



Residual effects of lime and sewage sludge inputs on soil fertility and tree and pasture production in a *Pinus radiata* D. Don silvopastoral system established in a very acidic soil

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ARTICLE INFO

Article history:

Received 1 February 2012

Received in revised form 1 August 2012

Accepted 2 August 2012

Keywords:

Agroforestry

Waste

Sowing

Afforestation

Dose

Fertilisation

ABSTRACT

In Galician (Spain) silvopastoral systems, nutrient availability to the pasture and trees can be limited by soil acidity. Liming and fertilisation with sewage sludge could enhance the productivity of silvopastoral systems (including understory and trees) by increasing Ca and reducing Al in the soil. This study evaluated changes in soil chemical properties, tree growth and understory production in test plots, both limed and unlimed, in a silvopastoral system located on an acidic forest soil under *Pinus radiata* D. Don. This research compared the effects of different doses of sewage sludge (160, 320 and 480 kg total N ha⁻¹) with the effects of mineral fertilisation (8% N – 24% P₂O₅ – 16% K₂O) and no fertilisation. The initial lime applications improved soil fertility (increasing soil pH, effective exchange capacity, and the saturation percentage of Ca and reducing the saturation percentage of Al) more than the sewage sludge. However, the most significant effects of sewage sludge were found over the long term after high doses of sewage sludge were applied (480 kg total N ha⁻¹). Therefore, the use of sewage sludge as a fertiliser improves both soil fertility and the productivity of silvopastoral systems in the long term as long as an adequate disposal of this residue is guaranteed.

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1. Introduction

Wildfires are one of the main environmental problems in the forests of northern Spain (Silva-Pando et al., 2002; Rigueiro-Rodríguez et al., 2009) because traditional afforestation practices in this region have transformed agricultural land into forest land without understory management, which is costly (Rigueiro-Rodríguez et al., 2008). Galicia, located in northwestern Spain, is one of the most fire-prone areas in the country, accounting for approximately 35% of the area of Spain affected by forest fires in 2010 (MARM, 2010). Therefore, adequate management of these afforested areas is needed to prevent forest fires. Silvopastoral systems are a sustainable land management strategy in areas where trees, animals and pasture are integrated (Mosquera-Losada et al., 2008). Such systems are promoted by the EU (Council Regulation 1698/2005 (EU, 2005)) due to their environmental benefits; for example, the integration of grazing in a forest reduces fuel loads and, thus, the risk of fire (Rigueiro-Rodríguez et al., 2009; Pasalodos-Tato et al., 2009). Moreover, this type of agroforestry system has other environmental advantages; it improves nutrient recycling, controls soil erosion, promotes biodiversity and increases carbon

sequestration (Rigueiro-Rodríguez et al., 2008; Howlett et al., 2011), and its multifunctionality has many economic and social benefits (Rozados-Lorenzo et al., 2007). *Pinus radiata* D. Don is the most commonly used exotic conifer for afforestation and reforestation in Spain, especially in the north, due to its fast growth (its rotation age is between 25 and 35 years) (Crecente-Campo et al., 2009). In Galicia, it covers an estimated area of 90,000 ha (11% of the wooded area) (Xunta de Galicia, 2001). Moreover, this is one of the most widely used tree species in the establishment of silvopastoral systems in areas such as Australia, New Zealand and Chile (Peri et al., 2007; Benavides et al., 2009). The establishment of silvopastoral systems with *P. radiata* D. Don is important from an economic and environmental point of view because the pasture component provides an earlier economic return (Fernández-Núñez et al., 2007), and the fire risk is lower than with exclusive forest systems (Rigueiro-Rodríguez et al., 2005).

Soils in Galicia tend to be acidic because of the region's humid climate, the prevalence of subtractive systems, frequent fires and, often, acidic parent material (Álvarez et al., 2002), which can limit the productivity of silvopastoral systems at both the understory and the tree level. Therefore, it is advisable to use liming and fertilisation to improve soil fertility as well as the productivity of the tree and understory vegetation (Rigueiro-Rodríguez et al., 2008). Liming is a common practice in Galician soils devoted to pasture production; the use of liming tends to reduce the natural acidity

