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Fertilization in pastoral and *Pinus radiata* D. Don silvopastoral systems developed in forest and agronomic soils of Northwest Spain

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ABSTRACT

The effects of fertilization, pasture sowing and tree plantation on soil fertility and tree and pasture production can vary depending on the soil type. Tree plantation is recognized as a way to reduce nutrient leaching and increase land profitability in agronomic and forest soils, meanwhile pasture fertilization and sowing is usually associated to better pasture productivity and quality. Fertilization can be performed with mineral fertilizers, which have become expensive in recent times, or with organic fertilizers like sludge, which is being promoted worldwide. This study aims to evaluate the effects of sludge fertilization, tree planting and pasture sowing on different variables of soil (KCl-pH, cation exchange capacity, total N, total and Mehlich P, nitrate and soil organic matter) and pasture (production, botanical composition, crude protein and P concentration) in treeless and agroforestry systems established in forest and agronomic soils. The experimental design was a randomized block following an incomplete factorial design with three replicates and nine treatments including two types of soils (forestry and agronomic), two types of vegetation (natural and sown), two types of fertilization (sludge fertilization and mineral fertilization, with a no fertilizer control) in afforested and treeless pastures. Pasture production and quality was better under agronomic soils, which also had higher levels of KCl-pH, cation exchange capacity, nitrate, total N and P than forest soils. Tree establishment did not modify nitrate or P leaching, probably due to the youth of the trees when most of nitrate was leached at the beginning of the experiment, but reduction of soil KCl pH and pasture crude protein was found in forest soils, when trees and pasture were together established, probably due to the high extractions of these systems compared with unsown forests. Moreover, the sludge inputs increased pasture production better than the mineral fertilizer in the forest soils, probably due to the greater amount of nutrients applied by the former. Sowing enhanced the presence of sown grasses in the forest understory, but their presence reduced pasture quality, and they disappeared within a short period of time. Therefore, the use of the sludge as fertilizer allows nutrient recycling of this residue in soils of low fertility and increases productivity and preserves fertility compared with mineral fertilizer at short (forest soils) and medium (agronomic soils) term.

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1. Introduction

Agroforestry systems are sustainable land management techniques that are promoted by the EU (European Union, Council Regulation 1698/2005 [EU, 2005]) and are considered a good management tool that can be implemented by farmers in the different countries of Europe (Graves et al., 2008).

Monterey pine [*Pinus radiata* (D. Don)] is a tree species that is currently used in silvopastoral systems in temperate areas like Australia, New Zealand, and Chile (Hawke, 1991; Knowles, 1991; Benavides et al., 2009) due to its fast growth. The species is widely used in the Atlantic biogeographic region of Europe (mostly in the North of Spain and West of France) in both forestry and farm grassland soils. Adequate fertilization practices in Monterey pine silvopastoral systems should be implemented to increase tree and pasture growth simultaneously at the same time that nutrient leaching risk is reduced. Recent increases in inorganic fertilizer prices along with environmental concerns have reduced the use of inorganic nitrogen fertilizers in the EU (EFMA, 2009), which are currently being replaced by organic fertilizers like sewage sludge as a cheaper nitrogen resource.

In EU countries, sewage sludge production has increased since the early nineties due to the implementation of European Directive 91/271/EEC (EU, 1991), which was enacted to enhance continental water quality. Therefore, it is necessary to find an adequate means of disposal for these residues in compliance with the environmental policies of the EU. One alternative that has been adopted in various countries around the world is the application of sewage sludge to soils as fertilizer (EPA, 1994), which is regulated in Europe by the directive 86/278/EEC (EU, 1986). The use of sewage sludge

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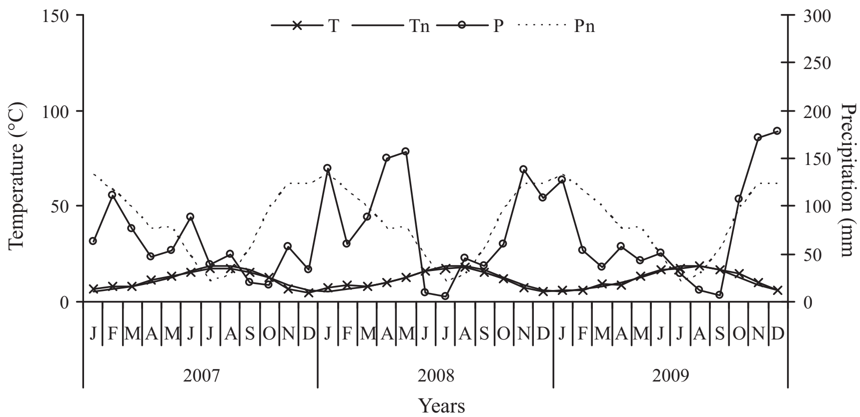

Fig. 1. Mean monthly precipitation and mean monthly temperature in 2007, 2008, and 2009 and mean normal data for the study area. T, mean monthly temperature (°C); T_n, mean normal temperature; P, mean monthly precipitation (mm); and P_n, mean normal precipitation.

as fertilizer is being promoted because it eliminates waste and reduces environmental pollution while imparting organic matter and macronutrients, particularly N and P, to the soil (Loehr et al., 1979; Rosswall, 1982; Beltrán et al., 2002; Mosquera-Losada et al., 2010). The study of the proportion of nitrogen that is readily mineralizable is important in determining the dose of sewage sludge that should be applied to the soil (Barry et al., 1986) in order to enhance both understory and overstory production in silvopastoral systems and to evaluate nitrate leaching risks (Simon and Le Corre, 1992; EPA, 1994). Sludge mineralization depends on soil types, pH and microbial soil activity (Smith, 1996) and this process is usually faster in agronomic than in more acid forest soils in North Western Spain. Moreover, the impact of sludge mineralization also depends on land use, being nitrate leaching risk usually higher in exclusive agronomic use (grasslands) than in silvopastoral systems due to the presence of the tree that may use the nitrate not employed by the pasture (Nair et al., 2008; Rigueiro et al., 2008).

Monterey pine and pasture growth response to sewage sludge inputs can be modified by the type of soil in which it is applied due to the different N and P availability in forestry and agronomic soils, which also affects nitrate leaching. Northwestern Spain forest soils usually have high organic matter content, which can act as a source of nutrients for crops. However, P availability is usually lower in forest soils due to high Al and Fe levels (Nair and Graetz, 2002). P and N availability can modify tree and pasture development as well as nitrate and P losses and pasture botanical composition (Campbell et al., 1993; Kellas et al., 1995; Nair et al., 2008). The impact of sewage sludge inputs in different soil types on nitrate and P cycling in agroforestry systems compared with treeless systems has not been evaluated in Western Europe.

The aim of this study is to evaluate the soil, productivity (tree and pasture) and environmental (nitrate and, P leaching) response to mineral or municipal sewage sludge inputs in grasslands and silvopastoral systems developed under Monterey pine established in agronomic and forest soils.

