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Do improved pastures enhance soil quality of cork oak woodlands in the Alentejo region (Portugal)?

A. R. Rodrigues · F. Costa e Silva · A. C. Correia · M. C. Bicho · M. Madeira · J. Coutinho

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Abstract Portuguese forest sustainability is currently threatened by forecasted climate changes and inappropriate management practices. Specifically, large cork oak woodland areas (*montados*) are subjected to soil degradation and tree recruitment impeachment. A study was developed to compare soil properties in cork oak woodlands with improved pastures (IP) grazed by cattle and natural understorey management (NU) without grazing. The IP system did not lead to soil organic C concentration increase, soil organic C stock being 0.7 kg m^{-2} lower in the upper 30 cm soil layer, compared to the NU system. Under the IP management, soil N content was 39.7 g m^{-2} higher up to 30 cm depth, and N mineralization potential was increased by 50% in the 10 cm top soil layer. Soil bulk density and C mineralization potential were similar in both systems. Sowing legume-rich pastures can result in an immediate soil quality improvement, especially regarding N availability, although grazing may hamper tree recruitment. Managing the natural understorey appears suitable for soil organic C maintenance, and also allows tree recruitment, while soil N availability limitation could be overcome by fertilizer applications.

Keywords Nitrogen · Management system · Organic carbon · Bulk density · Soil fertility

A. R. Rodrigues (✉) · F. Costa e Silva ·
A. C. Correia · M. C. Bicho · M. Madeira
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa,
1349-017 Tapada da Ajuda, Lisboa, Portugal
e-mail: arfelizardo@isa.ulisboa.pt

F. Costa e Silva
Instituto Nacional de Investigação Agrária e Veterinária I. P, Quinta do Marquês, Av. da República,
2780-159 Oeiras, Portugal

J. Coutinho
Departamento de Biologia e Ambiente, Escola de Ciências da Vida e Ambiente, Universidade de Trás-os-Montes e Alto Douro, 5000-911 Vila Real, Portugal

Introduction

Evergreen oak woodlands (*montado* in Portugal, *dehesa* in Spain) are the most widely spread agroforestry systems in the Iberian Peninsula, occupying more than 3 million hectares (Eichhorn et al. 2006). Oak trees (mainly *Quercus ilex* and *Q. suber* L.) are intercropped with agriculture, pastures or natural shrubs, forming complex and highly variable landscapes. Cork oak woodlands are especially important in Portugal, for their role on the supply of raw material for the cork industry. However, their sustainability is now being questioned, particularly owing to soil degradation, productivity decline and lack of tree natural regeneration (Bugalho et al. 2011; Costa et al. 2014). In this context, the future of *montado* is dependent on management decisions that promote soil restoration and tree recruitment, thus ensuring the system long-term viability (Escribano et al. 2018).

Recent *montado* history is marked by land use intensification, as landowners have followed EU subsidies in an attempt to increase the system profitability (Belo et al. 2014). In the last decades, some areas were converted to permanent pastures and grazing pressure was increased by replacement of traditional pig and sheep herds for cattle (GPP 2018). Sowing improved pastures—selected mixtures of legume and grass species—has become an interesting alternative for enhancing pasture yield and improving soil functions in oak woodlands (Carranca et al. 2015; Gómez-Rey et al. 2012; Hernández-Esteban et al. 2018). Their potential for soil organic carbon (C) accumulation has been reported (Teixeira et al. 2015), and since 2009 the Portuguese Carbon Fund granted financial support for this management option, and therefore an increase in national sown pasture area occurred (APA 2017). Nevertheless, information regarding the effect of improved pastures establishment on *montado* agroecosystems is scarce (Gómez-Rey et al. 2012; Hernandéz-Esteban et al. 2018; Rodrigues et al. 2015).

Grazing can enhance soil nutrient cycling and accumulation (Bilotta et al. 2007), but excessive animal trampling can also damage soil structure by compaction. Also, animal excessive feeding might limit the growth of trees and shrubs, which may seriously threaten tree recruitment and drive losses of soil fertility (Dahlgren et al. 1997; López-Sánchez et al. 2014).

Montado areas are often colonized by naturally occurring shrub species, which can enhance standing biomass (Correia et al. 2014), increase soil organic C sequestration and fertility (Gómez-Rey et al. 2013), while soil N changes may depend on shrub species (Moreno and Obrador 2007; Simões et al. 2009). Also, shrub cover has been associated with successful tree recruitment (Dias et al. 2016; Simões et al. 2016), while warranting feed diversity for grazers and increasing natural biodiversity conservation potential (Moreno and Pulido 2009). As the excessive accumulation of shrub biomass may increase fire risks and compete with trees for water and nutrients (Caldeira et al. 2015), periodical shrub cutting is recommended, and practices ensuring minimum soil disturbance are financially supported by the Portuguese government (APA 2017).