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of soil and promote humus decomposition and nutrient mobilisation in acidic soils (Baley, 1995; Álvarez et al., 2010; Saarsalmi et al., 2011). Either mineral or organic fertiliser can be used. However, due to recent increases in inorganic fertiliser prices, their use has been reduced in the EU (EFMA, 2009). They are being replaced by organic fertilisers such as sewage sludge, which provides a cheaper source of N. The use of sewage sludge as a fertiliser has been adopted in many countries around the world due to its specific organic matter and macronutrient content, particularly its N and P content (Cogger et al., 2004; Mosquera-Losada et al., 2010). However, when this residue is used as a fertiliser, its heavy metal concentration must be considered. Indeed, this heavy metal concentration is higher than normal levels in soil (Smith, 1996), and it is regulated in Spain by the R.D. 1310/1990 (BOE, 1990) and by the European Directive 86/278/EEC (EU, 1986). It is important to apply no more than an effective dose of the sewage sludge because a dose exceeding the crop needs could cause nitrate to leach into the ground water and contaminate it (EPA, 1994). Several studies have demonstrated that the nitrate-leaching risk tends to be higher in areas used exclusively for agronomy (i.e., grasslands) than in silvopastoral systems; in the latter, the trees may use the excess nitrate from the pasture (Nair et al., 2008; Mosquera-Losada et al., 2011a). The calculation of the sewage sludge dose should consider both crop needs and the mineralisation rate. The residual effect of sewage sludge is more important than that of mineral fertilisers. Long-term sewage sludge input effects should be considered when measuring the improvement in soil fertility, the understory and tree production.

The impact of the application of lime and inorganic and organic fertilisers on the fertility of agronomic soils with pasture has been already studied (Li et al., 2006; Mosquera-Losada et al., 2011b). However, the long-term effects on either the silvopastoral systems established in forest soils or on tree growth have not been adequately evaluated. This study evaluated changes in soil chemical properties, tree growth and understory production in test plots, both limed and unlimed, in a silvopastoral system located on an acidic forest soil under *P. radiata* D. Don. This research compared the effects of different doses of sewage sludge (160, 320 and 480 kg total N ha⁻¹) with the effects of mineral fertilisation (8% N–24% P₂O₅–16% K₂O) and no fertilisation.

2. Materials and methods

2.1. Characteristics of the study site

The experiment was conducted in Pol (Lugo, Galicia, northwestern Spain, European Atlantic Biogeographic Region) at an altitude of 748 m above sea level. Fig. 1 shows the mean monthly temperatures and precipitation for 1998, 2001, 2002 and 2003 as well as the mean for the previous 30 years. For the months of November and December 2002, there are no data for the mean monthly temperatures and precipitation due to a technical problem at the weather station. The data show that 1998 was the driest year, with precipitation levels (942 mm) in all months that were lower than the annual mean for the study area (1083 mm). April 1998, which was a very rainy month (324 mm), was an exception. In 2001, 2002 and 2003, the total annual rainfall (1233.5 mm, 1296 mm and 1111 mm) was higher than that of any year in the last 30 years due to especially high precipitation levels at the beginning of 2001 and 2003 and in the last months of 2002 and 2003. However, in these years, drought periods were also registered, mainly in the summer months. The annual mean temperature was mild (12 °C), with low temperatures at the beginning and the end of the years under study, which had a limiting effect on pasture production and tree growth.

The experiment was carried out on forestland. The soil was sedimentary and classified as Umbrisol (FAO, 1998) or Inceptisol

(USDA, 2006), with a depth of approximately 50 cm. It was very acidic (the initial soil pH in KCl was 4.30), with a high initial concentration of soil organic matter (SOM) (12.32%) and N (0.52%). At the beginning of the experiment, all of the 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). The soil texture was a sandy clay loam (63% sand, 26% clay and 11% silt).

2.2. Experimental design

The experiment was established in 1997 and used a five-year-old *P. radiata* D. Don planted in 1993 with a density of 1667 trees ha⁻¹, which have a mean height and diameter of 2.15 m and 5.19 cm, respectively. The experiment used a randomised block design with three replicates. In autumn of 1997, the soil was cleared and ploughed, and the experimental plots were established. Each plot had a square of 5 × 5 trees and occupied 96 m², and plots were sown in autumn of 1997 with a mixture of 25 kg ha⁻¹ of *Lolium perenne* var. Brigantia, 10 kg ha⁻¹ of *Dactylis glomerata* var. Artabro and 4 kg ha⁻¹ of *Trifolium repens* cv. Huia after ploughing. All cell plots were initially fertilised with 120 kg P₂O₅ ha⁻¹ and 200 kg K₂O ha⁻¹ in autumn 1997 to initially improve pasture establishment. The established nine treatments were no fertilisation (NF) and three sewage sludge doses based on N application (S1: 160 kg total N ha⁻¹; S2: 320 kg total N ha⁻¹; and S3: 480 kg total N ha⁻¹), with or without liming applied in 1997 before sowing (2.5 t CaCO₃ ha⁻¹). A no fertilisation (NF) treatment was also established as a control in the limed and unlimed plots. A control mineral treatment (MIN) in the unlimed plots was also included because the combination of lime and the MIN treatment is not usually applied in the area. The MIN treatment consisted of the application of 500 kg of 8% N – 24% P₂O₅ – 16% K₂O ha⁻¹ in accordance with conventional practice for fertilising pastures from 1998 to 2003. Sewage sludge was applied in 1998, 1999 and 2000. To evaluate the residual effect of these treatments, mineral fertiliser was added in 2001, 2002 and 2003 in the plots previously fertilised with sewage sludge, initially because in the higher doses the sludge was not easily incorporated (some unincorporated sewage sludge rests were visually visible) and later to improve pasture production.

