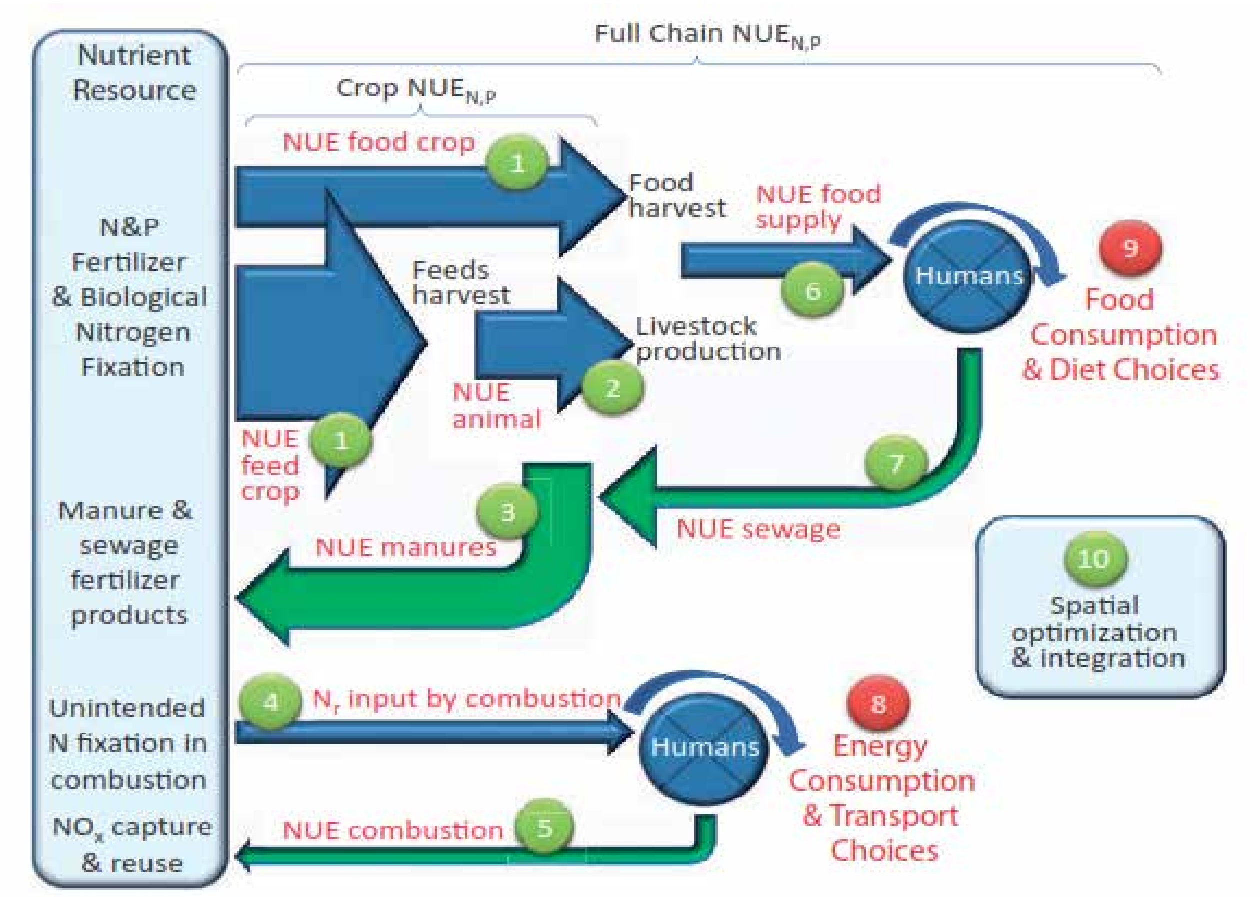
Nutrient recovery and reuse appears to be a very obvious approach to deal with some of the goals and concerns surrounding nutrient use relieving some of the tensions. However it is important to be realistic about what this can contribute and what it cannot.