In the light of global climate change scenarios forecasted for the Mediterranean region (IPCC 2015), management systems that ensure *montado* resilience and long-term sustainability should be developed. Such systems must improve soil functions, which can be assessed by measuring physical, chemical and biochemical soil properties—the so called soil quality indicators (Pulido et al. 2017). Understanding how different management systems are affecting soil properties of cork oak woodlands is essential to ensure permanent tree recruitment and cork productivity, that is, to address their long-term sustainability.

In this context, soil physical, chemical and biological properties were evaluated, regarding accumulation and mineralization of soil organic C and N, and soil fertility development. For that, two representative cork oak woodland areas were examined, one with natural understorey and absence of grazing and another with an improved pasture grazed by cattle. The authors hypothesized that improved pasture management would result in soil organic C build-up and higher soil nutrient availability. Therefore, results will provide useful information for land managers and policy-makers endeavouring proper management systems aiming the sustainability of cork oak woodlands.

Materials and methods

Study area

The study was conducted at *Herdade da Machoqueira do Grou*, Coruche county, Southern Portugal (39°08′18.29″N, 8°19′57.68″W), in a pure cork oak (*Quercus suber* L.) stand representative of the largest cork oak woodland area in Portugal. The climate is Mediterranean, with hot and dry summers and mild wet winters. Mean annual rainfall (1980–2002) is 685 mm, and mean annual air temperature (1960–1989) is 15.2 °C (SNIRH 2017). Landscape is made of Pliocenic and Mio-Pliocenic formations (Zbyszewski 1953), topography being mostly gently undulating (slope gradient: 6–8%; SROA 1965). Soils are developed on sandstones, and classified as Dystric Arenosols associated with Dystric Regosols (IUSS 2015); they are coarse textured (clay less than 60 g kg^{-1}), strongly to moderately acidic, with low nutrient status.

The pure cork oak stand was installed in 1965, with approximate density of 177 trees per hectare, and canopy cover reaching 30–60%. In 1992, it was divided in two areas (estates) with different management regimes: one area was converted into a permanent natural pasture for extensive cattle grazing, while the other was kept ungrazed with its natural understorey vegetation, comprising an herbaceous layer and shrubs, mainly *Cistus* sp., *Lavandula stoechas* L. and *Ulex* sp.

In August 2009, the grazed area was tilled with a disking harrow followed by mechanical spreading of 500 kg ha^{-1} of dolomitic limestone (20% MgO, 65% CaO) and 500 kg ha^{-1} of phosphate fertilizer (18% P_2O_5, 10% CaO, 27% SO_3). A pasture mixture (IP; *Trifolium* spp., *Ornithopus* spp. and *Biserrula pelecinus* L.) was then broadcast seeded, and a roller was used to level soil surface and warrant seed cover. The area has been ever since grazed by about 1.4 cows per hectare for 1 month every year (0.1 LU ha^{-1} year^{-1}), at the end of spring, which ensures the control of natural shrub species.

In the natural understorey vegetation area (NU), management is exclusively oriented for cork production, and no fertilizers were applied. The shrub growth is controlled with a rotary mower every 4–6 years, the last control being carried out in February 2014. Seedling protection is ensured by adjusting the cutting height to its maximum distance to the soil surface, and sapling damage is prevented by postponing the control of shrub patches where they occur.

Vegetation measurements

Standing herbaceous vegetation biomass and soil litter layer mass have been evaluated since 2009 in late spring (end of May). A total of 14 points, seven in each experimental area, were marked along four south-north transects (spaced 50 m). Two 0.4 × 0.4 m samples were randomly taken around each point. Samples of herbaceous vegetation and soil surface-litter were dried (24 h at 65 °C) and weighed. The three main botanical groups in herbaceous biomass—grasses, legumes and forbs—were treated separately. In 2011, biomass and coverage of the main shrub species (*Cistus salviifolius* L., *C. crispus* L. and *Ulex airensis* Esp. Santo, Cubas, Lousã, C. Pardo & J. C. Costa) were quantified in the NU area. Above-ground biomass of shrubs was collected inside four 30 m^2 randomly selected plots, samples being oven dried and weighed (Correia et al. 2014). Tree litter fall (leaves, branches, flowers and fruits) was collected monthly, from 2011 to 2016, in 16 littertraps (0.5 m^2) distributed in two transects in the NU experimental site. Given the similar tree density, age and dendrometric traits at NU and IP, estimates were considered representative of both study systems.

Soil sampling

Sampling took place between 2014 and 2017 in IP and NU adjacent areas. The two areas were comparable in terms of soil fertility until 1992, as they were subjected to similar management and located on the same geology, soil type and topography. To alleviate possible pseudo replication problems (Stamps and Linit 1999), in each management system an area of 200 × 100 m was delimitated, 15 m from the boundary, and within it 20 sampling plots (20 × 20 m) were established, considering a grid of 5 × 5 m cells in each (Fig. 1). Given the high tree density in study areas, sampling plots were randomly selected.