2.3. Sewage sludge

The anaerobically digested sludge came from a municipal waste treatment plant in Lugo. Following the U.S. Environmental Protection Agency (EPA) recommendations, the doses were based on the percentage of total N and the dry matter content of the sewage sludge (Table 2) (EPA, 1994); the EPA established that approximately 25% of the total applied N is mineralised during the first year when sewage sludge is anaerobically digested. The EU Directive 86/278/CEE (EU, 1986) and the 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 1998, 1999 and 2000 is summarised in Table 2.

2.4. Field samplings and laboratory analyses

A composite soil sample per plot was randomly taken at a depth of 0 to 5.5 cm in December of 1998, 2001, 2002 and 2003. In the laboratory, the soil samples were air-dried, passed through a 2 mm sieve and ground with an agate mortar. The soil pH was determined in KCl (1:2.5) (Faithfull, 2002), and extraction with 0.6N BaCl₂ was used to determine the concentrations of Al and the exchangeable cations (K, Ca, Mg and Na) in the exchange complex (Mosquera and Mombiela, 1986). The K, Ca, Mg and Na exchangeable

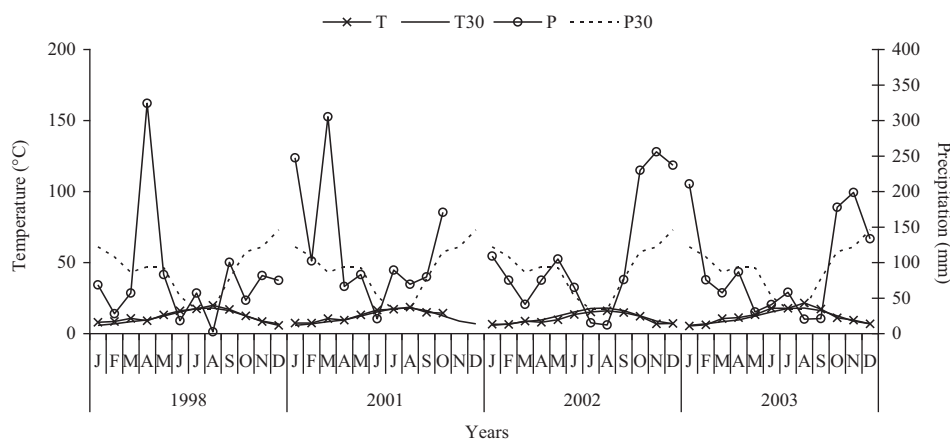


Fig. 1. Monthly precipitation and mean temperatures for the study area in 1998, 2001, 2002 and 2003 and mean data for the last 30 years. T: mean monthly temperature ($^{\circ}\text{C}$), T30: mean temperature over the last 30 years ($^{\circ}\text{C}$), P: monthly precipitation (mm) and P30: mean precipitation over the last 30 years (mm).

Table 1

Heavy metal concentrations in 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 (–) indicates an element concentration below the detection limit of the technique used for its determination.

	Heavy metal concentrations					
	mg kg ⁻¹					
	Zn	Cu	Cr	Cd	Ni	Pb
Initial soil	17.2	8.2	13.2	–	–	–
Spanish legal limits	150–450	50–210	100–150	1–3	30–112	50–300

concentrations were measured with a VARIAN 220FS Spectrophotometer using the atomic emissions for K and Na and the absorptions for Ca and Mg. The Al concentrations were analysed after valoration with 0.01 N NaOH using phenolphthalein (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).

The tree total height and normal diameter at 1.30 m were measured in the inner nine trees of each plot in January 1998 and 2001 and in December 2003 with a pole and callipers, respectively, to avoid the border effect.

The estimated phytomass production (i.e., the sum of the pasture production, the needle production and the senescent material production) was determined by randomly collecting four pasture samples. 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 July and December of 1998 and in May, July and November of 1999, 2000, 2001, 2002 and 2003. At the laboratory, two of the pasture samples were dried (72 h at 60 $^{\circ}\text{C}$) and weighed to estimate phytomass production, and the other two were separated by hand according to the different species and then dried (72 h at 60 $^{\circ}\text{C}$) to determine their botanical composition. The cumulative phytomass production was calculated by summing the consecutive harvests of the phytomass.

Table 2

Chemical properties of the sewage sludge 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).

