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Response to sewage sludge fertilisation in a *Quercus rubra* L. silvopastoral system: Soil, plant biodiversity and tree and pasture production

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ABSTRACT

Silvopastoral systems are sustainable form of land management promoted by European Union. The productivity of the herbaceous and tree components in a silvopastoral system could be limited by soil fertility. The use of adequate doses of organic fertilisers like sewage sludge could enhance the productivity of both pasture and trees and promote biodiversity. The quantification of the best dose of sewage sludge to be applied in a silvopastoral system is important in order to enhance production and biodiversity in a silvopastoral system, while avoiding nitrate contamination of the ground water. This study aims to evaluate the effects of different doses of sewage sludge (100 kg total N ha^{-1}, 200 kg total N ha^{-1} and 400 kg total N ha^{-1}) on different variables of soil (soil pH, effective exchange capacity and the saturation percentage of Al, K, Ca, Mg and Na), tree growth and pasture (production, species richness and botanical composition) as compared to the fertilisation treatment in a silvopastoral system under *Quercus rubra* L. Sewage sludge applications initially improved soil nutrient levels (effective exchange capacity and Ca saturation percentage) and subsequently pasture production and tree growth when 200 and 400 kg of total N ha^{-1} were applied. On the other hand, the establishment of pasture and trees improved soil conditions at a medium term due to the organic matter input into the sandy soil, which increased species diversity specially at a 100 kg of total N ha^{-1} dose.

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1. Introduction

Silvopastoral systems are agroforestry systems in which tree and pasture production is combined. These systems are currently being promoted by the EU (Council Regulation 1698/2005 (EU, 2005)). Silvopastoral systems can produce social benefits, as the economic return is obtained earlier than when exclusive forest systems are used. As a result, silvopastoral systems tend to enhance the stabilisation of the rural population. Silvopastoral systems also provide environmental benefits such as the improvement of nutrient recycling, the control of soil erosion, a reduction in fire risk and an increase in carbon sequestration (Rigueiro-Rodríguez et al., 2008; Howlett et al., 2011). Furthermore, silvopastoral systems can promote biodiversity through the creation of micro-sites within the plantation, such as shaded and unshaded areas. These micro-sites occur as a result of the presence of trees not found in purely agronomic land. Biodiversity can be further promoted through the reduction of habitat fragmentation (Rois et al., 2006).

*Quercus rub*ra L. is a native species from the Atlantic coast of North America that is widely used for reforestation in Galicia and in other regions of Northern Spain (Álvarez-Álvarez et al., 2000). The exotic *Quercus rubra* L. is preferred over the native *Quercus robur* L. by European foresters because of its faster growth, which yields earlier profits for forest farmers (Renou-Wilson et al., 2008). *Quercus rubra* L. is frequently used in the establishment of silvopastoral systems (Balandier and Dupraz, 1999; Lehmkuhler et al., 2003) because this species possesses an open crown that allows light to reach the pasture surface, making it compatible with pasture production. Furthermore, because it is a deciduous species, it allows better light penetration than perennial conifers during the autumn and early spring, and it provides shading during the summer. Thus, evapotranspiration is reduced, leading to enhanced pasture production as compared to pasture under conifers or on open pasture sites (Álvarez-Álvarez et al., 2000).

In Galician silvopastoral systems, the productivity (of both understory and trees) can be limited by low soil fertility as a result of increased acidity (Zas and Alonso, 2002). The use of fertilisers can modify the productivity of various components of the system (including the pasture and trees) as well as its botanical composition (Mosquera-Losada et al., 2009). One alternative that has been adopted in various countries around the world is the application of sewage sludge to soil as fertiliser (EPA, 1994). In Europe, this is regulated by the directive 86/278/EEC (EU, 1986). The use of sewage sludge as fertiliser is being promoted by the EU due to its specific

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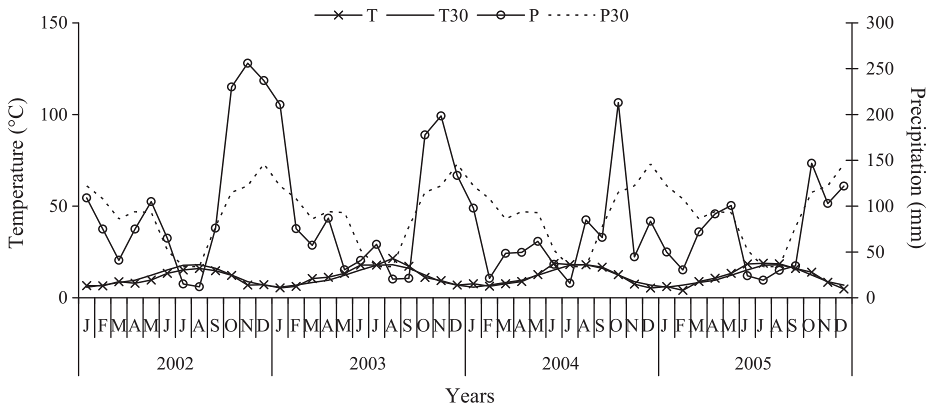

Fig. 1. Monthly precipitation and mean temperatures for the study area in 2002, 2003, 2004 and 2005 and mean data for the last 30 years. *T*: mean monthly temperature (°C), *T*30: mean temperature over the last 30 years (°C), *P*: mean monthly precipitation (mm) and *P*30: mean precipitation over the last 30 years (mm).

organic matter and macronutrients content, particularly nitrogen (N) (MMA, 2006).