2. Materials and methods

2.1. Characteristics of the study site

The experiment was initiated in December 2006 through the use of 27 cilindric pots of about 2 m^3 (144 cm height × 134.5 cm width) that were installed in the town of Piugos (Lugo, Galicia, NW Spain, European Atlantic Biogeographic Region) at an altitude of 470 m above sea level and filled with soils. Soils are gleyic umbrisols (FAO classification) and Umbrept Inceptisols (USDA system). Fig. 1 shows the monthly mean precipitation and temperature values for 2007, 2008, and 2009 and the normal mean precipitation and temperature values of the study area. The total annual rainfall was 658.1, 1000, and 872.7 mm in 2007, 2008, and 2009, respectively. Meanwhile, the rainfall registered in the spring of 2007, 2008, and 2009 was 439.8, 604.5, and 368.4 mm, respectively. In general, these years were drier than the mean year (998.3 mm) for the study area. However, the mean monthly precipitation in 2007 was higher than the mean normal precipitation from June to August, which reduced the drought period found in 2008 and 2009 that limited pasture growth. The annual mean temperature was mild (12 °C).

Fifteen pots were filled with agronomic soil from Sarria (Lugo, Galicia, NW Spain) and the other with forest soil (12 pots) from Bascuas (Condesmo, Lugo, Galicia, NW Spain). In each pot, a lysimeter was installed at a depth of 135 cm to study the leaching of nutrients. The lysimiter was a PVC pipe of 2 cm of diameter introduced after making a hole in the pots. The tube is completely adjusted to the pot and no water is leached outside with the exception of the hole of the PVC pipe.

Initial agronomic soil analyses showed a highly acid KCl pH (4.46) (Faithfull, 2002), low soil organic matter (SOM: 36.3 g kg^{-1}) (Kowalenko, 2001), and a total N (1.9 g kg^{-1}) and P (0.3 g kg^{-1}) (Castro et al., 1990). Meanwhile, the forest soil analyses also had a highly acid KCl pH (4.27) (Faithfull, 2002), higher SOM (72 g kg^{-1}) (Kowalenko, 2001) and total P (0.8 g kg^{-1}) contents and a lower concentration of total soil N (1.8 g kg^{-1}) (Castro et al., 1990) than the agronomic soils. All heavy metal concentrations in both the agronomic and forest soils (Table 1) were below the maximum thresholds for the use of sewage sludge as fertilizer, as specified by the EU Directive 86/278/CEE (EU, 1986) and Spanish legislation under R.D. 1310/1990 (BOE, 1990).

2.2. Experimental design

The experimental design was a randomized block with three replicates and nine treatments. Treatments followed a design that consisted of a fractional factorial design of a 2p fully factorial, with "p" = 4 factors (2 levels per factor). The treatments established were chosen because they are the most traditional practices in the area of study (agronomic soil without tree, forest soil without pasture, and silvopastoral systems) in forest and agronomic lands. The treatments consisted of the following: (1) Agronomic soil + pasture sowing (Agronomic + P); (2) Agronomic soil + pasture sowing + sewage sludge (Agronomic + PS); (3) Agronomic soil + pasture sowing + mineral (Agronomic + PM); (4) Agronomic soil + pasture sowing + sewage sludge + tree (Agronomic + PST); (5) Agronomic soil + pasture sowing + mineral + tree (Agronomic + PMT); (6) Forest soil + sewage sludge + tree (For-

Table 1
Heavy metal concentrations in the agronomic soil and in the forest soil at the beginning of the experiment and legal limits established by European Directive 86/278 and Spain R.D. 1310/1990. Limits depend on soil pH (minimum: soil pH < 7, maximum: soil pH > 7). –, element concentration below detection limit of the technique used in its determination.

Soil	Heavy metal concentrations (mg kg^{-1})					
	Cd	Cu	Cr	Ni	Pb	Zn
Initial agronomic soil	0.1	1	0.9	–	17.7	28.8
Initial forest soil	0.9	7.8	2	–	–	32.5
Spanish law limits	1–3	50–210	100–150	30–112	50–300	150–450

est + ST); (7) Forest soil + mineral + tree (Forest + MT); (8) Forest soil + pasture sowing + sewage sludge + tree (Forest + PST); and (9) Forest soil + pasture sowing + mineral + tree (Forest + PMT). The following physical parameters were used:

- Pasture sowing (P): the pasture was sown with a mixture of cocksfoot [*Dactylis glomerata* (L.)] var. Artabro (12.5 kg ha^{-1}) (Dg), ryegrass [*Lolium perenne* (L.)] var. Brigantia (12.5 kg ha^{-1}) (Lp), and white clover [*Trifolium repens* (L.)] var. Huia (4 kg ha^{-1}) (Tr) in December 2006.
- Tree (T): a one-year-old Monterey pine tree was planted in January 2007.
- Sewage sludge (S): an anaerobically digested sludge with an input of 320 kg total N ha^{-1} applied in December 2006.
- Mineral (M): in the Agronomic + PM, Agronomic + PMT, Forest + MT, and Forest + PMT treatments, 500 kg ha^{-1} of 8 (% N):24 (% P_2O_5):16 (% K_2O) were applied at the beginning of the years 2007, 2008, and 2009, and 40 kg of N ha^{-1} as calcium ammonium nitrate (26% of N) was applied after each harvest.

2.3. Sewage sludge

Anaerobically digested sludge was taken from the municipal waste treatment plant of Lugo. A calculation of the required amount of sludge was conducted according to its percentage of total N and dry matter content (EPA, 1994) and taking into account that around 25% of the total N from anaerobically digested sewage sludge is available in the first year after application. EU Directive 86/278/CEE (1986) and Spanish regulation R.D. 1310/1990 (BOE, 1990) regarding heavy metal concentrations in the application of sewage sludge to soil were also considered. The composition of the sewage sludge applied is summarized in Table 2.

Table 2
Chemical properties of the sewage sludge applied and legal limits established by European Directive 86/278 and Spain R.D. 1310/1990. Limits depend on soil pH (minimum: soil pH < 7, maximum: soil pH > 7).

Parameters	Values	
	Anaerobic sludge	Spanish law limits
Dry matter (%)	20.47	
pH	7.47	
N (g kg^{-1})	35	
P (g kg^{-1})	17.8	
K (g kg^{-1})	3.5	
Ca (g kg^{-1})	27.1	
Mg (g kg^{-1})	8.4	
Na (g kg^{-1})	1.5	
Fe (g kg^{-1})	17.9	
Cr (mg kg^{-1})	39.4	1000–1500
Cu (mg kg^{-1})	142.7	1000–1750
Ni (mg kg^{-1})	29.4	300–400
Zn (mg kg^{-1})	1248.56	2500–4000
Cd (mg kg^{-1})	0.7	20–40
Pb (mg kg^{-1})	84.4	750–1200
Mn (mg kg^{-1})	6.1	

2.4. Field samplings and laboratory determinations

Soil samples were collected at a depth of 25 cm, as described in R.D. 1310/1990 (BOE, 1990) in March 2008 and in January 2009. In the laboratory, the pH of the KCl was determined as 1:2.5 soil:0.1 M KCl (Faithfull, 2002). The total C content in the soil was determined by oxidation of the total organic matter with potassium dicromate and sulphuric acid. The excess of dicromate was valorated with Mohr salt (Kowalenko, 2001). The percentage of organic matter was calculated by multiplying the total C content of the soil by the de Van Bemmelen factor (1.724). Cation exchange capacity (CEC) was calculated as the sum of the concentrations of Ca, K, Mg, Na and Al expressed as cmol(+) kg^{-1} of soil, after extraction with 0.6 N $BaCl_2$ (Mosquera and Mombiela, 1986). The total soil N and total soil P concentrations were determined after micro-kjeldahl digestion with a TRAACS-800+ autoanalyzer, as described by Castro et al. (1990) (US-786-86 A method, for N and US-787-86 A method, for P (Bran+Luebbe, 1979)). The available P was measured after extraction with Mehlich 3 (Mehlich, 1985) with the TRAACS-800+ autoanalyzer (US-787-86 A method (Bran+Luebbe, 1979)) and water volume measured with a volumetric ware. Total nitrate leached was estimated by multiplying nitrate concentration and water leached in each sampling. Nitrate leached for a period in each sampling was summed to obtain the global period nitrate leached.