Parameters	Values			
	Anaerobic sludge (1998)	Anaerobic sludge (1999)	Anaerobic sludge (2000)	Spanish legal limits
Dry matter, %	25	25	23.5	
pH	6.9	6.9	6.9	
N, g kg ⁻¹	32.1	32.1	42.3	
P, g kg ⁻¹	9.3	5.2	16.5	
K, g kg ⁻¹	2.5	2.5	2.6	
Ca, g kg ⁻¹	6.7	6.9	6.9	
Mg, g kg ⁻¹	5.4	4.3	6.5	
Na, g kg ⁻¹	0.8	0.2	1.4	
Fe, g kg ⁻¹	19.5	16.1	22.9	
Mn, mg kg ⁻¹	228	164	292	
Zn, mg kg ⁻¹	821	746	1320	1000–1500
Cu, mg kg ⁻¹	244	154	241	1000–1750
Cr, mg kg ⁻¹	39	141	74	300–400
Cd, mg kg ⁻¹	5	1	1.5	2500–4000
Ni, mg kg ⁻¹	21	30	49	20–40
Pb, mg kg ⁻¹	203	94.7	184	750–1200

2.5. Statistical analysis

The soil variables were analysed with repeated ANOVA measures (proc glm procedure), and Mauchly's criterion was used to test for sphericity. If sphericity assumption was met then univariate approach output was used, otherwise multivariate output (Wilks' Lambda test was taken into account). The model used was $Y_{ij} = \mu + A_i + T_j + TA_{ji} + \varepsilon_{ij}$, where Y_{ij} is the dependent variable, μ is the variable mean, A_i is the year i , T_j indicates treatment j , TA_{ji} is the treatment-year interaction and ε_{ij} is the error.

The data obtained from the soil, trees and phytomass were analysed by ANOVA (proc glm procedure) using the models $Y_{ijk} = \mu + L_i + F_j + B_k + LF_{ij} + LB_{ik} + FB_{jk} + \varepsilon_{ijk}$ and $Y_{ik} = \mu + T_i + B_k + TB_{ik} + \varepsilon_{ik}$, where Y_{ijk} and Y_{ik} are the dependent variables, μ is the variable mean, L_i is the lime effect i , F_j is the fertilisation effect j , B_k is block k , LF_{ij} is the lime-fertilisation interaction (lime \times fertilisation), LB_{ik} is the lime-block interaction, FB_{jk} is the fertilisation-block interaction, T_i indicates treatment i , TB_{ik} is the treatment-block interaction and ε_{ijk} and ε_{ik} are the errors.

The LSD test was used for subsequent pairwise comparisons ($p < 0.05$; $\alpha = 0.05$) if the ANOVA was significant. The statistical software package SAS (2001) was used for all analyses. Only the data that the ANOVA results indicated were significant are presented in this paper.

3. Results

3.1. Soil

3.1.1. KCl soil pH

Table 3 shows that the KCl soil pH was significantly lower in 2003 than in 1998 and 2001. As observed in Fig. 2, at the beginning of the study in 1998, soil pH was higher in all limed treatments than in the treatments without lime ($p < 0.001$). However, for 2001, the lime effect was not evident when the same dose of fertiliser was compared. Finally, the lime inputs significantly increased the KCl soil pH based on a comparisons between the limed and unlimed treatments at low (S1: 160 kg total N ha⁻¹) and medium (S2: 320 kg total N ha⁻¹) doses of sewage sludge ($p < 0.001$) in 2002 and the high (S3: 480 kg total N ha⁻¹) dose in 2003 ($p < 0.05$). Moreover, for all limed treatments, the pH was lower in soil with no fertilisation than in all soil receiving any dose of sludge in 2002, and the pH was also lower in soil with no fertilisation than in soil receiving a high dose of sewage sludge in 2003. Finally, when all established treatments were compared with the control treatments (i.e., MIN and NF without lime), the combination of lime and sewage sludge caused greater increases in soil pH than the control treatments in 1998, 2001 and 2002 and the mineral treatment in 2003.

3.1.2. EEC and the saturation percentages of Al, K, Ca, Mg and Na in the soil exchange complex

The soil EEC and the saturation percentages of Ca and Mg in the soil exchange complex were significantly higher in 2001, 2002 and 2003 than in 1998 (Table 3), with the exception of the percentage of Ca saturation in 2001. By contrast, the saturation percentage of Al decreased significantly over time. The saturation percentages of K and Na were higher in the soil exchange complex in 2001 than in 1998, but in 2002 and 2003, the percentages were similar to those observed in 1998 (Table 3).

In 1998, the ECC was significantly increased by the limed treatment ($p < 0.05$) when no fertilisation was applied (Fig. 3). However, the improvement in the ECC as a consequence of the limed treatment disappeared in subsequent years of the study. For lime-treated soil, a higher EEC was found in 1998 in soil fertilised with

a high dose of sewage sludge than in soil receiving a medium dose. The positive effect of the high dose of sewage sludge on soil ECC was also observed in the unlimed treatments as compared to the NF plots in 2002 ($p < 0.05$). At the same time, the combination of lime and a high dose of sewage sludge caused an increase in the soil EEC as compared with the control treatments in 1998; a medium dose of sewage sludge combined with lime caused a similar increase in 2002.