Five sampling plots were randomly selected in each study area for soil bulk density assessment. In each plot, three grid cells were randomly selected, and undisturbed soil samples were collected in their centre at 0–10, 10–20 and 20–30 cm depth, by carving metal cylinders (ca. 368.8 cm^3) into each soil layer. Soil

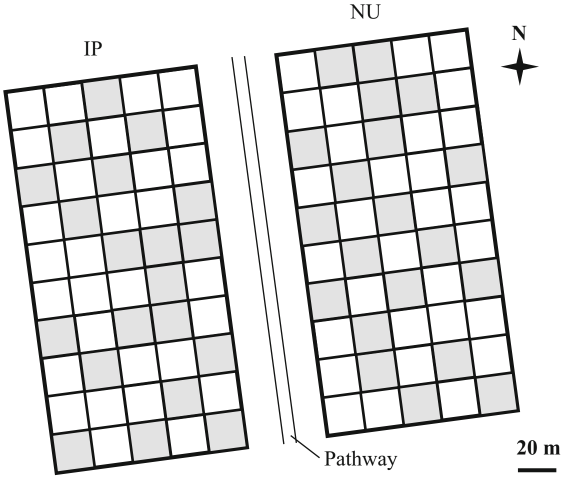

Fig. 1 Sampling plot distribution at the improved pasture (IP) and natural understory (NU) systems in *Herdade da Machoqueira do Grou*

cores were trimmed to the exact cylinder volume and transferred to plastic bags.

In each system, disturbed soil samples were collected for soil fertility assessment in six randomly selected plots. Samples were taken with an auger in the centre of five grid cells (randomly selected) from each sampling plot, at 0–10, 10–20 and 20–30 cm depth. A total of 30 samples were taken per each soil depth and study area. Soil was sampled up to 30 cm soil depth, in conformity with international standards for soil organic C stock calculation (FAO 2017).

For assessing soil organic C and N mineralization, six sampling plots were randomly selected per management system. In the centre of four randomly selected cell grids at each sampling plot, soil cores were taken with an auger from the top 10 cm layer; samples were combined two by two, resulting in two composite samples per plot, and a total of 12 composite samples for each study system.

Laboratory procedures

Soil bulk density

Samples were oven-dried at 40 °C for a week, and then 10 g subsamples were placed overnight at 105 °C to allow dry weight calculations. Soil bulk density was determined as the ratio between sample dry weight and cylinder volume (Blake and Hartge 1986).

Soil fertility

Samples were air dried and then passed through a 2 mm sieve. Analyses were carried out on the $<$ 2 mm soil fraction. Soil pH was determined with a potentiometer (Metrohm 632) in soil suspensions in distilled water and 1 M KCl (1:2.5) after 1 h of intermittent shaking. Soil total organic C concentration was determined by the potassium dichromate oxidation following De Leenheer and Van Hove (1958). Particulate C fraction was separated by wet sieving soil samples at 53 µm, respective organic C concentration being determined as above. Total N was determined by the Kjeldahl procedure, using a Kjeltec digestion and distillation apparatus and a separated automated titration device. C and N stocks were calculated using soil bulk density and rock fragments correction (Poeplau et al. 2017). Non-acid exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were extracted with 1 M ammonium acetate solution (pH 7 adjusted) and determined by atomic absorption spectroscopy (AAS). Exchangeable Al^{3+} was extracted with 1 M KCl solution (Barnhisel and Bertsch 1982) and determined by AAS. Extractable K and P were evaluated by the Egnér-Riehm (1958) test and determined by AAS and UV–visible spectroscopy, respectively. Hot water soluble C and N contents, as indicators of soil microorganism preferential substrates and product availability (Haynes 2000), were determined by suspending soil in distilled water (1:5) at approximately 85 °C for 1 h (Khanna et al. 2001). Total dissolved organic C and N were determined in the resultant water extracts by using an automated segmented flow analyser (Houba et al. 1994).

Soil biochemical indicators

Samples were sieved and the $<$ 2 mm soil fraction was kept refrigerated (about 4 °C) in closed plastic bags to keep field moisture and restrain biologic activity. Six subsamples were used in the fumigation-extraction procedure (Vance et al. 1987): three replicates were immediately extracted with 50 mL of 0.5 M K_2SO_4 solution, while remaining three were first chloroform fumigated for 24 h. Additionally, soil subsamples (50 g) were rewetted at approximately 60% of their water field capacity and placed in hermetic glass containers along with 0.5 M NaOH solution. Containers were incubated in the dark at 25 °C for 120 days. Trapping solutions were changed at days 1, 2, 3, 4, 7, 15, 28, 56 and 119, and dissolved CO_2 has been precipitated with 0.5 M Ba_2Cl, the excess NaOH being titrated with 0.5 M HCl. Soil C potential mineralization was assessed by calculating the total amount of respired CO_2-C per initial soil organic C unit. Metabolic coefficient (qCO_2) was calculated as the CO_2–C respired at the seventh day of incubation per initial microbial biomass C unit. Approximately 1000 g soil samples (n = 12) were incubated in the dark at 25 °C and 60% water field capacity inside plastic bags, for 16 weeks. Soil subsamples were taken (days 0, 7, 14, 28, 42, 56, 70, 84, 98 and 112) and extracted with a 2 M KCl solution. Extracts were used for NO_3^-–N and NH_4^+–N determination in an automated segmented flow analyser (Houba et al. 1994). Net N mineralization potentials were calculated as final net mineralized N per initial total N.