Water was extracted each week from the lysimeters unless drought caused a lack of water. Nitrate was determined according to Bremner (1965) using a continuous-flow analytical system (TRAACS-800+).

Tree height and diameter were measured with graduated ruler and caliper, respectively, in September 2009.

To estimate pasture production, botanical composition, and crude protein (CP) and P content of the pasture, two samples of pasture were randomly taken with an electric hand clipper at a height of 2.5 cm per pot (0.3 m^2 × 0.3 m^2) in May, June, and August 2007; in May and July 2008; and in May and June 2009 (autumn data were not used in this study). Later, the samples were labeled and transported to the laboratory, where the samples were weighed and separated by hand according to the different plant species and the senescent material. They were then dried at 60 °C for 72 h to determine the harvest pasture production and the botanical composition weight. The CP and P content of the pasture were determined after micro-kjeldahl digestion with a TRAACS-800+ autoanalyzer, as described by Castro et al. (1990).

2.5. Statistical analysis

The data obtained from soil, tree and pasture variables were analyzed with three 2-way ANOVAs (proc glm procedure) following the model $Y_{ij} = \mu + F_i + T_j + \varepsilon_{ij}$. The first ANOVA was performed to discern the effects of soil type (agronomic vs. forest) with mineral and sludge fertilization in Pasture + Tree (silvopastoral systems) with two levels of fertilization (F: sludge and mineral) × two types of soil (T: Forest and agronomic) and their interactions (treatments Agronomic PMT, Agronomic PST, Forest PMT and Forest PST); where Y_{ij}

is the studied variable; μ is the variable mean; F_i is the fertilizer factor i; T_j is the soil type factor j; and ε_{ij} is the error. The second 2-way ANOVA was performed to discern the effects of two levels of pasture vegetation (S: sown and unsown pasture) with two levels of fertilization (F: sludge and mineral) and their interactions on forest soil (Treatments Forest + PMT, Forest + PST, Forest + ST and Forest + MT) where Y_{ij} is the studied variable; μ is the variable mean; F_i is the fertilizer factor i; T_j is the vegetation factor j; and ε_{ij} is the error. The third 2-way ANOVA was performed to discern the effects of two levels of tree plantation (T: tree and no tree plantation) with two levels of fertilization (F: sludge and mineral) and their interactions on agronomic soil (Treatments agronomic + PMT, agronomic + PST, agronomic + PM and agronomic PS) where Y_{ij} is the studied variable; μ is the variable mean; F_i is the fertilizer factor i; T_j is the vegetation factor j; and ε_{ij} is the error. Finally a 1-way ANOVA of one factor with three levels of fertilization F (NF, mineral and sludge) was to discern the effects of fertilization on agronomic soil with herbaceous vegetation (treatments NF, agronomic PM and agronomic PS). The Tukey's HSD test was used for subsequent pair wise comparisons ($p < 0.05$; $a = 0.05$). The statistical software package SAS (2001) was used for all analyses.

3. Results

3.1. Soil

3.1.1. KCl soil pH, CEC, SOM percentage, total N and total and Mehlich P

The KCl soil pH, the CEC and the total soil levels of N and P and P extracted by Mehlich 3 in 2008 and 2009 are shown in Fig. 2. The soil pH was significantly affected by the type of soil ($p < 0.01$) in *Pasture + Tree* treatments in 2008 (agronomic: 4.91 vs. forest:

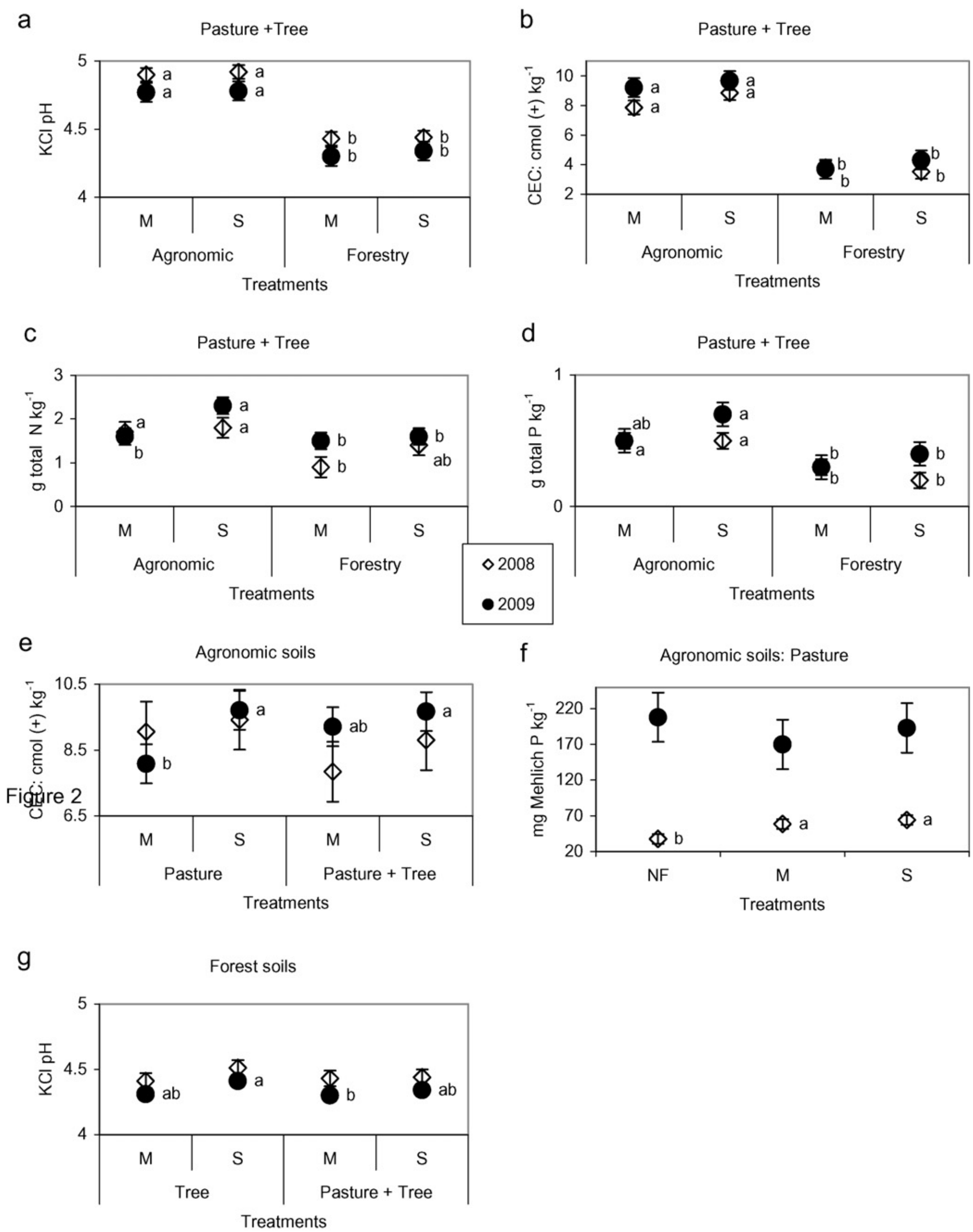

Fig. 2. Soil pH in KCl (a), CEC (cmol(+) kg^{-1}) (b), and total N (c) and P (d) concentrations in soil (g kg^{-1}) in Pasture + Tree treatments, CEC (cmol(+) kg^{-1}) in agronomic soils (e), P Mehlich 3 (mg kg^{-1}) in no forested agronomic soils (f) and soil pH in KCl in forest soils (g) in 2008 and 2009. M, mineral fertilization; S, sewage sludge fertilization. Different letters indicate significant differences between treatments within the same year. Vertical lines indicate mean standard error.