The saturation percentages of the different cations (Al, K, Ca, Mg and Na) in the soil EEC can be seen in Fig. 4. The saturation percentage of Al was significantly reduced by the lime inputs in 1998 when the same levels and types of fertiliser were compared ($p < 0.001$); moreover, there were no differences between the limed and unlimed treatments in 2002 for the treatments with the high and medium doses of sewage sludge. There was no significant difference between the limed and the unlimed treatments for the high dose in 2003. Moreover, in 1998, the saturation percentage of Al in the limed treatments was lower in the fertilised plots receiving the high dose of sewage sludge than in the limed plots that received no fertilisation. In the later years (2002 and 2003), the fertilisation with sewage sludge caused a significant reduction of the Al saturation percentage, independently of the dose applied, as compared with the NF treatment (for 2002, $p < 0.001$; for 2003, $p < 0.05$); the only exception was for the low dose of sewage sludge in the last year of the study in 2003. Based on a comparison of all treatments with the control treatments in 1998, 2002 and 2003, adding lime reduced the saturation percentage of Al in all plots except in the limed and NF treatment in 2002 and 2003. In general, the saturation percentage of Ca was high in the treatments with a lower saturation percentage of Al in 1998 and 2002 ($p < 0.001$) and in 2003 ($p < 0.05$).

In addition, in 2002, the application of lime in the NF plots decreased the saturation percentage of K in the soil exchange complex ($p < 0.05$). A lower saturation percentage of K was observed in the plots fertilised with a high dose of sewage sludge than in the unlimed and the NF plots in the same year. Moreover, the combination of lime and the medium or high dose of sewage sludge reduced the saturation percentage of K as compared with the control treatments in 2002. This effect was found only when comparing with the MIN treatment in 2003 ($p < 0.05$).

The proportion of Mg was lower in the limed plots and the plots that were not fertilised or that were fertilised with the medium dose of sewage sludge as compared to the plots that received the same fertilisation treatments but without lime ($p < 0.05$) in 2002. In addition, in 2003, the inputs of lime in the plots receiving a high dose of sewage sludge caused the Mg saturation percentage to increase ($p < 0.01$). Fertilisation with the high dose of sewage sludge within those limed treatments increased the Mg saturation percentage in the soil exchange complex over that of both the NF treatment in 2002 and all treatments in 2003. However, among the unlimed treatments, the highest saturation percentage of Mg was found in the plots fertilised with the medium dose of sewage sludge as compared with the NF plots and the low sewage sludge treatments. Finally, in this study, the Na saturation percentage was not modified by any of the treatments ($p > 0.05$).

3.2. Tree height and diameter

Fig. 5 shows the tree heights and diameters for each treatment in 2001 and 2003. Tree heights were significantly affected by the lime and fertilisation interaction in 2001 and 2003, while only tree diameters were affected in 2001 ($p < 0.05$). These tree variables were positively affected by the limed treatment in the NF plots. However, in plots fertilised with sewage sludge, there were no observed differences across the treatments ($p > 0.05$).

Table 3

Soil pH, effective exchange capacity (EEC) ($\text{cmol}(+) \text{kg}^{-1}$) and the saturation percentage of Al, K, Ca, Mg and Na in the soil exchange complex (%) in 1998, 2001, 2002 and 2003. Different letters indicate significant differences between years. *: $p < 0.05$, ***: $p < 0.001$, SEM: mean standard error.

Parameter	Year				Year effect	SEM
	1998	2001	2002	2003		
KCl pH	4.13 a	4.05 ab	3.96 bc	3.91 c	***	0.04
EEC ($\text{cmol}(+) \text{kg}^{-1}$)	5.92 b	8.87 a	9.31 a	8.59 a	***	0.23
Al (%)	51.31 a	34.35 b	41.41 b	34.96 b	***	2.32
K (%)	1.57 bc	8.79 a	1.21 c	1.96 b	***	0.33
Ca (%)	39.14 b	42.23 ab	49.04 a	49.61 a	*	2.24
Mg (%)	5.52 b	6.61 b	6.33 b	10.87 a	***	0.31
Na (%)	2.46 b	8.02 a	2.02 b	2.60 b	***	0.27