Statistical analyses

Differences between the two study systems (IP and NU), for the determined soil properties at each depth were assessed by Student's *t* tests whenever population's normal distribution (Shapiro–Wilk test) and homogeneity of variances (Levene's test) were proven or achieved by logarithmic or arcsin transformations (only for 0–10 cm depth hot water soluble C proportion). For non-parametric variables, the Kruskal–Wallis test was used. Statistical analyses were conducted in R software (R Core Team 2014).

Results

Vegetation

Standing biomass of herbaceous vegetation in the IP system was about 1.6 times higher than that in the NU (Fig. 2). Legumes were the least represented botanical family for both systems, although their biomass was, on average, three times higher in the IP (0.12 Mg ha^{-1}) than in NU (0.04 Mg ha^{-1}) (data not shown). Grasses were the predominant botanical group, representing about 42 and 46% of total herbs in the IP and NU, respectively. An average of 3.9 Mg ha^{-1} year^{-1} tree litter fall was estimated. The mass of the soil surface litter was similar in both systems. The aboveground biomass of 3-year old shrubs in the NU accounted for 1.59 Mg ha^{-1}.

Soil bulk density, organic C and total N

Soil bulk density values did not show significant differences between the study systems at any depth (Table 1). Soil organic C concentrations and amounts did not differ between management systems up to 30 cm soil depth. Total N concentrations in the 0–10 and 10–20 cm soil layers were significantly higher in the IP (0.91 and 0.41 g kg^{-1}, respectively) than in NU (0.65 and 0.30 g kg^{-1}, respectively). A similar trend was observed for the total N amount, with the IP soil containing about 1.4 times that of NU, in the 0–10 cm soil layer. Soil C:N ratio was significantly lower in the IP system, up to 30 cm depth.

Particulate organic matter and hot water soluble C and N

Particulate organic matter C concentration and relative proportion to total organic C did not differ significantly between NU and IP (Table 2). Hot water soluble C concentration in the 0–10 and 10–20 cm soil layers was significantly higher in the IP (0.63 and 0.34 g kg^{-1}, respectively) than NU (0.48 and 0.24 g kg^{-1}, respectively). HWS-C proportion of total organic C in the 0–10 and 10–20 cm soil layers was

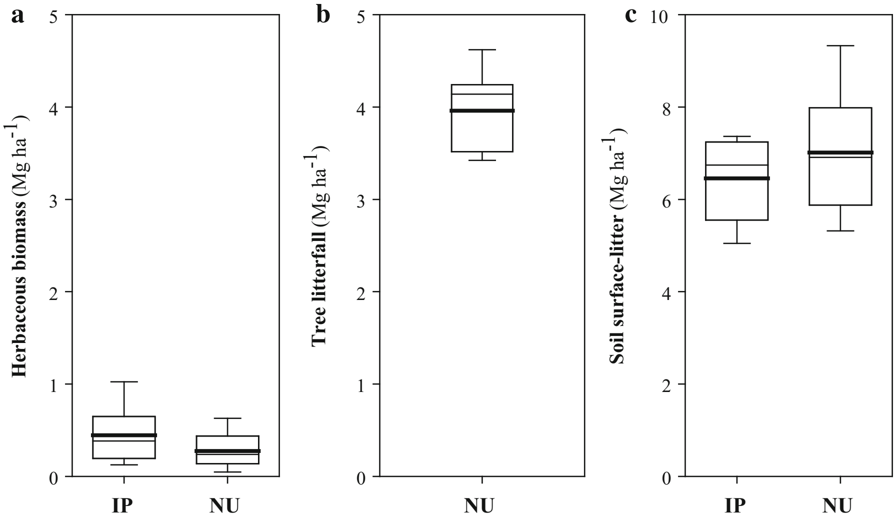

Fig. 2 Boxplot statistics for **a** herbaceous biomass and **c** soil surface-litter in late spring, during the 2009–2017 period (except 2010), for improved pasture (IP) and natural understorey (NU) systems; and **b** yearly tree litter fall for the 2011–2016 period in the NU. Mean values are represented with thick lines

Table 1 Soil bulk density, soil organic C and N concentration and amounts in the 5-year old improved pasture (IP) and natural understorey (NU)