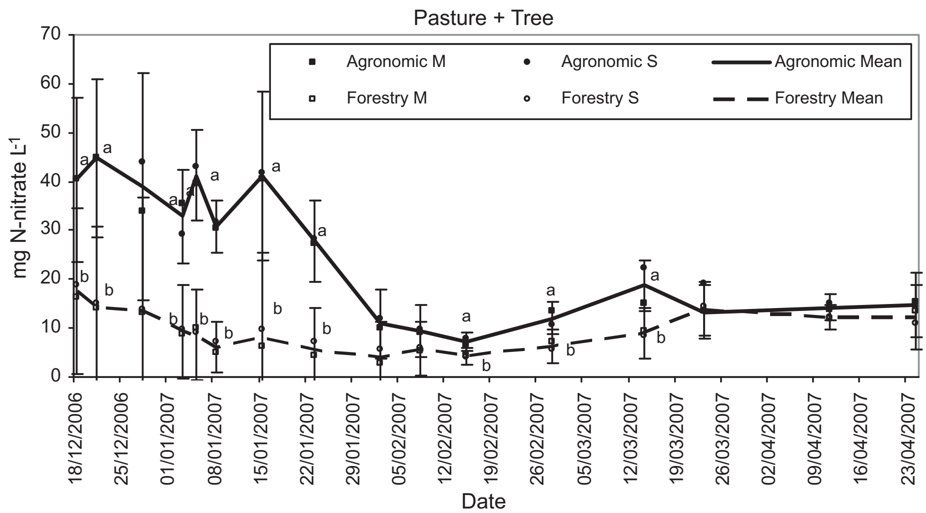

Fig. 3. Nitrate (mg N-nitrate L^{-1}) concentration in leached water in Pasture + Tree treatments. M, mineral; S, sludge. Different letters indicate significant differences between soil mean treatments. Vertical lines indicate mean standard error.

4.44) and 2009 (agronomic: 4.77 vs. forest: 4.33) as happened with CEC in 2008 ($p < 0.001$; agronomic: 8.35 cmol(+) kg $soil^{-1}$ vs. forest: 3.65 cmol(+) kg $soil^{-1}$) and 2009 ($p < 0.001$; agronomic: 9.44 cmol(+) kg $soil^{-1}$ vs. forest: 4.01 cmol(+) kg $soil^{-1}$). Soil total N and P were also significantly affected by the type of soil. Soil total N ($p < 0.01$ and $p < 0.001$) and P ($p < 0.001$ and $p < 0.01$) were significantly higher in agronomic soils than in forest soils in 2008 (agronomic: 1.7 g total N kg^{-1} and 0.5 g total P kg^{-1} vs. forest: 1.1 g total N kg^{-1} and 0.2 g total P kg^{-1}) and in 2009 (agronomic: 2 g total N kg^{-1} and 0.6 g total P kg^{-1} vs. forest: 1.6 g total N kg^{-1} and 0.3 g total P kg^{-1}). For the SOM percentage, no significant differences between the treatments were found ($p > 0.05$ (data not shown)). No differences in soil variables appeared between treatments when only *Forest soils* were taken into account, with the exception of KCl pH, which was significantly reduced when mineral fertilization was applied and tree and pasture was established compared with those treatments planted with trees and receiving sludge fertilization, but without pasture sowing. On the other hand, in the *Agronomic soils*, the soil CEC was significantly higher when the pasture was fertilized with sludge (9.69 cmol(+) kg^{-1} soil) than with mineral (8.65 cmol(+) kg^{-1} soil) in 2009 ($p < 0.01$), being P extracted by Mehlich 3 significantly ($p < 0.001$) improved when mineral or sludge fertilized was applied in 2008 and compared with no fertilization treatment in agronomic soils.

3.1.2. Nitrate concentration in leaching water

The significant effects of the treatments on nitrate concentrations in the leaching water are shown in Fig. 3. The nitrate concentration in the leaching water of agronomic soils was usually above the maximum set by the EU directive for drinking water in all treatments (<11.3 mg NO_3^--N L^{-1}) (EU, 1980) in December 2006 and in the first months of 2007. The nitrate concentrations of all treatments measured from May 2007 to 2009 were below the maximum allowed by the EU directive for drinking water (always below 5 mg NO_3^--N L^{-1}) and without differences between treatments (data not shown). With respect to the effects of the treatments in the *Pasture + Tree* pots at the beginning of the experiment, the results show that by 12 March 2007 the nitrate concentrations in the leaching water were significantly higher in Agronomic treatments sown with pasture and planted with trees than in the same Forest treatments. After this sampling date, no differences were found between treatments. However, the total nitrate leached was significantly higher ($p < 0.05$) when sewage sludge (3.05 g of nitrate until 24 May 2007) was applied in *Forest soils* compared with mineral fertilizers (1.89 g of nitrate until 24 May 2007). There were not differences between treatments in the subsequent years ($p > 0.05$).

3.2. Trees

3.2.1. Tree heights and diameters

Tree heights (179 cm) and basal diameters (41.25 mm) for each treatment were not significantly affected by any of the treatments in 2009.

3.3. Pasture

3.3.1. Production

Pasture production for the different fertilization treatments in the spring 2007, 2008, and 2009 can be observed in Fig. 4. Significant differences were detected between the treatments in all years ($p < 0.001$ in the spring of 2007, 2008, and 2009) with the exception of the spring 2007 and 2008 when the planting of trees were evaluated in agronomic soils and the spring 2008 when the three types of fertilization were compared in treeless pastures established in agronomic soils. The highest levels of pasture production were generally found in the spring of 2008 (2.2–13.4 Mg pasture ha^{-1}), while the lowest values were detected in the spring of 2009 (1.2–10.3 Mg pasture ha^{-1}). When the Agronomic and Forest treatments are compared (*Pasture + Tree* treatments), it is apparent that pasture production was lower in the Forest treatments (Forest + PMT and Forest + PST) fertilized with mineral or sludge than in Agronomic treatments (Agronomic + PMT and Agronomic + PST), with the exception of the first year of the study, when pasture production was similar in those pots fertilized with sewage sludge in forest soils (PST) to both Agronomic treatments (Agronomic + PMT and Agronomic + PST). Within the Agronomic treatments the fertilization with sewage sludge in no planted pots (Agronomic + PS) had higher pasture production than pots fertilized with mineral and planted with trees (Agronomic + PMT) in the last year of the study. On the other hand, in 2007, within the Agronomic treatments, pasture production was lower in no fertilized pots than in those fertilized with sewage sludge (Agronomic + PS). However, mineral fertilization reduced pasture production in the last year of the study compared with no fertilization treatment. Moreover, in the *Forest soils*, the mineral fertilization decreased pasture production (Forest + MT and Forest + PMT), while the fertilization with sewage sludge increased this variable (Forest + ST and Forest + PST) in 2007 and 2009. However, pasture production was reduced in