It is clear, particularly from the quantification of the nutrient flows through the agri-food system, that there is little hope of recovering all the N and P which leaks from the food chain. A significant proportion of the N losses escape as gases to the atmosphere or is leached into water ways, ultimately to seas, oceans and ground water. It is therefore imperative that there is an unrelenting drive to improve the nutrient use efficiency of each stage in the food chain, crop production, animal production, food processing and consumption too to minimize these losses.

This is not a new message, and it requires action at many levels and by many parties which will have to be sustained over many years. The report 'Our Nutrient World' (Sutton *et al* 2013) depicts ten Key Actions through which the overall full chain nutrient use efficiency should be tackled. This is shown in Figure 15 adapted from this publication with the addition of an extra recycling (green arrow) stream from the food industry back to the nutrient resource box. The ten routes are listed in Table 14 together with the main actors who will have to change their behaviour. Actions 4, 5 and 8 are directed to sectors in the economy outside food and agriculture. Actions 1 and 2 are the prime responsibility of farmers and all those who work with them. Actions to engage nutrient recovery and reuse are pertinent to Nos. 3, 6, 7 and 10.

[100] *Material resource taxation, an analysis for selected material resources", October 2015, 82 pages, ETC/SCP, ETC/WMGE and EEA https://etc-wmge.vito.be/sites/etc-wmge.vito.be/files/ETC- working-paper-material-resource-taxation_final.pdf Summarised on the ESPP Newsletter 118 January 2016.*

FIGURE 15. Identifying actions to improve Nutrient Management



(Source: Sutton et al 2013, "Our Nutrient World")

TABLE 14. Key actions and actors to improve nutrient management

	Key Action	Principal actors
1.	Improve nutrient use efficiency in crop production	Crop farmers
2.	Improve nutrient use efficiency in animal production	Livestock **farmers**
3.	Increase the fertiliser equivalence of animal manure	Livestock **farmers** + new manure processors, **NRR sector**
4.	Low-emission combustion and energy efficient systems	Technologists in transport and energy sector
5.	Development of NOx capture and utilization technology	Technologists in energy sector
6.	Improve nutrient efficiency in fertiliser and food supply reducing food waste	Fertiliser and food industry and waste processors, **NRR sector**
7.	Recycling nitrogen and phosphorus from waste water systems, animal waste and municipal waste.	Water treatment industry, waste processors, municipalities & farmers
8.	Energy and transport savings	Energy and transport sectors
9.	Lowering personal consumption of animal protein	All citizens
10.	Spatial and temporal optimization of nutrient flows	Food & feed industries and livestock farmers, **NRR sector**

(Based on Sutton et al 2013)

There is no escaping the fact that the gross scale of the nutrient flows – and the damaging effects of the associated leakages – will ultimately only be reduced when and if the human population and its nutrient demand contracts. This is not likely to be achieved this century. One of the strongest imperatives in any society is that the population has access to food, and preferably at affordable prices without the pressure of food price inflation. The forces driving growth in demand for nutrients to feed the human population are the growth of the population, income levels, dietary preferences and changing dietary habits. Most regions do not have overt population policies although public hygiene and health services and migration control policies have strong influence on the net increase or fall in population. It is policy everywhere to increase material living standards through economic growth. Thus nutrient demand will grow worldwide, although less so in the EU.

As discussed in Chapter 3, livestock production is an intrinsically less efficient form of agriculture as demonstrated by nutrient use efficiency. Efficiency varies considerably between species and systems. Nitrogen losses per unit of food protein from beef are more than 25 times those of cereals, and 3.5 to 8 times higher than cereals for pig, poultry, meat, eggs and dairy. In fact, around 81-87% of the total emissions of ammonia, nitrate and nitrous oxide related to EU agriculture are related to livestock consumption (Westhoek *et al* 2015). The global consumption of meat is forecast to increase 76% on recent levels by mid-century due to a 'protein transition' playing out across the developing world as the consumption of meat increases alongside rising incomes (Wellesley *et al* 2015) and whilst meat consumption is not expected to increase in Europe (and may in fact decline due reasons of health awareness and cost), per capita demand for meat has reached a plateau, but at levels considered excessive by nutritionists. The WHO estimates that current average per capita protein intake in the EU exceeds by 70% the recommended dietary intake (Westhoek *et al* 2015).