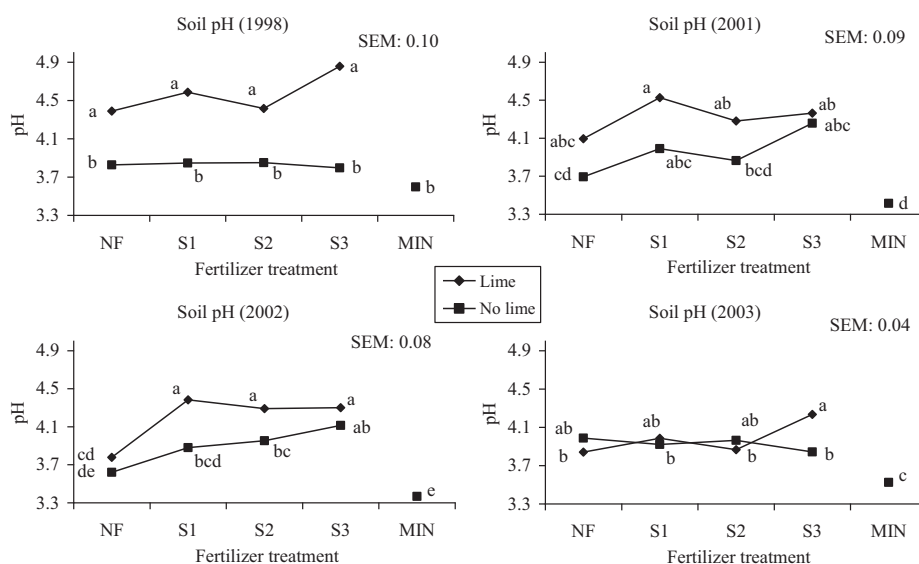


Fig. 2. Soil pH under each treatment in 1998, 2001, 2002 and 2003. NF: no fertiliser; S1: low sewage sludge dose ($160 \text{ kg total N ha}^{-1}$); S2: medium sewage sludge dose ($320 \text{ kg total N ha}^{-1}$); S3: high sewage sludge dose ($480 \text{ kg total N ha}^{-1}$) and MIN: mineral fertiliser. Different letters indicate significant differences between fertiliser treatments. SEM: mean standard error.

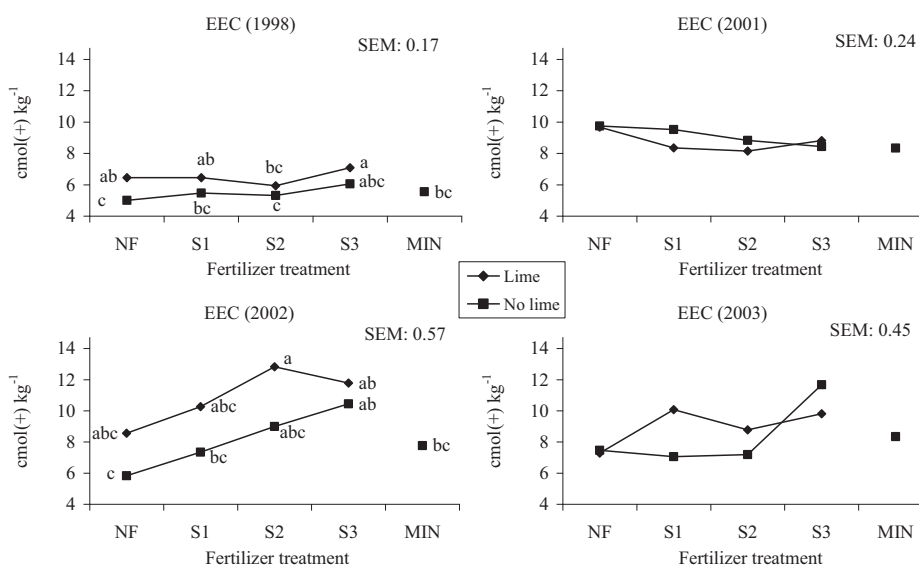


Fig. 3. Effective exchange capacity (EEC) ($\text{cmol}(+) \text{kg}^{-1}$) under each treatment in 1998, 2001, 2002 and 2003. NF: no fertiliser; S1: low sewage sludge dose ($160 \text{ kg total N ha}^{-1}$); S2: medium sewage sludge dose ($320 \text{ kg total N ha}^{-1}$); S3: high sewage sludge dose ($480 \text{ kg total N ha}^{-1}$) and MIN: mineral fertiliser. Different letters indicate significant differences between fertiliser treatments. SEM: mean standard error.