The main problem with the agricultural use of sewage sludge is the higher heavy metal concentration of the sludge than in the soil (Smith, 1996). This problem is one of the set of indications regulated in Spain by the R.D. 1310/1990 (BOE, 1990) and by the European Directive 86/278/EEC (EU, 1986). Thus, the agronomic rate that can be safely applied depends both on the heavy metal concentrations in the sludge and on the nitrogen concentration and the proportion of the nitrogen that can readily be mineralised within the first year after application to the soil (Barry et al., 1986; EPA, 1994; Smith, 1996). A sewage sludge application rate exceeding the crop needs could result in nitrate contamination of the ground water by leaching. The sewage sludge should therefore be applied as close to the time of maximum nutrient uptake by crops as feasible (EPA, 1994).

The effects of the application of sewage sludge in silvopastoral systems in northwest Spain established under *Pinus radiata* D. Don (López-Díaz et al., 2009; Rigueiro-Rodríguez et al., 2010a; Mosquera-Losada et al., 2010a), *Populus canadensis* Moench (Mosquera-Losada et al., 2011) and *Fraxinus excelsior* L. (Rigueiro-Rodríguez et al., 2010b) have been already studied. The objective of the present study is to evaluate the effects of different doses of sewage sludge (100 kg total N ha^{-1}, 200 kg total N ha^{-1} and 400 kg total N ha^{-1}) on changes in soil chemical properties, tree growth, understory production and biodiversity as compared to the no fertilisation treatment in a silvopastoral system under *Quercus rubra* L.

2. Materials and methods

2.1. Characteristics of the study site

The experiment was established in autumn 2001 in A Pastoriza (Lugo, Galicia, NW Spain, European Atlantic Biogeographic Region) at an altitude of 480 m above sea level. Fig. 1 shows the mean monthly precipitation and temperatures for 2002–2005 as well as the previous 30 years. The total annual rainfall was 1296 mm, 1111 mm, 822.9 mm and 824.3 mm in 2002, 2003, 2004 and 2005, respectively. In general, very low precipitation was observed in these years as compared with the mean for the last 30 years, and this limited pasture production and tree growth. However, in 2002 and 2003, there was a period of high precipitation from October to December. October 2004 and 2005 were also very rainy months (212.9 mm and 146.8 mm, respectively). The annual mean temperature was mild (12 °C) with low temperatures at the beginning and at the end of the years under study.

The experiment was carried out on abandoned agricultural land. The soil texture at the beginning of the experiment was sandy (91.81% sand, 4.92% silt and 3.27% clay) with a moderately acidic pH of 5.2 as well as high levels of soil organic matter content, total N and total P (10.34%, 0.25% and 0.09%, respectively). All heavy metal concentrations in the soil (Table 1) were below the maximum threshold for using sewage sludge fertiliser as specified by the European Union Directive 86/278/CEE (EU, 1986) and Spanish legislation under R.D. 1310/1990 (BOE, 1990).

2.2. Experimental design

At the beginning of the experiment in autumn 2001, the soil was ploughed, and the pasture was sown with a mixture of *Dactylis glomerata* L. var. Artabro (12.5 kg ha^{-1}), *Lolium perenne* L. var. Brigantia (12.5 kg ha^{-1}) and *Trifolium repens* L. var. Huia (4 kg ha^{-1}). Naked-root *Quercus rubra* L. plants were planted at a density of 1112 trees ha^{-1}, with 3 m × 3 m between rows. The experimental design was a randomised block with three replicas and four treatments distributed in experimental units of 144 m^2 with 25 trees arranged in a frame of 5 × 5 trees. The treatments consisted of (a) no fertilisation (0 N), (b) fertilisation with anaerobically digested sludge with an input of 100 kg total N ha^{-1} in March 2002 and 2003 (100 N), (c) fertilisation with anaerobically digested sludge with an input of 200 kg total N ha^{-1} in March 2002 and 2003 (200 N) and (d) fertilisation with anaerobically digested sludge with an input of 400 kg total N ha^{-1} in March 2002 and 2003 (400 N). Inputs of 57.5 kg CO_3Ca ha^{-1}, 115 kg CO_3Ca ha^{-1} and 229.95 kg CO_3Ca ha^{-1} were also applied when low (100 kg total N ha^{-1}), medium (200 kg

Table 1
Heavy metal concentrations in the soil at the beginning of the experiment and the 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). A dash (–) signifies an element concentration below the detection limit of the technique used for its determination.

	Heavy metal concentrations (mg kg^{-1})					
	Cd	Cu	Cr	Ni	Pb	Zn
Initial soil	–	11.6	–	2.1	37.6	11.9
Spanish legal limits	1–3	50–210	100–150	30–112	50–300	150–450

Table 2
Chemical properties of the sewage sludge 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 (2002)	Anaerobic sludge (2003)	Spanish legal limits
Dry matter (%)	22.27	23.82	
pH	7.08	7.49	
N (g kg^{-1})	29.7	25.4	
P (g kg^{-1})	19.9	19.6	
K (g kg^{-1})	3	3.9	
Ca (g kg^{-1})	3	3.2	
Mg (g kg^{-1})	6.2	6.8	
Na (g kg^{-1})	0.7	1.2	
Fe (g kg^{-1})	26	13.9	
Cr (mg kg^{-1})	87.9	81.4	1000–1500
Cu (mg kg^{-1})	242.8	195.8	1000–1750
Ni (mg kg^{-1})	98.7	142.8	300–400
Zn (mg kg^{-1})	364.7	748	2500–4000
Cd (mg kg^{-1})	4.4	10.9	20–40
Pb (mg kg^{-1})	130.6	78.7	750–1200
Mn (mg kg^{-1})	311.7	358.8	

total N ha^{-1}) and high (400 kg total N ha^{-1}) sludge were added to the soil, due to the high levels of calcium that the used sludge had.