So the policy levers which may have the most potential to reduce global nutrient flows may be those that seek to influence dietary and lifestyle choices, especially livestock product consumption. To date most governments have not entered this field to any significant extent, even though the evidence of the health consequences of excessive levels of meat consumption and the cost to society continue to mount (Bouvard *et al* 2015). Governments shy away from addressing the direct consumption habits of their populations perhaps assuming it to be a too politically sensitive or too difficult practically. A recent study by Chatham House (Wellesley *et al* 2015) challenges this government assumption. Indeed, the results of focus groups across four major meat producing countries showed that public disengagement with the diet-climate relationship suggest it is not the result of active resistance, but rather it is the product of a lack of awareness sustained through government inaction. They argue that if governments were to signal the urgent need for change and to initiate public debate on the need for dietary change, the disengagement would likely dissipate. They therefore urge governments to develop policies that encompass a range of measures, from soft measures such as awareness raising to encourage behavioural change and adjustments in public procurement standards to more interventionist measures, such as taxation and subsidy reform (Wellesley *et al* 2015). Evidently the biggest impact of such measures will be in countries where the demand for animal protein is growing the most, but even in Europe, there is a long way to go before diets even approach the WHO recommended daily intake.

A special report by the European Nitrogen Assessment (Westhoek *et al* 2015) shows exactly why efforts should be made to reduce meat consumption globally, even if by only a limited margin. The study looked into the effects of a number of alternative diets with an on average 50% reduction of meat and dairy consumption and the effect that these changes would have on nitrogen losses from EU agriculture, as well as GHG emissions, land use and human health. In the first diet change scenario, they looked at a reduction in pig meat, poultry meat and eggs, in another a reduction in beef and dairy and finally in the third a reduction in all types of livestock products. The modelling showed that a reduction in the consumption of these livestock products by up to 50% could reduce current reactive nitrogen emissions by as much as between 37% and 42%. This clearly emphasises that the biggest impact on nutrient overloads will come from consumption change.

The purpose of this section is to be clear about to which of the general goals and concerns about nutrient flows nutrient recovery and reuse can contribute. The critical point about nutrient recovery and reuse is that every tonne of recovered and reused N and P offers the following benefits[101]:

- Less water and atmospheric pollution, because the N and P in one of the waste streams has been captured and is thus prevented from leaking[102].
- Less depletion of finite reserves (P) and use of the fossil fuel natural gas (N) contributing to GHG emissions.
- Reduction in environmental pollution associated with the mining, processing and transport of phosphorus and the manufacture of nitrogenous fertilisers.
- Diversification of nutrient supply thereby reducing reliance on imported phosphate rock and natural gas.
- Deferment of approach towards any natural limit imposed by finite phosphate rock.

Note that although nutrients are injected into the EU food chain through manufactured nitrogenous and phosphorus fertilisers and through imported animal feed, the reuse of recovered nutrient will only potentially dis-

[101] *The effective substitution of mined and manufactured N and P by recovered nutrients will also depend on the form in which they are presented and their plant availability. Therefore, it will be subjected to quality and processing.*

[102] *Life cycle analyses (LCA) are needed to assess the impacts of recovery processes.*

place mineral fertiliser. The ratio of this displacement will depend on the substitutability of the recovered nutrient compared to its mineral counterpart. This is unlikely to be a one to one relationship, it will depend on how well it is taken up and utilised by plants and how efficiently it can be applied. This requires assessment for each specific recovered product.

This study was launched with a preconception that nutrient recovery and reuse were strongly motivated by the need to escape the finiteness of a critical resource (phosphorus) and a switch to circular economy principles. However the most revealing aspect of the recent research on nutrient flows is that a more important driver for NRR is the **avoidance of pollution** by intercepting nutrients which would otherwise escape into the environment. The highest priority message about nutrient use is that its efficiency is low and all effort should be directed to improving it. Nutrient recovery and reuse *per se* cannot change farmers' decisions about fertilizer use and feeding of livestock, neither can it influence citizens decisions about their dietary balance. Whilst it can provide an important contribution to more sustainable nutrient management, it is not the solution.