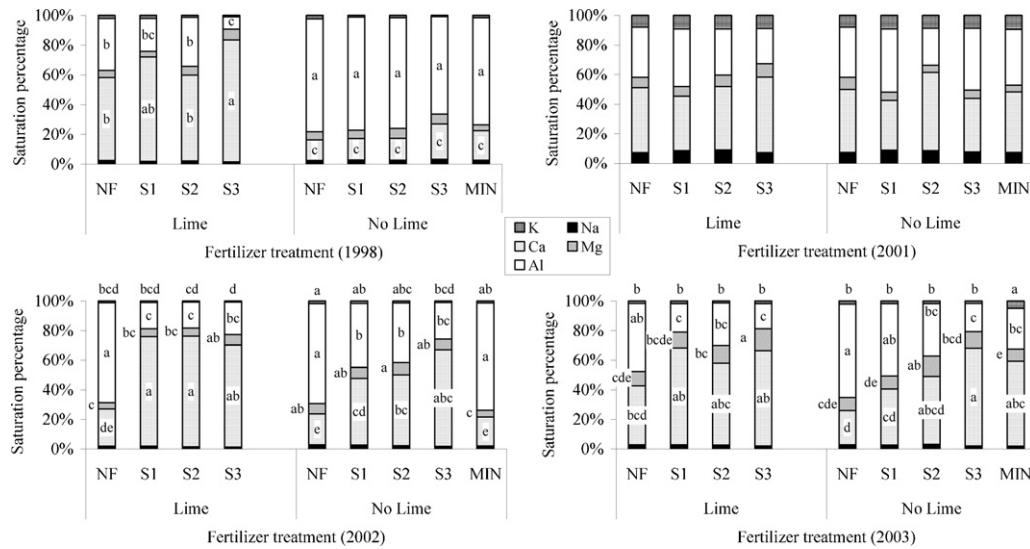


Fig. 4. Saturation percentage of Al, K, Ca, Mg and Na in soil exchange complex (%) (b) under each treatment in 1998, 2001, 2002 and 2003. NF: no fertiliser; S1: low sewage sludge dose (160 kg total N ha⁻¹); S2: medium sewage sludge dose (320 kg total N ha⁻¹); S3: high sewage sludge dose (480 kg total N ha⁻¹) and MIN: mineral fertiliser. Different letters indicate significant differences between fertiliser treatments.

3.3. Cumulative phytomass production

The cumulative phytomass production during the experimental period is shown in Fig. 6. In 1999, lime was found to have a significant effect ($p < 0.05$) on cumulative phytomass production; production was 11.87 Mg ha⁻¹ in the lime-treated plots and 10.93 Mg ha⁻¹ in the plots with no lime. However, this effect was not observed in the other years of the study ($p > 0.05$). Moreover, in 1998 and 1999, the cumulative phytomass production was significantly affected by the type of fertilisation ($p < 0.001$) and, from 2000 to 2003, by the lime and fertilisation interaction ($p < 0.05$). The cumulative phytomass production was significantly higher when the medium or high dose of sewage sludge was applied as opposed to other treatments in 1998 (NF: 3.65^b; S1: 3.88^b; S2: 4.8^a; S3: 5.68^a; MIN: 3.54^b expressed as Mg ha⁻¹) and 1999 (NF: 9.33^c; S1: 10.26^c; S2: 12.47^b; S3: 14.45^a; MIN: 9.10^c expressed as Mg ha⁻¹); note that the different superscript letters indicate significant differences among the treatments. Moreover, from 2000 to 2003, the addition of lime and the high dose of sewage sludge caused a greater increase in the cumulative phytomass production as compared to the other limed treatments and the control treatments.

4. Discussion

The fertility of the soil in this study is considered low because the soil pH is very acidic (i.e., 3.5–4.8) (Slattery et al., 1999), the soil EEC is low (i.e., 5–11.8 cmol(+) kg⁻¹) (Fuentes-Yagüe, 1999), and the saturation percentage of Al is high (namely, up to 76% in some treatments). The acidity of the soil could be due to the type of bedrock (mainly quartz) and to the fact that the soil has not been recently limed or fertilised, suggesting that cations either were extracted by the pasture and the trees or leached out of the soil (Adams et al., 2001). Moreover, the low soil EEC could be due to the high proportion of sand that it contains (63%) (Brady and Weil, 2008; Rigueiro-Rodríguez et al., 2010a and Mosquera-Losada et al., 2011b). In the Galician silvopastoral systems, low soil pH and low soil EEC can limit pasture production (Whitehead, 2000; Nilsson, 2003) and tree growth (Sánchez-Rodríguez et al., 2002) due to low nutrient availability. However, these soil variables could be modified by applying lime or organic fertilisers such as sewage sludge (Mosquera-Losada et al., 2011b). In this study, the mean soil pH in 2003 was low compared to previous years. This result could be explained by the effect of the mineral treatment on the mean soil pH. Mineral fertilisation usually increases N