2.3. Sewage sludge

Anaerobically digested sludge from a municipal waste treatment plant of Lugo was used. The required amount of sludge was calculated based on the percentage of total N and dry matter content (EPA, 1994), keeping in mind that approximately 25% of the total N from anaerobically digested sewage sludge is available in the first year after application. EU Directive 86/278/CEE (EU, 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 in 2002 and 2003 is summarised in Table 2.

2.4. Field samplings and laboratory determinations

Soil samples were collected at a depth of 25 cm in March 2003 and in January 2004, 2005 and 2006, as described in R.D. 1310/1990 (BOE, 1990). In the laboratory, soil pH was determined in water (1:2.5) (Faithfull, 2002). Al concentrations in the exchange complex and the exchangeable cations (K, Ca, Mg and Na) were determined by extraction with 0.6 N $BaCl_2$ (Mosquera and Mombiela, 1986). The K, Ca, Mg and Na exchangeable concentrations were measured with a VARIAN 220FS Spectrophotometer using the atomic emissions for K and Na and the absorptions for Ca and Mg. Al concentrations were analysed after valoration with 0.01 N NaOH using phenolphthaleine (1%) in an alcohol-based solution as an indicator (Mosquera and Mombiela, 1986). The effective exchange capacity (EEC) was determined by taking the sum of K + Ca + Mg + Na + Al and the saturation percentage of Al, K, Ca, Mg and Na using the quotients Al/EEC, K/EEC, Ca/EEC Mg/EEC and Na/EEC, respectively (Mosquera and Mombiela, 1986).

Tree height and diameter were measured with a graduated ruler and a calliper, respectively, in September 2006.

Estimated pasture production and botanical composition was determined by randomly collecting four samples of pasture. The four samples were cut with an electric hand clipper at a height of 2.5 cm per plot (0.3 m × 0.3 m) in June 2002, July and December 2003, June, July and December 2004 and May, July and December 2005. One week after sampling, all plots were grazed by mature sheep (Galician breed) at a stocking rate of 50 sheep over the whole experimental area (1728 m^2). At the laboratory, two pasture samples were dried for 72 h at 60 °C and weighed to estimate pasture production. The other two samples were separated by hand to determine the proportions of the different plant species and the senescent material. These two samples were then dried for 72 h at 60 °C to determine the botanical composition on a dry weight basis. The species richness was determined yearly. Annual abundance diagrams omitting the percentage of senescent material (Magurran, 1988) were completed.

2.5. Statistical analysis

The data on tree and pasture variables were analysed using ANOVA (proc glm procedure) following the model $Y_{ij} = \mu + T_i + B_j + \varepsilon_{ij}$, where Y_{ij} is the studied variable, μ is the variable mean, T_i indicates treatment i, B_j is the block j, and ε_{ij} is the error. Soil variables and species richness were analysed with repeated ANOVA (PROC GLM procedure) following the model $Y_{ijk} = \mu + A_i + T_j + B_k + \varepsilon_{ijk}$, where Y_{ijk} is the studied variable, μ is the variable mean, A_i is the year i, T_j indicates treatment j, B_k is the block k, and ε_{ijk} is the error. The Tukey's HSD test was used for subsequent pairwise comparisons ($P < 0.05$; $a = 0.05$). The statistical software package SAS (2001) was used for all analyses.

3. Results

3.1. Soil characteristics

Table 3 shows that the soil pH, EEC and Ca saturation percentage in the soil exchange complex were significantly higher in 2006 than at the beginning of the study (2003) ($p < 0.001$). However, the saturation percentage of Al and K in the soil exchange complex decreased significantly in 2006 as compared with 2003 ($p < 0.001$). Furthermore, the Na saturation percentage in the soil exchange complex was higher in 2004 and 2006 than in 2003 and 2005 ($p < 0.001$).

In 2003, soil EEC and Ca saturation percentage in the soil exchange complex were affected significantly by the applied fertilisation treatments ($p < 0.05$) (Fig. 2). However, in 2004, 2005 and 2006 the effect of the treatments on EEC, Ca saturation percentage, soil pH and saturation percentages of Al, K, Mg and Na was

Table 3
Soil pH, effective exchange capacity (EEC) (cmol(+) kg^{-1}) and saturation percentage of Al, K, Ca, Mg and Na in the soil exchange complex (%) in the years 2003, 2004, 2005 and 2006. Different letters indicate significant differences between years. ns: not-significant, $^{***}p < 0.001$, SEM: mean standard error.