Nutrient recovery and reuse *per se*, is neutral as far as the goal of providing for the **food needs of the population**. Whether a molecule of reactive nitrogen or phosphorus taken up by a plant root originated from fertiliser manufactured from natural gas or phosphate rock, or from nutrient recovered from manures, processed sewage water or food waste makes not the slightest difference. If more food output is required then more nutrients have to be supplied. What matters is the efficiency of the system which supplies it.

The **viability of agricultural production** also depends critically on the efficiency with which farm inputs are used. It is not in farmers' interests that their soil organic matter continues to decline. Some aspect so NRR can certainly help ameliorate this. Neither is it in farmers' interests that purchased fertiliser or animal feed leaks directly or indirectly into water courses or into the atmosphere. The challenge is to help farmers to avoid this leakage and waste. Farmers' fear is that regulation of fertiliser application or manure management may add costs not recoverable in product prices, or reduce revenue because yields or product quality falls through what they see as insufficient nutrient. Livestock farmers may turn to scale to help contain unit costs, but then run into problems of local over-concentration of production and nutrient surplus in their region. For crop farmers, a critical question about the utility of nutrient recovery and reuse is the substitutability of recovered nutrients with respect to price and quality. For livestock farmers the challenge of utilizing nutrient recovery and reuse is principally about the cost of the novel manure management systems and the help available to invest in them.

It is clear by this point that the main focus of increased nutrient recovery and reuse is to **avoid pollution of air and water** by gathering up the nutrients and recycling them back into agricultural production. This is where the language and mind-set change of the circular economy has its main contribution. By switching from the language of **waste** to be disposed, to resource, or secondary raw material, to be processed and reused offers a way to reduce this pollution. This is the prize sought. According to the calculations in the European Nitrogen Assessment this is a very big prize indeed. Even accepting the wide uncertainties in the methodology and costs imputed, the estimated annual costs to society of the pollution and leakages associated with nutrients was €75 to €485 billion in the EU27 (van Grinsven *et al* 2013), comparable to the GDP of a country like Belgium. The majority of these costs arise from the damage to ecosystems and public health. The externalities appear to be extremely large. None of the actors in the food chain – fertiliser manufacturers, farmers, food processors and consumers, especially livestock product consumers – are paying the full social costs of their activity, i.e. private costs plus the external costs to the environment.

Rectifying these distortions need not necessarily add to production costs in the food chain. Surveys of the technical and economic performance of farm business units show that there is a wide disparity of efficiency between the best and worst performers. Narrowing the gap in performance of fertiliser and feed use efficiency offers the possibility to improve farm financial performance as well as reduce the unwanted side effects of excess nutrients. This is not a new message and much extension work in agriculture for decades has been devoted to achieving this goal. However, even if efforts to drive increased nutrient recovery and reuse were to result in higher costs of fertiliser and feeds this could be associated with lower social costs as the externalities are reduced, and it would also send the desirable signal to economise further on these inputs. Besides, in the absence of curtailing wasteful use, all the while demand for human nutrients continues to grow the scarcity of mined nutrient and the costs of manufactured nutrients will be driven up anyway. It is preferable to pay the higher costs to reduce the unwanted side effects, than to simply add to the scale of pollution.

An upscaling in nutrient recovery and reuse would also make a significant contribution to reducing the costs associated with food chain waste. The creation of a strong market trading in products derived from these waste streams would convert them into valued secondary resource, rather than unwanted cost. In addition, the recovery of nutrients from these waste steams would help to limit the amount of nutrients being 'lost' and thereby contributing to environmental pollution. Of course, the primary goal should be to reduce waste, particularly food waste which is estimated to be a massive 30% of all food that is being produced but the very nature of food production and biological processes means that some waste will always be inevitable and therefore nutrient recovery and reuse will play an essential role in the waste management hierarchy of the circular economy.