Depth (cm)	System	Bulk density (g $cm^{-3)}$	Organic C (g kg^{-1})	Total N (g kg^{-1})	C:N	Organic C (kg $m^{-2)}$	Total N (g m^{-2})
0–10	IP	1.18 ± 0.02	17.5 ± 1.07	0.91 ± 0.05	19.5 ± 1.23	1.6 ± 0.10	84.8 ± 5.1
	NU	1.18 ± 0.03	21.4 ± 2.43	0.65 ± 0.06	32.6 ± 1.32	1.85 ± 0.14	61.9 ± 6.1
		n.s.	n.s.	***	***	n.s.	***
10–20	IP	1.27 ± 0.03	7.5 ± 0.39	0.41 ± 0.02	18.9 ± 0.87	0.7 ± 0.04	41.0 ± 2.4
	NU	1.26 ± 0.03	9.0 ± 0.66	0.30 ± 0.02	30.0 ± 1.51	0.9 ± 0.07	30.6 ± 1.8
		n.s.	n.s.	***	***	n.s.	***
20–30	IP	1.34 ± 0.02	5.1 ± 0.45	0.30 ± 0.02	17.3 ± 0.82	0.5 ± 0.05	31.0 ± 2.5
	NU	1.31 ± 0.01	6.0 ± 0.42	0.24 ± 0.02	27.3 ± 1.91	0.6 ± 0.04	24.6 ± 1.8
		n.s.	n.s.	*	***	n.s.	*

Mean ± standard error (n = 30) and statistical significance: n.s. $p \geq 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 2 Soil particulate (POM-C) and hot water soluble C (HWS-C) and N (HWS-N) concentrations, and corresponding percentage in relation to total soil organic C (POM-C/C, HWS-C/C) and N (HWS-N/N) in the 5-year old improved pasture (IP) and natural understorey (NU)

Depth (cm)	System	POM-C (g kg^{-1})	HWS-C (g kg^{-1})	HWS-N (g kg^{-1})	POM-C/C (%)	HWS-C/C (%)	HWS-N/N (%)
0–10	IP	8.2 ± 0.80	0.63 ± 0.04	0.08 ± 0.00	44.9 ± 2.08	3.8 ± 0.21	9.6 ± 0.53
	NU	9.6 ± 1.51	0.48 ± 0.06	0.05 ± 0.01	41.6 ± 2.99	2.4 ± 0.21	8.2 ± 0.65
		n.s.	*	***	n.s.	**	n.s.
10–20	IP	2.2 ± 0.24	0.34 ± 0.03	0.03 ± 0.00	27.7 ± 1.73	4.6 ± 0.23	8.6 ± 0.49
	NU	2.2 ± 0.25	0.24 ± 0.02	0.02 ± 0.00	25.1 ± 2.18	2.8 ± 0.16	7.7 ± 0.53
		n.s.	***	***	n.s.	***	n.s.
20–30	IP	1.3 ± 0.15	0.23 ± 0.03	0.02 ± 0.00	25.5 ± 1.23	4.5 ± 0.29	7.0 ± 0.53
	NU	1.6 ± 0.18	0.22 ± 0.03	0.02 ± 0.00	26.8 ± 2.76	4.3 ± 0.79	9.6 ± 1.18
		n.s.	n.s.	n.s.	n.s.	*	n.s.

Mean ± standard error (n = 30) and statistical significance: n.s. $p \geq 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

also significantly higher in the IP than NU (3.8 and 4.6%, 2.4 and 2.8%, respectively).

Hot water soluble N concentration followed the trend of total N, being higher under IP than NU soils, up to 20 cm depth. HWS-N relative proportion to soil total N was not different between management systems.

Carbon mineralization

After 28 days of incubation, soil samples from the IP released significantly more CO_2–C than those from NU, but between the 56 and 120th day this tendency was reversed (Fig. 3). Mean total respired CO_2–C was significantly lower for IP (523.4 mg kg^{-1}) than NU (676.2 mg kg^{-1}) soils.

N mineralization

Soil from IP showed initial higher mineral N (NH_4^{+-} and NO_3^{-}) concentrations than that from NU (Table 3). Net N mineralization and mineralized N per unit of initial soil N were also higher in IP (88.3 mg kg^{-1} soil; and 69.6 mg g N) than NU soils (52.9 mg kg^{-1} soil; and 45.5 mg g^{-1} N).

In IP, net nitrification prevailed over net ammonification, the latter being negative from day 28 until the end of the incubation (Fig. 4). In NU, net

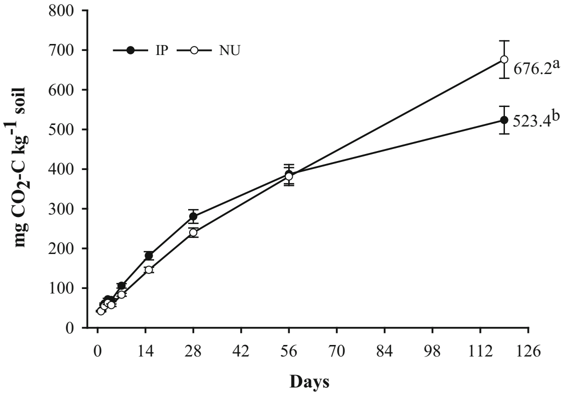

Fig. 3 Accumulated CO_2–C released by soils from the 5-year old improved pasture (IP) and the natural understorey (NU) systems during an incubation period of 120 days. Values at the end of each line are mean mineralized C (n = 12); different superscripted letters indicate significant differences between management systems ($p < 0.05$)

ammonification largely prevailed throughout the incubation period, and net nitrification was significantly lower than in IP. At the end of incubation, net NH_4^+-N concentration was 8.4 times greater in soils from NU than in those from IP system.