Parameter	Year				Year effect	SEM
	2003	2004	2005	2006		
pH	5.4bc	5.27c	5.51b	5.72a	***	0.04
EEC (cmol(+) kg^{-1})	4.94c	5.16c	6.30b	7.84a	***	0.21
Al (%)	39.4a	37.1a	41.11a	28.65b	***	0.01
K (%)	1.36a	1.36a	1.15b	0.75c	***	0.0004
Ca (%)	41.37b	41.25b	39.61b	52.14a	***	0.01
Mg (%)	13.00	13.37	12.95	11.28	ns	0.002
Na (%)	4.87b	6.92a	5.18b	7.18a	***	0.002

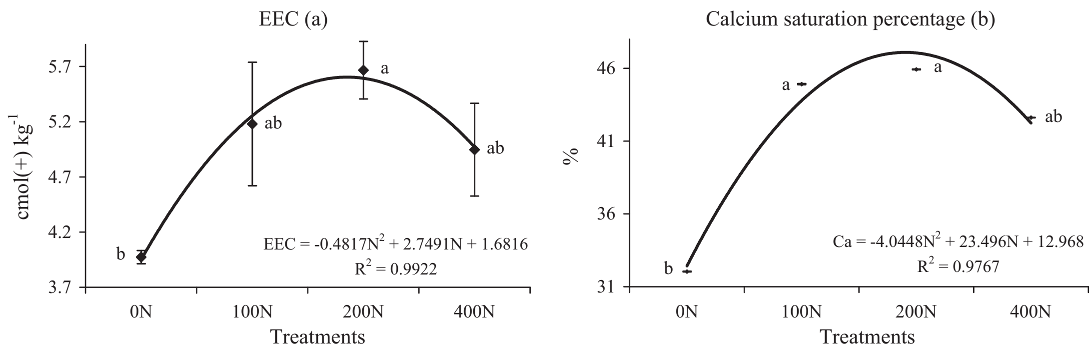

Fig. 2. Effective exchange capacity (EEC) (cmol(+) kg^{-1}) (a) and calcium saturation percentage in soil exchange complex (%) (b) under each treatment in 2003. 0 N: 0 kg total N ha^{-1}; 100 N: 100 kg total N ha^{-1}; 200 N: 200 kg total N ha^{-1} and 400 N: 400 kg total N ha^{-1}. Different letters indicate significant differences between treatments. Vertical lines indicate mean standard error.

not statistically significant. The application of sewage sludge at a rate of 200 kg total N ha^{-1} (200 N) increased soil EEC more than when no fertilisation (0 N) was applied. Furthermore, the Ca saturation percentage in the soil exchange complex also increased when sewage sludge inputs had been previously done. The increase in the Ca saturation percentage was larger when low (100 N) and medium dose (200 N) of sewage sludge were applied than when no fertiliser treatment was used.

3.2. Tree heights and diameters

Fig. 3 shows the tree heights and diameters for each treatment in 2006. During this year, tree heights and diameters were significantly affected by the fertilisation treatment applied ($p < 0.001$). The application of a medium and a high dose (400 N) of sewage sludge increased more the tree heights than the no fertilisation. The tree diameters were larger under the medium doses of sewage sludge as compared with no fertilisation.

3.3. Pasture

3.3.1. Production

Annual pasture production for the different fertilisation treatments in 2002, 2003, 2004 and 2005 can be observed in Fig. 4. Pasture production was significantly affected by the dose of sewage sludge in 2003 ($p < 0.05$) and 2004 ($p < 0.001$). In 2002 and 2005, no significant differences were detected between the treatments. The highest levels of pasture production were found in 2004 (9.3–17.5 Mg ha^{-1}), while the lowest values were reported in 2002 (3.9–4.3 Mg ha^{-1}). In 2003 and 2004, the application of medium and high sewage sludge treatments increased pasture production more than the no fertilisation and low fertiliser. Cumulative pasture production during the experimental period confirmed an increased pasture production at the medium and high sewage sludge treatments in 2004 and 2005 ($p < 0.001$) (Fig. 5).

3.3.2. Species richness

Fig. 6 shows that species richness was significantly higher at the end of the experiment in 2004 and 2005 than in 2002 and 2003 ($p < 0.001$). In 2002, species richness was significantly affected by the fertilisation treatments ($p < 0.05$). In this year, the low sewage sludge treatment increased species richness more than the medium fertiliser treatment. The fertilisation treatments applied also significantly effected ($p < 0.05$) the average species richness in the years 2002, 2003, 2004 and 2005 (0 N: 6^b; 100 N: 8^a; 200 N: 6^b; 400 N: 7^b) (different superscript letters indicate significant differences between treatments). The average species richness was higher under the low fertiliser sewage sludge treatment compared with the other treatments.

3.3.3. Pasture abundance diagrams

Pasture abundance diagrams for the different fertilisation treatments in 2002, 2003, 2004 and 2005 are shown in Fig. 7. From Fig. 6, the abundance diagrams confirm that the number of species was higher at the end of the study (2005) than at the beginning (2002). In 2002, the number of dicotyledonous species was higher than the number of monocotyledonous species in all treatments. However, in subsequent years (i.e., 2003, 2004 and 2005), the proportion of dicotyledonous species was higher than the proportion of monocotyledonous species in the no fertiliser treatment and the low fertiliser sewage sludge treatment. In the other treatments (200 N and 400 N), there were more monocotyledonous than dicotyledonous species. *Agrostis capillaris* L. and *Holcus lanatus* L. were present in all treatments and all years. They were also the most dominant species throughout the study. *A. capillaris* L. was the dominant species in the no fertilisation treatment, and in the low and