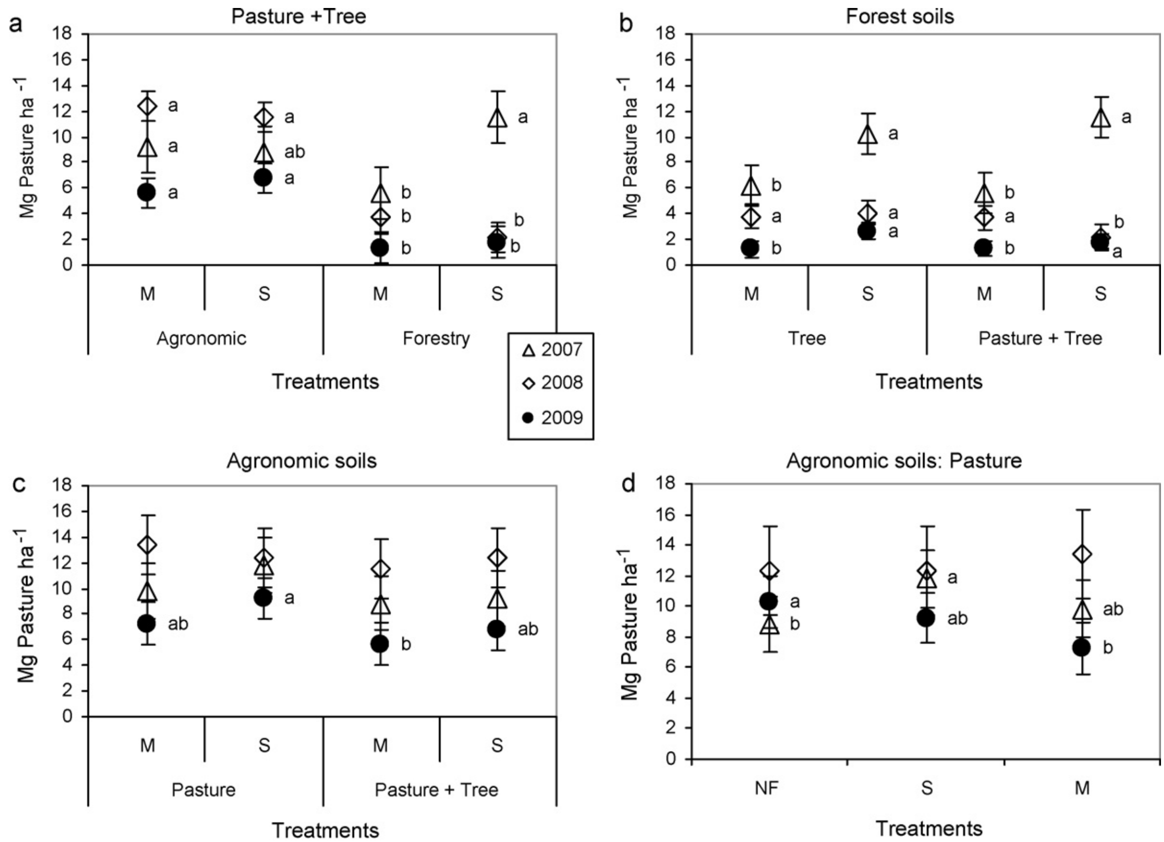

Fig. 4. Spring pasture production (Mg ha^{-1}) under Pasture + Tree (a), Forest (b), Agronomic (c) and Agronomic not afforested soils (d) in 2007, 2008, and 2009. Different letters indicate significant differences between treatments within the same year. Vertical lines indicate mean standard error.

forest soils when pasture was sown, tree was planted and sewage sludge was applied compared with the rest of the treatments in 2008.

3.3.2. Botanic composition

The significant ANOVA results of the weight proportion (% dry matter) of the sown species (cocksfoot, ryegrass, and white clover) and the most representative spontaneous species (chamomile (Cha) [*Chamomilla recutita* (L.)], creeping bentgrass (Crb) [*Agrostis stolonifera* (L.)], narrowleaf plantain (Np) [*Plantago lanceolata* (L.)], and yarrow (Yar) [*Achillea millefolium* (L.)]) in the pasture over the entire study period are shown in Table 3. There were other spontaneous species, though their contributions were minimal (data not shown). In general, the percentage of cocksfoot was significantly affected by treatments (Table 3) in all harvests of the spring–summer of 2007 and 2008, with the exception of the first harvest of 2007 and harvests of 2008 when the effect of planting trees within agronomic soils was evaluated. Moreover, all ANOVAs of cocksfoot were also significant in May 2009, but cocksfoot was not affected by treatments when the comparison of two types of soil (agronomic and forest) in *Pasture + Tree* pots was carried out in the first harvest of 2009. Regarding ryegrass, it was only affected by treatments in August 2007 (when (1) agronomic and forest soils were compared in *Pasture + Tree* pots and (2) treatments within forest soils were evaluated), in May 2008 in all treatments (with the exception of the evaluation of tree plantation in agronomic soils) and in May 2009 (when agronomic and forest soils in *Pasture + Tree* pots were compared and the effect of tree planting within agronomic soils was evaluated). The fertilization with mineral or sludge initially increased the proportion of cocksfoot in forest soils compared with agronomic soils in *Pasture + Tree* treatments (Fig. 5). Moreover, the positive effect of the mineral fertilization compared with the sludge fertilization on cocksfoot percentage in forest soils was more evident as the study advanced. On the contrary, agronomic soils had a significantly higher proportion of clover than forest soils mostly when sludge instead of mineral was applied in August 2007, May 2008 and July 2008.

Within the *Forest soils*, there was a positive effect of pasture sowing on the proportion of sown species (cocksfoot and ryegrass) in all harvests until May 2009 (Fig. 5). The establishment of cocksfoot in forest soils was better with mineral than with sludge fertilization. On the contrary, creeping bentgrass was the main pasture species found in forest unsown pots in 2007 and 2008 (Fig. 5). Creeping bentgrass percentage was significantly higher in unsown than sown forest treatments from the start of the experiment to July 2008, when the increment of the percentage of creeping bentgrass in unsown pots compared with sown pots was only significant if mineral fertilization was used. In May 2009, mineral fertilization improved the percentage of creeping bentgrass in unsown pots compared with those pots previously sown and fertilized with sludge.

Within *Agronomic soils*, the percentage of cocksfoot was significantly (Table 3) improved when sewage sludge (12.6% and 22.3%) instead of mineral (4.19% and 7.5%) was used in May and August 2007, respectively. On the contrary, the percentage of cocksfoot was significantly higher in mineral (44.17^{a}%) than sludge (12.5^{b}%) in no afforested pots in May 2009, but no differences were found in agronomic afforested pots regarding the percentage of cocksfoot (26.68^{ab}% and 22.32^{ab}% in mineral and sludge, respectively) in the same harvest (different superscript letters indicate significant differences between treatments). However, in May 2009, the use of sludge (11.42^{a}%) increased the proportion of ryegrass compared with mineral (1.15^{b}%) in no afforested pots, and sludge (1.80^{b}%) in afforested pots, but the percentage of ryegrass was similar in both

Table 3
ANOVA results for treatments with significant effects for sown grasses (cocksfoot (Dg), ryegrass (Lp), and white clover (Tr)), spontaneous species (chamomile (Cha), creeping bentgrass (Crb), narrowleaf plantain (Np) and yarrow (Yar)) in May, June, and August 2007; May and July 2008; and May 2009.