Microbial C and N

Soil C mineralization, microbial C and N biomass and respective proportions relative to soil organic C and total N did not show significant differences between the study systems (Table 4). Soils from the NU system showed significantly higher microbial C:N ratio (6.9) and lower metabolic coefficient (2.1 mg g^{-1} h^{-1}) than in those from the IP (5.4, and 3.0 mg g^{-1} h^{-1}, respectively).

Soil fertility

Soil pH in water was significantly higher in the IP system up to 10 cm depth whereas the same was observed for pH in KCl for all soil layers (Table 5). Extractable P concentration in the IP soil was significantly higher, up to 20 cm depth, than in NU, while no significant differences were observed regarding extractable K. IP soils showed higher concentrations of exchangeable Ca^{2+} and Mg^{2+} up to 10 and 20 cm depth, respectively. Exchangeable Al^{3+} concentration in the 0–10 cm soil layer was significantly lower in IP than in NU soils.

Discussion

High tree density at the study area led us to assume homogeneous tree cover for sampling, so our results are more likely to characterize an oak forest stand than a typical open oak woodland (< 80 trees ha^{-1}; Moreno and Pulido 2009). It should not be overlooked that results from the improved pasture are influenced by the overlapping effects of cattle grazing and fertilizer application, being not possible to disentangle the specific effect of pasture sowing.

Soil bulk density in the study areas ranged between 1.18 and 1.34 g cm^{-3}, in the upper 0–10 and 20–30 cm soil layers, respectively. These values are similar to those reported by Gómez-Rey et al. (2012), for long-term natural and improved pastures grazed by sheep, under Mediterranean climate and sandy loam textured soils. Although improved pastures are commonly associated with surface soil porosity enhancement (Haynes and Williams 1993), such a trend was not observed in our study, probably due to the low soil

Table 3 Initial soil mineral N concentrations, net mineralized nitrate- and ammonium-N, and mineralized N per unit of soil N (MN/N), after 112 days of aerobic incubation, in soils from the 5-year old improved pasture (IP) and the natural understorey (NU)

System	Initial mineral N			Net mineralized N			
	NH_4^+–N (mg kg^{-1})	NO_3^-N (mg kg^{-1})	(NH_4^+ + NO_3^-)–N (mg kg^{-1})	NO_3^-N (mg kg^{-1})	NH_4^+–N (mg kg^{-1})	N (mg kg^{-1})	MN/N (mg g^{-1})
IP	6.6 ± 0.43	0.97 ± 0.05	7.6 ± 0.44	93.7 ± 5.82	− 5.4 ± 0.43	88.3 ± 5.94	69.6 ± 2.71
NU	3.9 ± 0.23	0.65 ± 0.02	4.5 ± 0.24	17.7 ± 5.18	45.2 ± 11.9	52.9 ± 10.1	45.5 ± 6.67
	***	***	***	***	***	**	**

Mean ± standard error (n = 12) and statistical significance: n.s. $p \geq 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

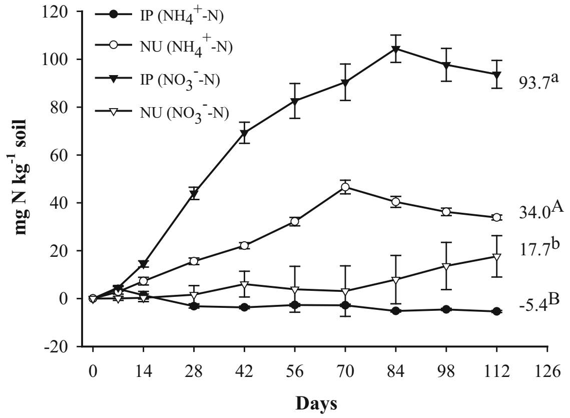

Fig. 4 Evolution of net NH_4^+–N and net NO_3^-–N concentrations in the 5-year old improved pasture (IP) and natural understorey (NU) soils, along 16-week aerobic incubation. Values at the end of each line are mean net mineralized N (n = 12); different superscript letters (uppercase for NH_4^+–N; lowercase for NO_3^-–N) indicate significant differences between management systems ($p < 0.05$)

organic C content. Also, the low stocking rate practiced, with cattle permanence being short and occurring only in late spring, may explain why soil porosity showed no significant modifications in the grazed pasture, as compared to the natural understorey, suggesting the absence of soil compaction risks in the former. In fact, values up to 30 cm depth were below 1.5 g cm^{-3}, the threshold above which root development might be constrained for similar textured soils (Brady and Weil 2017).