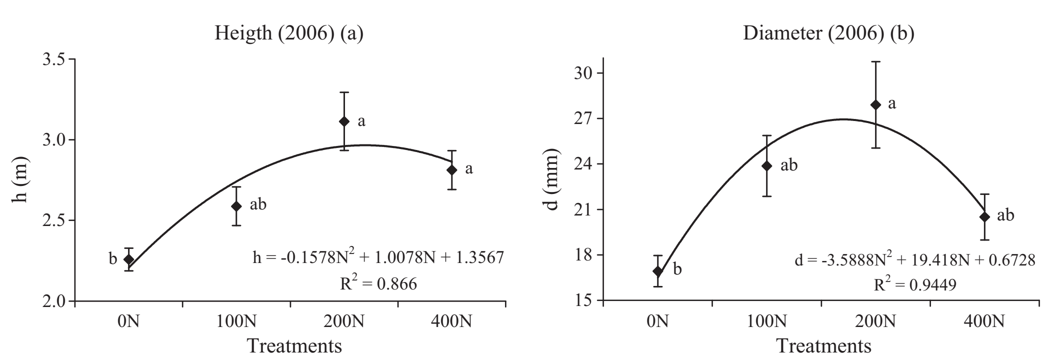

Fig. 3. Tree heights (m) (a) and tree diameters (mm) (b) under each treatment in 2006. 0 N: 0 kg total N ha^{-1}; 100 N: 100 kg total N ha^{-1}; 200 N: 200 kg total N ha^{-1} and 400 N: 400 kg total N ha^{-1}. Different letters indicate significant differences between treatments. Vertical lines indicate mean standard error.

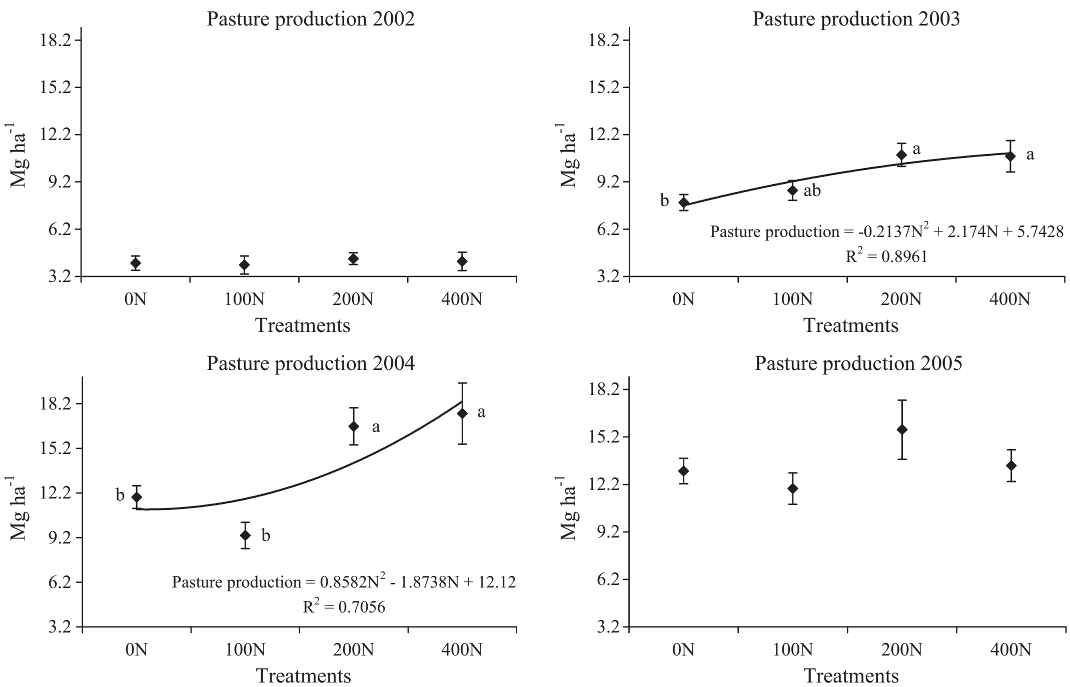

Fig. 4. Pasture production (Mg ha^{-1}) under the each fertiliser treatment in 2002, 2003, 2004 and 2005. 0 N: 0 kg total N ha^{-1}; 100 N: 100 kg total N ha^{-1}; 200 N: 200 kg total N ha^{-1} and 400 N: 400 kg total N ha^{-1}. Different letters indicate significant differences between treatments. Vertical lines indicate mean standard error. Only significant regressions are shown.

medium sewage sludge treatments. However, the proportion of *H. lanatus* L. was higher when the high sewage sludge treatment was applied as compared to the other treatments. The presence of sown species (*D. glomerata* L., *L. perenne* L. and *T. repens* L.) was low.

4. Discussion

The use of sewage sludge as a fertiliser is usually described as beneficial for plant growth due its contribution to the improvement of soil properties (Smith, 1996; Egiarte et al., 2009; Mosquera-Losada et al., 2006, 2011; Rigueiro-Rodríguez et al., 2010a,b). In this study, we found an initial amelioration of different soil properties such as EEC and Ca saturation percentage. The changes in Ca saturation percentage can be explained by the Ca inputs from the sewage sludge application (100 N applied 57.5 kg CO_3Ca ha^{-1}, 200 N added 115 kg CO_3Ca ha^{-1} and 400 N applied 229.95 kg CO_3Ca ha^{-1}). However, these Ca contributions to the soil were not enough to modify other soil properties such as soil pH. López-Díaz et al. (2007) used a silvopastoral system established with *Pinus radiata* D. Don to show that soil fertility increased as the pH and the Ca saturation percentage increased due to the input of Ca from sewage sludge. The change in soil pH observed by López-Díaz et al. (2007) may be due to the high dose of sewage sludge used in comparison to our study. Furthermore, the sewage sludge was applied for three consecutive years, which implies a higher total Ca input into the soil as compared to our study (230 kg CO_3Ca ha^{-1}, 461.4 kg CO_3Ca ha^{-1} and 692.4 kg CO_3Ca ha^{-1}) in the López-Díaz et al. (2007) experiment. The effects of additional Ca on soil improvement under favourable weather conditions are evident in the tree and pasture production results.