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ANNEX I

Nitrogen transformations in soil

These transformations/processes can be grouped depending on whether they increase or decrease the concentration of reactive nitrogen compounds in soils. Since plants take up nitrogen from soils in the form of ammonium (NH_4^+) and nitrate (NO_3^-), processes that increase the presence of these compounds will be beneficial for plant growth. These processes are nitrogen fixation, mineralisation and nitrification:

- **Nitrogen fixation**. nitrogen fixation occurs when atmospheric nitrogen is converted to ammonia (NH_3) by nitrogen fixing bacteria.
- **Mineralisation** implies the conversion of an organic substance into an inorganic substance. In the case of nitrogen, an organic compound will be transformed into ammonium (NH_4^+). This is done by soil microorganisms and their activity will be favoured in well-aerated and warm soils when organic compounds with low carbon: nitrogen ratios are present.
- **Nitrification** is the name given to the conversion of ammonium or ammonia into nitrate through an oxidation by soil bacteria which obtain energy from the ammonium ions. In a first step, ammonium is converted to nitrite by bacteria called nitrosomonas. Immediately following this first step, another group of bacteria called nitrobacter convert nitrite into nitrate. This process benefits from warm, moist and well-aerated soils and leads to soil acidification due to the resulting free H^+ ions. Irrigation of dry soils or rapid soil aeration by tillage can enhance nitrification.

On the other hand, processes that decrease the availability of reactive nitrogen in soils are plant uptake, leaching, volatilisation, immobilisation and denitrification:

- **Plant uptake (nitrogen assimilation)**. (NO_3^-,NH_4^+) takes place in the roots through specific transporters which lead the ions into the shoot where nitrate is reduced to ammonia and dissolved ammonia converted to amino acids. Nitrate reduction to ammonia produces a negatively charged OH^- ion. To maintain the balance, the plant must excrete the OH^- ion (changing the pH of the area surrounding the roots) or uptake a positively charged ion (such as potassium, sodium or magnesium).
- **Leaching** is the main pathway of nitrate loss in soils. It relies on available soil water and a soil pore structure that allows the water to escape. Its rate depends on soil properties and rainfall. This is a physical process. Ammonium cations (NH_4^+) are adsorbed to the negatively charged soil colloids and do not leach from soils.
- **Volatilisation**. Ammonium can be converted to ammonia during the breakdown of organic materials. Dissolved ammonium and ammonia gas are found in equilibrium in soils following: $NH_4^+ + OH^- \rightarrow NH_3\uparrow + H_2O$. When ammonium is added into the soil or soil conditions (such as high pH) favour the conversion of ammonium into ammonia, ammonia gas will be released.
- **Immobilisation** is the reverse process of mineralisation. It can take place both through biological and abiotic (non-biological) processes. The decomposition of organic residues with a high C:N ratio requires microorganisms to use nitrate and ammonium as nitrogen sources. This nitrogen, then, is incorporated into the microorganisms and only becomes available once the microorganisms die. On the other hand, abiotic immobilisation is thought to play an important role in soils but the rates and mechanisms behind it are still not well understood.
- **Denitrification** is the reverse of nitrification, and is performed by anaerobic bacteria. In poorly drained soils, these bacteria will convert nitrate into nitrite and finally to nitrogen gas as follows: $2NO_3^-$ $2NO_2^-$ $2NO$ N_2O N_2. Denitrification requires very low oxygen rates in soils. Under fluctuating oxygen concentrations, changing pH and soil temperature, nitric oxide gas and nitrous oxide gas, a potent greenhouse gas, can also be released.