	Forest soil					Pasture + Tree					Agronomic soil			
	For	Fert	For × Fert	SEM		Soil	Fert	Soil × Fert	SEM		Silvo	Fert	Silvo × Fert	SEM
Sown species														
Tr May-08	*	*	*	5.2	Tr August-07	**	ns	ns	5.1	Dg June-07	ns	**	ns	6.7
Tr July-08	ns	*	ns	8.8	Tr May-08	**	ns	ns	8.5	Dg August-07	ns	*	ns	8.07
Dg May-07	***	ns	*	11.5	Tr July-08	***	ns	ns	7.5	Dg May-09	ns	**	**	13
Dg June-07	***	ns	ns	6.7	Dg May-07	***	**	*	8.6	Lp May-09	ns	ns	**	5.5
Dg August-07	***	ns	*	12.5	Dg June-07	**	ns	ns	9.0					
Dg May-08	***	ns	ns	17.3	Dg August-07	***	***	ns	9.4					
Dg July-08	***	ns	ns	15.2	Dg May-08	***	ns	ns	17.83					
Dg May-09	**	ns	ns	16.5	Dg July-08	*	*	ns	17.3					
Lp May-07	***	*	*	8	Lp August-07	ns	*	ns	16.3					
Lp June-07	***	ns	ns	12.8	Lp May-08	**	ns	ns	18.8					
Lp August-07	***	*	ns	12.8	Lp May-09	ns	ns	*	7.3					
Lp May-08	***	ns	ns	7.8										
Unsown species														
Crb May-07	***	ns	ns	24.6	Crb July-08	*	ns	ns	11.1	Crb May-07	**	*	ns	7.5
Crb June-07	***	ns	ns	24.8	Np July-08	*	*	ns	2.9	Crb May-08	ns	**	**	7.8
Crb July-08	**	ns	ns	19.1										
Crb May-09	**	ns	ns	21.8										
Yar July-08	**	ns	ns	10.2										

Agronomic soil	Fert	SEM
Sown species		
Dg May-07	**	2.7
Dg June-07	***	2.7
Dg August-07	**	8.4
Dg May-08	*	9.2
Dg July-08	*	6.8
Dg May-09	*	17.6
Lp May-08	*	17.1
Unsown species		
Crb May-08	***	7.04

SEM, mean standard error; ns, not significant.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

afforested pots (4.51[ab]% in mineral afforested pots). Mineral fertilization also increased the percentage of cocksfoot compared with no fertilization in agronomic soils (Fig. 5).

Regarding the spontaneous species, it was found that chamomile was initially better established in agronomic (21.87%) than forest soils (0.02%) in *Pasture + Tree* treatments in May 2007. On the other hand, the percentage of narrowleaf plantain [*P. lanceolata* (L.)] was significantly higher when sewage sludge was applied in agronomic soils (5.91[a]%) compared mineral fertilization (0.05[b]%) in forest soils in July 2008, but the percentage of this species was similar in mineral fertilized agronomic soils (2.47[ab]%) and in sludge fertilized forest soils (1.63[ab]%) in the same harvest. Finally, yarrow was improved within *Forest soils* when no sown was carried out but mineral fertilization was applied (18.81[a]%) compared with sludge fertilization with sowing (0.55[b]) but similar to the percentage found in those pots unsown and fertilized with sludge (12.48[ab]%) or sown and fertilized with mineral (2.88[ab]%) in July 2008.

3.3.3. *Pasture concentrations of CP and P*

The concentrations of CP and P in the pasture in the spring 2007 and 2008 are presented in Fig. 6. The concentration of CP was significantly affected by the treatments in August 2007 (soil effect: $p < 0.001$) and in December 2008 (soil effect: $p < 0.01$) in *Pasture + Tree* treatments and revealed that CP was higher in agronomic than forest soils, with the exception of pasture grown in agronomic pots fertilized with sludge in December 2008. On the other hand, the concentration of P in pasture was significantly affected by treatments in June (soil effect: $p < 0.001$) and August (soil effect: $p < 0.001$) 2007 and in December 2008 (soil × fertilization interaction effect: $p < 0.05$; soil effect: $p < 0.001$) when the effect of the type of soil was evaluated. As happened with CP, the concentration of P was significantly higher in agronomic than forest soils, with the exception of pasture developed in agronomic soils fertilized with sludge which did not differ from the same forest treatment.

Within *Forest soils*, the lack of sowing increased the CP concentration of pasture. Mineral fertilization in unsown treatments significantly increased the concentration of CP compared with sludge and mineral fertilization in sown pots in August 2007 (tree effect $p < 0.001$) and only with sludge fertilization in June 2007 (tree effect: $p < 0.001$).

4. Discussion

All soil studied variables (KCl pH, CEC, total N and P), excluding organic matter, were significantly higher in agronomic compared with forest soils and explains the better initial fertility stage and pasture production found in the Agronomic than in the Forest treatments. Moreover, the highest presence of white clover in the Agronomic treatments probably increased pasture production because *Rhizobium* N fixation is performed by this species (González, 1992; Whitehead, 1995; Green et al., 1999; López-Díaz et al., 2009), which increases the input of N into the soil (Mosquera-Losada et al., 1999), and the subsequent consumption of this nutrient by grasses. Authors such as González (1992) indicate that 30% of white clover in pastures developed in North Western