In 2006, the ranges of *Quercus rubra* L. heights and diameters were 2.25–3.11 m and 16.92–27.90 mm, respectively. These values were greater than the tree heights (1.38–1.99 m) and diameters (4–10 mm) reported by Kormanik et al. (2005) in a study carried

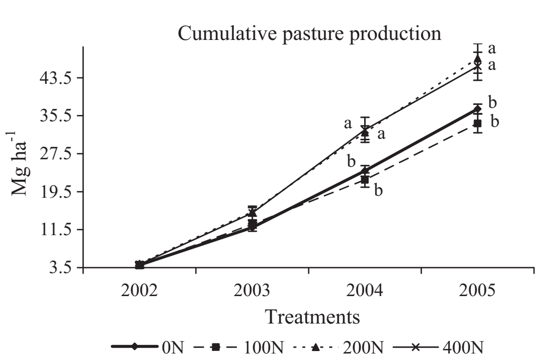

Fig. 5. Cumulative pasture production under each treatment for the period 2002–2005 (Mg ha^{-1}). 0 N, 0 kg total N ha^{-1}; 100 N: 100 kg total N ha^{-1}; 200 N: 200 kg total N ha^{-1} and 400 N: 400 kg total N ha^{-1}. Vertical lines indicate mean standard error.

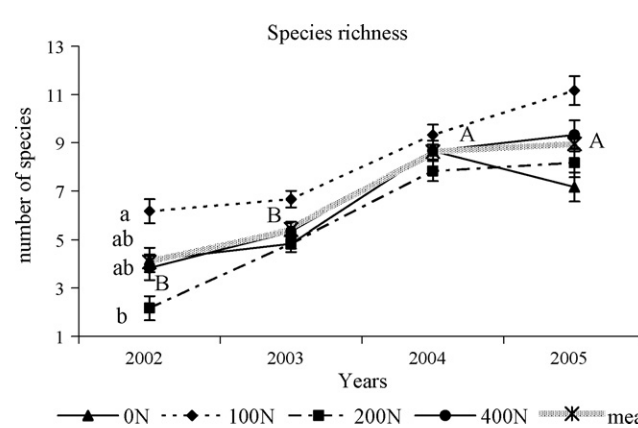

Fig. 6. Annual evolution of species richness under each treatment in 2002, 2003 2004 and 2005. 0 N: 0 kg total N ha^{-1}; 100 N: 100 kg total N ha^{-1}; 200 N: 200 kg total N ha^{-1} and 400 N: 400 kg total N ha^{-1}. Different capital letters indicate significant differences between years, and different lowercase letters indicate significant differences between treatment in each year. Vertical lines indicate mean standard error.