(Source: Brady and Weil 2010)

ANNEX II

TABLE A1. Overview and description of nutrient recovery processes and their current implementation status in the EU

Process	Description of the process, substrates and products
• **Ammonia stripping/ Scrubbing** OPERATING	**Process description** Ammonia stripping is an environmental engineering technology, used to convert ammonium-ions (NH_4^+) present in a liquid waste stream into ammonia gas (NH_3). The reaction is performed in an alkaline medium to increase ammonia recovery. Once the ammonium ions have been turned into ammonia gas, that gas can either be used as such, or it can be captured (or absorbed) again into a liquid stream, by means of an acid (usually H_2SO_4 or HNO_3) obtaining an inorganic salt solution *Simple and well established process, does not remove organic nitrogen*
	Typical substrate Waste water (liquid), emissions from manure drying or from stables (gas)
	Output products Ammonia water or salt solution (NH_4SO_4; NH_4NO_3)
• **Anaerobic Digestion** OPERATING	**Process description** Process of controlled decomposition of biodegradable materials under managed conditions, predominantly anaerobic and at temperatures suitable for mesophilic or thermophilic bacteria (JRC 2014) *Biogas produced, homogeneous product obtained, kills pathogens*
	Typical substrate Manure, organic wastes, slaughterhouse waste, sewage sludge
	Output products Digestate with a fertiliser effect (NPK) or soil improver and biogas
• **Composting** OPERATING	**Process description** Process of controlled decomposition of biodegradable materials under managed conditions, which are predominantly aerobic and which allow the development of temperatures suitable for thermophilic bacteria as a result of biologically produced heat (JRC 2014) *Contributes to soil organic matter; part of N lost as ammonia gas; low nutrient concentration; kills weeds and pathogens*
	Typical substrate Manure, organic (or bio)-waste, sewage sludge, digestate from various sources
	Output products Compost which helps soil organic matter Considered a soil improver. Low supply of plant available nitrogen. 40% compost from green and bio-waste used in agriculture
• **Drying and pelletising** OPERATING	**Process description** Compressing and shaping the dried substrate material into a pellet. Drying can be achieved using a range of techniques (e.g. conveyor belt, centrifuge, rotary drum) or using heat coming from electricity production from gas/biogas. *Large volume reduction, easy and safe packaging and transport; suitable for organic farming, high carbon content, can be combined with mineral fertilisers to create customised products*
	Typical substrate Solid manure
	Output products Fertiliser, organic soil amendmen

Process	Description of the process, substrates and products
• **Extraction from ashes following incineration**	**Process description**
	Use of acids to convert ashes into mineral fertilizers or convert ash P into its pure elemental form using a thermochemical process (Sommer *et al.* 2013)
	Very high P extraction efficiency, highly pure P obtained, end of pipe process
PILOT	**Typical substrate**
	Dewatered sludge, slaughterhouse waste
	Output products
	Mineral fertilizer, phosphoric acid, elemental P
• **Incineration or thermal treatment**	**Process description**
	Thermal treatment of wastes with or without recovery of the combustion heat generated (2000/76/EC). The process produces ash residuals (Sommer *et al.* 2013)
OPERATING	*Large volume reduction, kills pathogens, nitrogen is lost but it concentrates P and K in the ashes*
	Typical substrate
	Solid/dried manure, organic (or bio)-waste
	Output products
	Ashes. Fertilizer effect/direct application on acidic soils (ashes)
	Soil improver (biochar)
• **Precipitation/ crystallisation**	**Process description**
	P is removed from a wet/liquid substrate as a precipitate by forming a bond with a metal salt of aluminum, iron, calcium or magnesium
OPERATING	*Allows for P extraction during the sewage treatment process with large benefits for plant operation,*
	Typical substrate
	Wet sludge, digested manure
	Output products
	Struvite, mineral fertilisers
• **Ultrafiltration/ Reverse osmosis**	**Process description**
	A nutrient concentrate is obtained by applying pressure on a liquid and pushing it through a semiperme-able membrane
	Typical substrate
PILOT/OPERATING	Wastewater, slurry
	Output products
	Mineral concentrates, mineral fertilisers