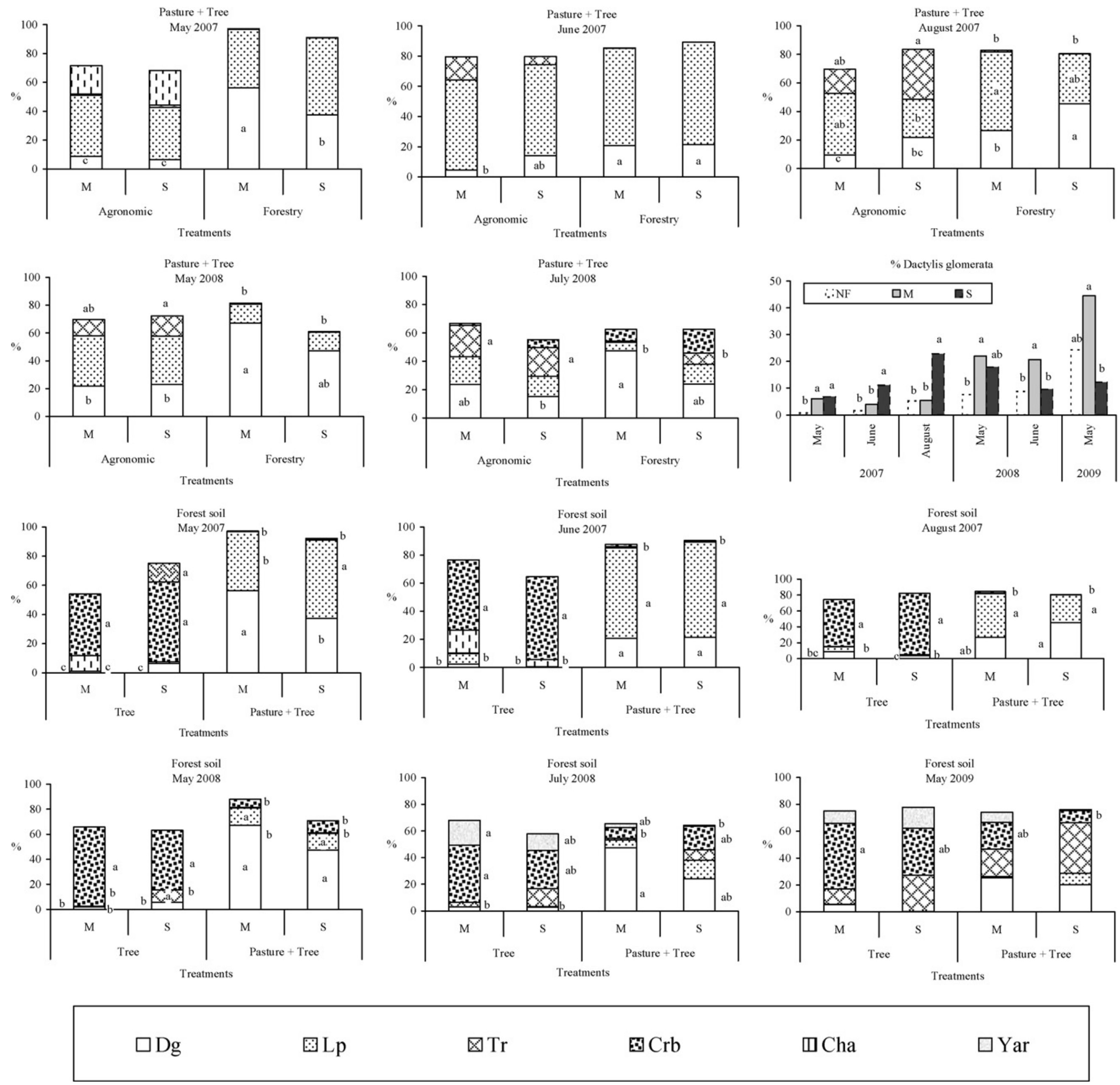

Fig. 5. Proportion in weight (% dry matter) of sown (Dg, cocksfoot; Tr, white clover; and Lp, ryegrass) and spontaneous species (Cha, chamomile; Crb, creeping bentgrass; and Yar, yarrow) in pasture under the different treatments in May, June, and August 2007; May and July 2008; and May and June 2009 of Pasture + Tree and Forest and Agronomic soils treatments. M, mineral; S, sludge; NF, no fertilization. Different letters indicate significant differences between treatments within the same harvest.

Spain can incorporate up to 250 kg ha^{-1} $year^{-1}$ of N. In any case, pasture production ranges found in the present experiment were similar to those usually described in North Western Spain forest soils (0.5–6 Mg pasture ha^{-1}) (Mosquera-Losada et al., 2001) and in North Western Spain agronomic soils (6–12 Mg ha^{-1}) (Mosquera-Losada and González-Rodríguez, 1999).

Although soil pH was reduced from the first to the last year of the experiment, N and P levels in soil were usually higher if sludge instead or mineral were used in Pasture + Tree treatments developed in agronomic soils. Soil pH in 2009 was reduced in comparison to 2008 probably due to the N mineralization (the step from NH_4^+ to NO_3^- occurs, and H^+ is released into the soil solution media after leaching of NO_3^- by rainfall (Whitehead, 1995)) and tree and pasture cation extractions from the soil (Mosquera-Losada et al., 2006). In the last year of the experiment, soil total N was higher if sludge instead of mineral fertilizer had been previously applied in pasture and tree agronomic soils. The sludge nutrient release rate is slower than those from mineral fertilizers (EPA, 1994; Smith, 1996) and this would explain the extended effect of the sludge in time on soil total N variable. The same tendency was found with total soil P.

Water pollution from nitrate leaching, was only relevant at the start of the experiment when both tree and pasture were at the establishment phase, and therefore they were less efficient taking up soil nutrients like nitrate. Afterwards, the adequate establishment of pasture and tree limited nitrate leaching, even though mineral fertilizer inputs were annually performed. At the beginning of the present experiment (2006), the nitrate-N content of the soil solution exceed the 11.3 mg L^{-1} limit for drinking water set by the EU (1980). In the following samplings, the concentrations of nitrate in the leached water from the agronomic soils were also above the value of 11.3 mg NO_3^--N L^{-1}, and it was higher than that found in forest soils (Knight et al., 1989). High initial soil pH of agronomic

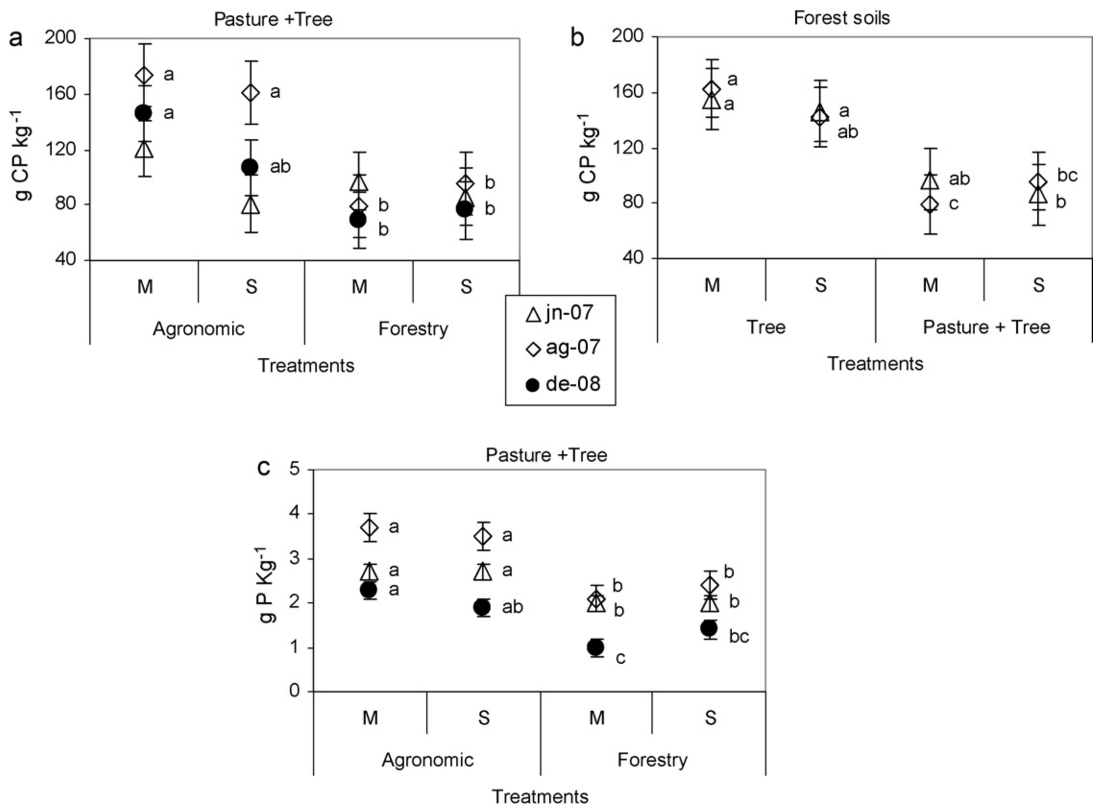

Fig. 6. Concentrations of crude protein (CP) in pastures (g kg^{-1}) under Pasture + Tree (a) and forest soil (b) treatments and P in pastures (g kg^{-1}) under Pasture + Tree (c) in the significant harvests of 2007, 2008, and 2009. M, mineral; S, sludge. Different letters indicate significant differences between treatments within each harvest. Vertical lines indicate mean standard error.

soil at the beginning of the experiment would explain a higher mineralization activity, and therefore nitrate leaching, in agronomic than in forest soils, which caused an increase of pasture production and the levels of CP. Moreover, the initial higher percentage of grasses instead of annual species in the Forest treatments than in the Agronomic treatments could also have reduced the leaching of nitrate in the forest soils, while taking into account that perennial grasses have a greater capacity for taking up soil nitrate than weeds (Humphreys et al., 2006; Abberton et al., 2008). Moreover, the initial establishment of dicotyledonous annual species, such as chamomile, could also have increased the nitrate leaching in the agronomic treatments when the annual species died, since dicotyledonous species are richer in N than monocotyledonous species (Hanley et al., 1992; Paré et al., 2006). The absence of annual species in the seed bank of the forest soils was probably the cause of the best initial establishment of the sown species in the forest soils that were simultaneously fertilized and sown than in the agronomic soils, where the annual species showed rapid-growth characteristics (abundant seed – rapid germination) (Grime et al., 2007; Mosquera-Losada et al., 2009).