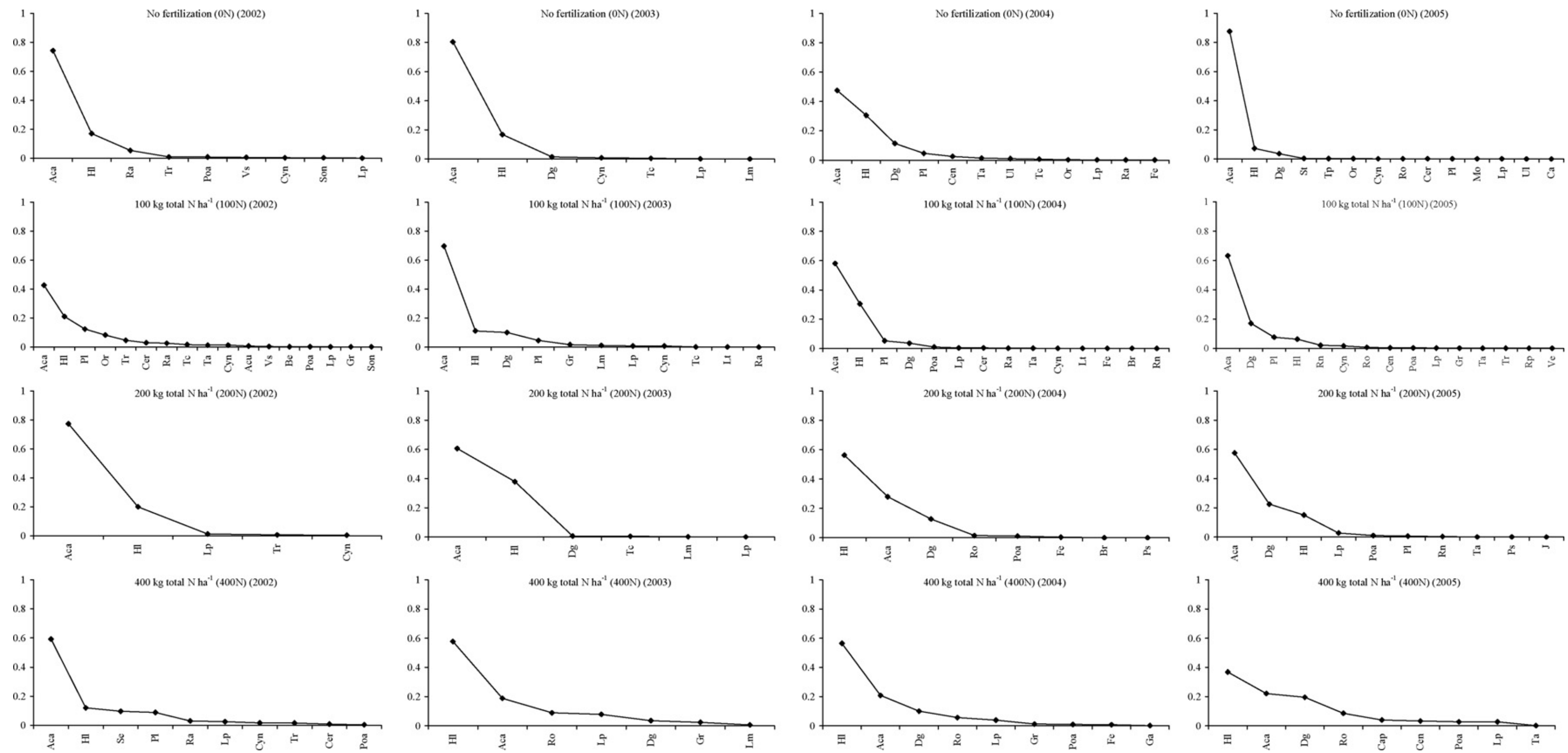

Fig. 7. Species abundance diagrams for the treatments applied in 2002, 2003, 2004 and 2005. Aca: *Agrostis capillaris* L., Acu: *Agrostis curtisii* Kerguélen, Be: *Bellis perennis* L., Br: *Bromus mollis* L., Ca: *Carduus* sp., Cap: *Capsella bursa-pastoris* L., Cen: *Centaurea limbata* Hoffmanns./Link, Cer: *Cerastium glomeratum* Thuill, Cyn: *Cynosurus cristatus* L., Dg: *Dactylis glomerata* L., Fe: *Festuca rubra* L., Ga: *Galium* sp., Gr: *Geranium rotundifolium* L., Hl: *Holcus lanatus* L., J: *Juncus effusus* L., Lm: *Lolium multiflorum* Lam., Lp: *Lolium perenne* L., Lt: *Lotus corniculatus* L., Mo: *Molinia caerulea* (L.) Moench, Or: *Ornithopus compressus* L., Pl: *Plantago lanceolata* L., Poa: *Poa pratensis* L., Ps: *Pseudarrhenatherum longifolium* (Thore) Rouy, Ra: *Rumex acetosa* L., Rn: *Ranunculus repens* L., Ro: *Rumex obtusifolius* L., Rp: *Raphanus raphanistrum* L., Se: *Senecio jacobaea* L., Son: *Sonchus oleraceus* L., St: *Stellaria media* L. (Vill), Ta: *Taraxacum officinale* Weber, Tc: *Trifolium campestre* Schreber, Tp: *Trifolium pratense* L., Tr: *Trifolium repens* L., Ul: *Ulex europaeus* L., Ve: *Veronica agrestis* L., and Vs: *Vicia sativa* L.

out in North Carolina after four years of experimentation on the same species. The largest tree heights were recorded at the medium and high sewage sludge treatments rather than the no fertilisation treatment. These results can be explained by the fact that these treatments resulted in high-nutrient inputs to the soil. Furthermore, the amount of N applied by these treatments may be too high for the pasture to take up but are "nevertheless" useful for the trees because the nitrate is leached to deeper soil horizons where tree roots are developed. Similar results were also reported by López-Díaz et al. (2009) and Rigueiro-Rodríguez et al. (2010a) regarding silvopastoral systems established under *Pinus radiata* D. Don in agrarian soils in Galicia. A reduction in soil nutrient leaching by root uptake in silvopastoral systems was also reported by Nair et al. (2007), Rigueiro-Rodríguez et al. (2008) and Mosquera-Losada et al. (2010a) as one of the main advantages of silvopastoral as compared with treeless pasture. Although the high doses of sewage sludge improved tree heights, it had no evident effect on tree diameters. This is likely due to the higher proportion of *H. lanatus* L. in this treatment as compared to the other treatments in which *A. capillaris* L. was the dominant species in the pasture. *H. lanatus* L. is a species associated with more fertile soils than *A. capillaris* L. (Grime et al., 2007) and can capture more soil N, which typically limits the diameter growth of trees. In 2008, Laliberté et al. (2008) performed a study by directly seeding *Quercus rubra* L. on recently abandoned pastureland in Canada to find that herbaceous vegetation had no early effect on tree height. However, it slightly decreased diameter, which could have long-term biological significance. In the present experiment it was shown that diameter development depends on the type of dominant herbaceous species growing in the silvopastoral system.

Similar studies carried out in abandoned agricultural soils in Galicia reported that the average production of the pasture was between 6 and 12 Mg ha^{-1} (Mosquera-Losada et al., 1999). In this study, this production range was surpassed in the last two years of the experiment in 2004 and 2005. However, annual pasture production was less than this reported range in 2002 and was similar to this reported range in 2003. The highest levels of annual pasture production in 2004 can be explained by the lack of drought during the summer months of this year, which increased the length of the growing season. This result was also observed by Rigueiro-Rodríguez et al. (2010a) and Mosquera-Losada et al., 2011 in silvopastoral systems established in the same area under *Pinus radiata* D. Don and *Populus canadensis* Moench, respectively. Moreover, in 2002, the mean monthly temperature was lower than the mean temperature over the previous 30 years, which could have limited pasture production and prevented a response to treatments in terms of pasture production. In 2003 and 2004, the medium and high sewage sludge treatments showed higher pasture production than the other treatments. This could be due to a residual effect (EPA, 1994; Smith, 1996) from N mineralisation after sewage sludge application for two consecutive years. Mosquera-Losada et al., 2011 and Rigueiro-Rodríguez et al. (2010a) also found high pasture production when the dose of the sewage sludge was increased. In 2005, significant differences were not detected between treatments because there was no further residual effect of sewage sludge application.