ANNEX III

TABLE A2. Phosphorus recovery routes from manure, sewage sludge and ashes

Recovery from sewage sludge or sludge water	Operational status and comments
Struvite precipitation from sludge liquor stream or sidestream or industry waste-waters with high P content, before or after anaerobic digestion and/or dewatering: e.g. NuReSys, Pearl/Ostara, AirPrex, Phospaq, Naskeo, Struvia/Véolia …	Only viable in sewage works operating enhanced biological phosphorus removal (EBPR). Around 20 full scale units operational today worldwide
P-recovery from sewage sludge by acid leaching, high temperature or high pressure processes, e.g. Gifhorn/Seaborne, Stuttgart, Phoxnan/Loprox	Pilot scale units tested
Budenheim process: no heating CO2 extraction of P from sewage sludge	1 m^3 pilot plant underway, Mainz sewage works
High temperature furnace processes to convert sewage sludge or its ash into phosphate slag, e.g. Kubota, Mephrec	Pilots have been operated. P-REX studies suggests that product may not be useful (P is not plant available)
Ion exchange systems and adsorbent/release systems	Lab scale
Adsorption onto biological materials or mineral (e.g. calcium silicates, shellfish waste, biochars, orange peel, straw ..) which can then be used as a nutrient enriched soil amendment	Many tests show feasibility. Some processes implemented full scale. Effective reuse of the P-loaded adsorbent material is not always the case.
Microbial fuel cells, including for P-recovery from iron phosphates	Experimental scale. Pilot trails planned, e.g. HES-CO Switzerland 2017
Recovery from sewage sludge ash	**Operational status and comments**
Use of P-containing ashes (sewage sludge incineration ash, meat and bone meal ash) as an ingredient in fertiliser production	Industrial scale testing underway at ICL, Timac, Compo, Borealis, Fertiberia …
P-recovery from sewage sludge incineration ash using acid / alkali / temperature processes, e.g. Leachphos, Outotec/AshDec, TetraPhos, Recophos Germany	Kanton of Zurich announced 5 M CHF pilot project 18/2/2016
Recophos thermal: electrical induction heated reduction to generate elemental phosphorus (P4) from sewage sludge or sludge incineration ash	10 kg/h pilot tested Austria 2015
Ecophos: hydrochloric acid treatment of sewage sludge incineration ash to produce industrial phosphates, plus a smaller unit planned in Bulgaria	60 000 tonnes/yr ash input factory under construction Dunkerque, France (starting from 2018)
Use without chemical modification or extraction	
Use of sewage or sewage sludge or manures to feed biomass production: algae, willow trees, …	Biomass produced can be processed to extract nutrients or other materials, used as a green fertiliser, used for energy, as fish food
Processing sewage sludge or manure to produce organic fertilisers (dry, pelletise, add other nutrients to balance specific crop needs)	Full scale operational for manures, usually after anaerobic digestion (e.g. COOPERL, Fertikal) = thousands of tonnes per year. Tested for sewage sludge (End-o-Sludg project).
Use in agriculture. Faces pressure because of concerns about contaminants, as well as space and transport challenges.	40% of European sewage sludge is used in agriculture, generally after treatments such as liming, anaerobic digestion, composting
Manure	**Operational status and comments**
Use in agriculture In areas of intensive livestock production, agricultural use of manure is increasingly under pressure and limited because of environmental constraints	A large proportion of EU manure is recycled to land, either directly (animals in field) or (from stables) after storage and stabilisation by mechanical spreading. Issues with N and volatile C loss during storage, transport, spreading
Struvite precipitation can also be operated on manure, but it is generally necessary to first solubilise phosphorus, e.g. swine manure QuickWash/Renewable Nutrients USA, USDA/TerraBleu USA, calf manure Putten NL (K-struvite)	A number of organisations have pilot scale tests in Europe.
Burning animal by-products meat and bone meal to produce a phosphorus fertiliser	E.g. SARIA (Fluid-Phos), producing 12 000 t/yr of fertiliser
Processing of chicken manure incineration ash (after energy valorisation) to produce a P-K fertiliser	Operating full scale at a number of sites.

(Source: Information provided by ESPP and P-REX).

THANK YOU

In addition to the invaluable comments and advice given to RISE on this report by the Report Advisory Group, named below, we would also like to thank the following people for their commentary during the projects evolution, and presentations and engagement in the RISE workshops on Nutrient Recovery and Reuse which helped shape the development of this piece of work.

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