There were no appreciably significant differences in the forest soils as a result of the different treatments of fertilization or sowing, mainly because most of the soil's biological activity was greatly restricted as pH was very low in the forest soils (Omil et al., 2007; Djukic et al., 2009). However, a positive effect of sewage sludge inputs on soil pH was detected when the less intensive system (no sowing) was compared with more intensive systems implying mineral fertilization and sown of pasture. The positive effect o sludge applications on soil pH in very acid soils were also described in soils receiving a higher total quantity of sludge than in the present experiment (López-Díaz et al., 2007). The improvement of soil pH caused by sludge applications may explain the increase of the total nitrate leaching and the pasture production in forest soils compared with mineral fertilizations. This result could be firstly explained by the residual effect of organic fertilizers compared with mineral fertilizers described by the EPA (1994) and secondly because the sludge added more Ca, Mg and micronutrients than the mineral fertilizer (Smith, 1996; López-Díaz et al., 2007; Mosquera-Losada et al., 2010).

Even though the forest soils were only significantly affected by the treatments in terms of KCl pH, they modified the botanical composition and CP in the initial samplings. However, these differences disappeared at the end of the study. The improvement in the percentage of ryegrass and cocksfoot species as a result of sowing caused a lower crude protein percentage than in the pastures of unsown forest soils. Sown species like ryegrass and cocksfoot are not usually adapted to the low fertility of forest soils, being less extractive than weeds in forest soils (Whitehead, 1995), thus reducing the proportion of N in the pasture. This reduction ultimately caused the reduction of the percentage of sown species at the end of the experiment in sown forest soils.

The response of the soil and pasture production variables to treatments within the agronomic soils did appeared two years after the experiment had begun, probably due to the better initial soil fertility. CEC was significantly increased in sludge fertilized treatments with or without tree planting than in mineral when trees were not planted, and it could be explained by the physical soil improvement caused by the sludge (Smith, 1996). Moreover, in 2009, those treatments with sludge fertilization in the agronomic soils without tree planting had higher pasture production than mineral fertilization treatment that had been previously planted. Mineral fertilization caused a direct increase of N, P, and K concentrations in soil, which can reduce other cation levels in soil, thus limiting pasture production (Whitehead, 1995). This effect can be seen in the lower CEC of the PM treatment compared with the rest of the agronomic treatments fertilized with the sludge in the last year of the study. Additionally, the presence of trees modified the soil conditions in the agronomic soil with the mineral fertilizer (PMT), which may also have reduced pasture production in this treatment due to the high extractions performed by both crops (tree and pasture), compared with agronomic treeless systems fertilized with mineral.

The initial improvement of soil P availability as a result of fertilization (mineral or sludge) was also previously described (Allen et al., 2006; Nair et al., 2007) and may help to explain the high production of pasture in sewage sludge fertilized pots compared with no fertilization in agronomic soils. Moreover, cation extraction may have reduced pasture production in mineral treatment compared with no fertilization at the end of the study.

In 2009, the Monterey pine heights and diameters varied from 164–193 cm to 49.5–58 mm, respectively. The tree diameters and heights were greater than those described by López-Díaz et al. (2009) in a study carried out in agrarian soils in North Western Spain, with a pH close to neutral (pH 6.3), and by Sánchez-Rodríguez (2000) in the Northwest of Spain. The higher growth of trees in our study could be explained by the high precipitation rate found in the summer during planting, which usually increases initial tree growth (Rigueiro-Rodríguez et al., 2000; Mosquera-Losada et al., 2006) and may have reduced the differences between treatments. A similar result was found by Rigueiro-Rodríguez et al. (2010), in which fertilization treatments initially modified the Monterey pine response, but differences between the treatments disappeared when a humid summer for tree growth occurred. Tree plantation did not affect nitrate leaching probably because trees were too young to uptake nitrogen from soil when the nitrate concentrations in soil were high. However, tree plantation reduced pasture production in agronomic soils fertilized with mineral and KCl pH, and CP concentration in forest soils compared with the less intensive treeless pastures (López-Díaz et al., 2007).

The concentrations of CP (58–183 g kg^{-1}) and P (1.6–4.8 g kg^{-1}) were similar to the concentrations described by Grime et al. (2007) (1.5–4.5 g kg^{-1}) and Whitehead (1995) (80–250 g kg^{-1}), respectively, with the exception of the CP concentrations in those harvests performed in the summer, which were usually lower due to the usual seasonal evolution of CP caused by the different pasture species' phenological growth states (Whitehead, 1995). The concentration of CP in the pasture did not reach the minimum requirements for the maintenance of live weight in sheep (94 g kg^{-1}) (NRC, 1985), horses (85 g kg^{-1}) (NRC, 1989), and goats (60 g kg^{-1}) (Lamand, 1981) in the summer harvests of 2007 and 2008. The concentration of P in all other harvests did meet the requirements for maintenance of live weight in sheep (1.6–3.7 g kg^{-1}) (NRC, 1985), horses (2 g kg^{-1}) (NRC, 1989), and goats (2.5 g kg^{-1}) (Lamand, 1981).

5. Conclusion

Fertilizer management, sowing and plantation practices caused different effects on the agrarian and forestry soils in our study. Agronomic soils were more fertile than the forestry soils due to the high pH and microbial activity of the former, which increases nitrate and P availability, and therefore the risk of leaching. Better nutrient availability in the agronomic soils increased pasture production as initially did sludge instead of mineral fertilization in forest soils due to the inputs of other nutrients done by sewage sludge compared with mineral, which probably increased mineralization in forest soils. Nitrate leaching was only relevant at the start of the experiment when trees and pasture were not enough developed to uptake nitrate. On the other hand, the soil variables evaluated in this study, with the exception of KCl, were not modified by fertilization or sowing treatments in the forest soils. However, the production, botanical composition and quality of the pasture developed in the forest soils were positively by sludge inputs instead of mineral due to the greater amount of nutrients applied with the former and the pH increase that sludge caused. The presence of grasses like cocksfoot or ryegrass was enhanced by sowing in forest soils. However, due to the low soil fertility, the quality of the pasture at the time these species were sown was low, and the sown grass species disappeared shortly after the establishment of the experiment. Finally, soil fertility was better preserved with the sludge than mineral fertilizer within the agronomic soils due to the broad range of nutrient applied with the former. Therefore, the use of the sludge as fertilizer allows nutrient recycling of this residue in poor soils and increases productivity and preserves fertility compared with mineral fertilizer at short (forest soils) and medium (agronomic soils) term.

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