Even though a clear initial effect on soil fertility was found, pasture and tree development also affected soil characteristics and subsequently impacted species richness over time. In this study, a change in soil pH was observed in 2006 with respect to the beginning of the experiment (2003), but this was not a result of sewage sludge inputs. The change in soil pH can be attributed to the incorporation of pasture litter, including leaves and roots from *Quercus rubra* L., into the sandy soil. The trees were able to take up cations (Ca, K, Mg) that had been previously moved downward in the soil with percolating water and incorporate these cations again into the silvopastoral system soil after leaves fell. Soil improvement following the establishment of a tree plantation as compared to leaving open swards has been previously described by Mosquera-Losada et al., 2011. Soil EEC in our study was low and below 10 cmol (+) kg^{-1} soil, which can be explained by the high sand fraction in the soil at the experimental site (Brady and Weil, 2008). At the beginning of the study (2003), a change in soil EEC was observed when sewage sludge was applied (Smith, 1996). However, when sewage sludge application ceased, the effect of the treatments on EEC disappeared. This is likely due to the sandy soil in the experimental area, which would allow the cations to be easily leached through the soil profile. Moreover, it was also observed that EEC and thus most available cations were higher at the end of the experiment (2006) than in previous years; however, there were no differences between fertilisation dose treatments. The change in EEC can be explained by the establishment of the pasture and trees, which increased the organic matter input into the soil (Nieder et al., 2003); a similar phenomenon was described for *Pinus radiata* D. Don and *Betula alba* L. by Fernández-Núñez et al. (2010). In other silvopastoral systems established in the same area by Mosquera-Losada et al., 2011 and Rigueiro-Rodríguez et al. (2010b) using *Populus canadensis* Moench and *Fraxinus excelsior* L., respectively, similar results for pH and EEC were observed. It is important to highlight the increased Ca saturation percentage in the exchange complex and the reduction in the Al saturation percentage in 2006 as compared to 2003, 2004 and 2005 (Smith, 1996). However, the K saturation percentage in the exchange complex was lower at the end of the experiment in 2006 than in the other years of the study, and the Mg saturation percentage followed the same trend. A strong antagonism between Mg and Ca (O'Riordan et al., 1987; Vivekanandan et al., 1991; Rigueiro-Rodríguez et al., 2006) and between K and Ca in the soil has been described, with both Mg and K being preferentially leached (Barber, 1995; Rigueiro-Rodríguez et al., 2006), which could explain these results. Moreover, reduction in K at the end of the experiment in 2006 and the lack of differences between treatments may also be attributed to low K in the sewage sludge (Mosquera-Losada et al., 2010b).

Regarding species richness, it was observed that the number of species increased in 2004 and 2005 as compared with 2002 and 2003. These results can be explained by the change in soil pH because the less restrictive edaphic conditions lead to an increase in the number of species (Mosquera-Losada et al., 2009). Increasing soil pH and low fertiliser inputs increased species richness mainly due to the increase of dicots (better developed in cation rich environments) and the reduction of monocot species, which increases their competitive advantage under more nitrogen rich environment (Grime et al., 2007). Moreover, the silvopastoral system was established under *Quercus rubra* L., which is a deciduous species and allows better light penetration than conifers. Species richness should be higher in this type of silvopastoral system as compared to those established under exotic conifer, such as *Pinus radiata* D. Don, in Galicia once tree canopy closure happens (Mosquera-Losada et al., 2006; Rigueiro-Rodríguez et al., 2011). The low sewage sludge treatment resulted in higher species richness than the medium and high sewage sludge treatments. As reported by Thompson et al. (2001), the increase in fertilisation reduces the invasion of weeds and the number of species. In contrast, *A. capillaris* L. was the most abundant species in the study, probably due to the grazing sheep but mostly when low doses of sewage sludge were applied. *A. capillaris* L. grows vegetatively from stolons (Grime et al., 2007), which spread due to damage during sheep grazing. This result was also found by Krahulec et al. (2001) in a study that took place in the Krkonose Mountains (Czech Republic). However, *H. lanatus* L. appeared under the high sewage sludge treatment because this species is associated with more fertile soils than *A. capillaris* L. (Grime et al., 2007). In this study, a reduction in tree diameter due to the higher uptake of N of *H. lanatus* L. as compared to *A. capillaris* L was observed. In the present study, the presence of sown species (*D. glomerata* L., *L. perenne* L. and *T. repens* L.) was low because *D. glomerata* L. was not well established due to the drought and grazing sheep. Furthermore, *L. perenne* L. and *T. repens* L. require more fertile soils than that found in this study (Rigueiro-Rodríguez et al., 2000; Grime et al., 2007).

5. Conclusion

While the effect of sewage sludge on pasture production depended on the weather conditions of a specific year, tree growth and pasture production increased when 200 and 400 kg of total N ha^{-1} were applied. Thus, we advise application of approximately 200 kg of total N ha^{-1} to enhance both components in a silvopastoral system. Sewage sludge applications initially improved soil nutrient levels (EEC and Ca saturation percentage); however, the establishment of pasture and trees improved soil conditions and increased species diversity, showing the most diversity under 100 kg of total N ha^{-1} treatments.

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