Although some studies report that pasture sowing can strongly enhance soil organic carbon accumulation at a short-term (e.g. Teixeira et al. 2015), in the present study a decrease of 0.7 kg organic C m^{-2} (though not statistically different) was estimated for the improved pasture system, compared with the natural understorey upper 30 cm soil layer. This trend may be explained, on one hand, by shrub elimination in the grazed area, which reduces soil organic residue inputs (Simões et al. 2009) and, on the other hand, by soil disturbance at pasture installation (disk harrowing) that might expose physically protected organic substrates, thus enabling their mineralization (Six et al. 2000). Our results are in accordance with those reported by Gómez-Rey et al. (2012) who observed negligible increases in the soil organic C stock up to 20 cm depth (0.18 and 0.84 kg m^{-2}, in open and tree covered areas, respectively) in a 26 years old improved pasture, as compared to a natural pasture with shrub control every 6 years.

Soil organic C stock in the natural understory management was similar to those reported for chestnut orchards growing on loamy soils (Borges et al. 2017), and to those obtained beneath tree crowns in sandy-loam soils under oak woodlands (Gómez-Rey et al. 2012), in Mediterranean conditions. This result highlights the important role of shrubs in the overall system C sequestration in our study site, which was estimated around 17% of total system C annual uptake (Correia et al. 2014). It should also be emphasized that structural heterogeneity introduced by shrubs is linked to several valuable ecosystem services, such as biodiversity conservation and tree recruitment facilitation (Dias et al. 2016; Simões et al. 2016).

Improved pasture system led to a strong decrease of soil C:N ratio (from 33 to 20, in the upper 10 cm layer). Such change suggests important modifications in soil organic matter quality and dynamics, especially regarding N mineralization patterns (Brady and Weil 2017). In fact, the substitution of shrubs with high C:N ratio residues (60–80; Simões et al. 2009) for a homogeneous legume-rich herbaceous cover, with considerably lower C:N ratio (25–30; Carranca et al. 2015), contributed to change soil organic matter

Table 4 Mineralized C per unit of soil organic C (MC/C), microbial biomass C and N contents (C mic, N mic) and corresponding percentages in relation to total organic C (C mic/C) and N (N mic/N), microbial C:N ratio and metabolic coefficient (qCO_2) in the 5-year old improved pasture (IP) and natural understorey (NU)

System	MC/C (mg g^{-1})	C mic (mg kg^{-1})	N mic (mg kg^{-1})	C mic/C[a] (%)	N mic/N[b] (%)	C:N mic	QCO_2 (mg g– h^{-1})
IP	26.0 ± 1.17	172.9 ± 13.6	31.9 ± 2.54	7.6 ± 0.03	25.0 ± 0.07	5.4 ± 0.10	3.0 ± 0.23
NU	30.1 ± 2.36	177.5 ± 12.1	26.1 ± 2.34	7.0 ± 0.02	24.0 ± 0.10	6.9 ± 0.25	2.1 ± 0.13
	n.s.	n.s.	n.s.	n.s.	n.s.	***	**

Mean ± standard error (n = 12) and statistical significance: n.s. $p \geq 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 5 Soil pH, extractable P and K, non-acid exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and extractable Al^{3+} concentrations in the 5-year old improved pasture (IP) and natural understorey (NU)

Depth (cm)	System	PH		P (mg kg^{-1})	K (mg kg^{-1})	Ca^{2+} (cmolc kg^{-1})	Mg^{2+} (cmolc kg^{-1})	Na^{+} (cmolc kg^{-1})	K^{+} (cmolc kg^{-1})	Al^{3+} (cmolc kg^{-1})
		H_2O	KCl							
0–10	IP	5.68 ± 0.07	4.50 ± 0.08	6.8 ± 0.7	41.9 ± 3.2	1.87 ± 0.20	0.43 ± 0.05	0.03 ± 0.00	0.10 ± 0.01	0.14 ± 0.05
	NU	5.23 ± 0.12	3.80 ± 0.07	3.3 ± 0.3	50.9 ± 4.9	0.69 ± 0.06	0.22 ± 0.02	0.05 ± 0.01	0.10 ± 0.01	0.44 ± 0.04
		**	***	***	n.s.	***	***	*	n.s.	***
10–20	IP	5.51 ± 0.05	4.23 ± 0.04	6.0 ± 1.0	29.4 ± 2.0	0.45 ± 0.05	0.17 ± 0.02	0.02 ± 0.00	0.08 ± 0.01	0.48 ± 0.06
	NU	5.33 ± 0.09	3.99 ± 0.04	2.1 ± 0.2	34.2 ± 2.5	0.30 ± 0.03	0.10 ± 0.01	0.04 ± 0.00	0.07 ± 0.01	0.63 ± 0.04
		n.s.	***	***	n.s.	n.s.	***	*	n.s.	n.s.
20–30	IP	5.66 ± 0.05	4.43 ± 0.03	3.1 ± 0.5	29.7 ± 2.2	0.56 ± 0.13	0.17 ± 0.03	0.03 ± 0.00	0.08 ± 0.01	0.48 ± 0.06
	NU	5.49 ± 0.07	4.17 ± 0.06	1.9 ± 0.2	34.5 ± 2.9	0.31 ± 0.04	0.09 ± 0.01	0.04 ± 0.01	0.07 ± 0.01	0.59 ± 0.04
		n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.

Mean ± standard error (n = 30) and statistical significance: n.s. $p \geq 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

quality. As a consequence, the establishment of improved pasture clearly enhanced soil nitrification potential, and soil N availability, which is in agreement with the trends reported by Gómez-Rey et al. (2012) for an older improved pasture.

Although soil N mineralization potential was increased by almost 50% (from 46 to 70 mg g^{-1}), it was not accompanied by soil pH increase, indicating that the initial lime and fertilizer applications might have balanced possible soil acidification effects (Haynes and Williams 1993). Regarding possible soil N losses, it should be emphasised that our N mineralization estimates, from sieved soil samples and under laboratory-controlled conditions, are certainly above the in situ mineralization amounts. Actually, soil N mineralization potentials in evergreen oak woodlands strongly decrease in the presence of herbaceous and tree decomposing roots (Gómez-Rey et al. 2011), and significant reduction of nitrate leaching is associated with oak root nitrate uptake (Nunes 2004). Therefore, the high tree density at our study site may ensure low risk of nitrogen losses.

The establishment of improved pastures did not lead to marked changes on the soil C cycle as soil C mineralization rates and microbial biomass C and N were similar to that occurring in the natural understory system. However, higher metabolic coefficient (qCO_2) and lower microbial biomass C:N ratio indicate that improved pasture soil microbial population may be less efficient in C metabolism than that from the natural vegetation area (Anderson and Domsch 1990). Improved pasture establishment enhanced the soil biochemical cycles, enabling the development of a soil microbial population with higher C consumption per unit of microbial biomass C, as compared to the natural understorey, following trends reported by Gómez-Rey et al. (2012) and Rosenzweig et al. (2016).

Besides similar soil organic C and POM-C proportions between the study systems, higher HWS-C in the improved pasture soil suggests enhanced soil microbial activity (Iqbal et al. 2010). This result is in agreement with Rodrigues et al. (2015) observations, in a 35-year old improved pasture from a Southern Portugal oak woodland, where HWS-C was more than doubled, along with a soil organic C increase, compared to an adjacent natural pasture. This trend, found only 5 years after pasture sowing and associated with a small decrease of soil organic C, highlights the efficiency of HWS-C as a soil organic matter indicator for monitoring changes of management and land use (Kalbitz et al. 2000).

Soil fertility was undoubtedly favoured by pasture sowing, mostly associated with significant N accumulation, up to 20 cm depth, but also as a consequence of fertilizer and lime inputs. Higher concentrations of extractable P and exchangeable Ca^{2+} and Mg^{2+}, agree with results reported for older improved pastures in oak woodlands, where chemical fertilizers were periodically applied (Gómez-Rey et al. 2012).

Increasing in non-acid cation concentrations contributed to a soil exchange complex with lower Al^{3+} saturation degree (from 29 to 5% in 0–10 cm layer) and, therefore, to change soil reaction from strongly to moderately acidic, which may also enhance nutrient availability (Brady and Weil 2017). These changes indicate a higher cation retention capacity, as the effective soil cation exchange capacity (sum of non-acid cations plus exchangeable Al^{3+}) in the 0–10 cm improved pasture soil layer reached 2.57 $cmol_c\ kg^{-1}$, while it was only 1.50 $cmol_c\ kg^{-1}$ in NU.

It is noteworthy that only a few years after pasture sowing, most of the studied soil properties were in accordance with results from older improved pastures in open oak woodlands (Gómez-Rey et al. 2012; Rodrigues et al. 2015). This confirms the potential of sowing legume-rich mixtures for soil N enrichment and a fast soil quality improvement in cork oak woodlands, although it can be associated with soil organic C losses, with negative consequences for soil functions. Meanwhile, improved pasture sowing is commonly projected for grazing (intensification system), which hampers tree recruitment and threaten the long-term viability of cork oak woodlands, unless shelters are effectively used for seedlings protection. In contrast, tree recruitment is mostly facilitated under the natural understorey management, which allows shrub growth, enables saplings protective measures, avoids soil organic carbon losses and assures long-term cork production. As under this system the soil is N limited, occasional applications of fertilizers may be useful to improve tree nutritional status and soil organic matter quality.

Conclusions

Improved pastures extensively grazed by cattle do not necessarily lead to higher soil organic C stock in cork oak woodlands, as compared to ungrazed systems with natural shrub understory. In contrast, pasture management can promote soil quality, namely by enhancing soil organic matter quality and fertility, without detriment of soil physical conditions. Management aiming sustainable cork oak woodlands should be based on practices that effectively promote tree regeneration, such as those followed in the natural understory vegetation system, in which occasional application of fertilizers might be a promising option for improvement of soil quality and tree nutrition status. Long-term studies are needed regarding cork production and quality, for the economic and environmental evaluation of differently managed cork woodlands.

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