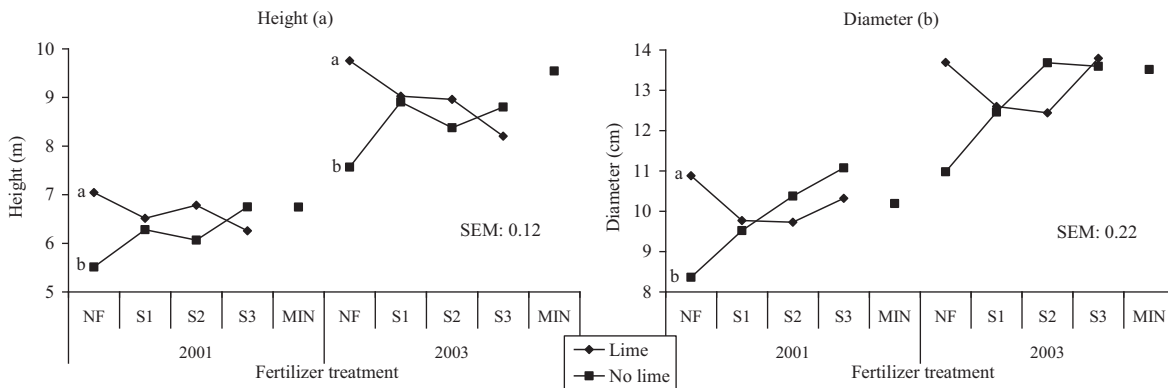


Fig. 5. Tree heights (m) (a) and tree diameters (cm) (b) under each treatment in 2001 and 2003. NF: no fertiliser; S1: low sewage sludge dose (160 kg total N ha⁻¹); S2: medium sewage sludge dose (320 kg total N ha⁻¹); S3: high sewage sludge dose (480 kg total N ha⁻¹) and MIN: mineral fertiliser. Different letters indicate significant differences between limed treatments within each fertiliser treatment. SEM: mean standard error.

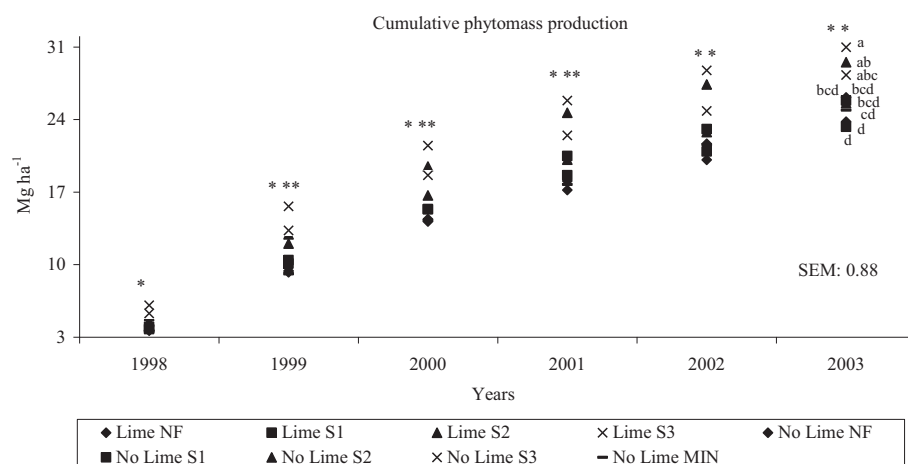


Fig. 6. Cumulative phytomass production under each treatment for the period 1998–2003 (Mg ha^{-1}). NF: no fertiliser; S1: low sewage sludge dose ($160 \text{ kg total N ha}^{-1}$); S2: medium sewage sludge dose ($320 \text{ kg total N ha}^{-1}$); S3: high sewage sludge dose ($480 \text{ kg total N ha}^{-1}$) and MIN: mineral fertiliser. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. Different letters indicate significant differences between fertiliser treatments. SEM: mean standard error.

mineralisation, specifically at the step at which NH_4^+ transforms into NO_3^- and H^+ is released into the soil solution media after NO_3^- is leached by rainfall (Whitehead, 1995). This in turn can increase tree and pasture cation extractions from the soil, thus causing soil acidification (Mosquera-Losada et al., 2006). The soil pH could have been reduced by the deposit of acidifying materials from the trees, such as pine needles. The negative effect of fast-growing conifer plantations compared with broadleaves on soil pH was observed by Adams et al. (2001) and Rigueiro-Rodríguez et al. (2012) in grassland afforested with conifers. Although soil pH decreased from the start to the end of the study, the EEC and the Ca percentage in the EEC increased. Lime, sewage sludge fertilisation and the broad use of mineral fertiliser in all the plots from 2001 could also explain the increased soil EEC and the availability of basic cations in 2001; the input of inorganic N probably reduced the C/N ratio, increasing the mineralisation of soil organic matter (Whitehead, 1995) and therefore the availability of cations for the pasture and trees. Nevertheless, it is important to highlight the reduction of the Al saturation percentage in the exchange complex in 2003 as compared to 1998 and, consequently, the increase of the Ca saturation percentage as a result of adding lime (Prado et al., 2007) and sewage sludge (Ferreiro-Domínguez et al., 2011) to the soil. Moreover, although in 2001 an increase of K and Na saturation percentages in the exchange complex was observed, the proportion of these cations decreased from 2002, probably due to the lixiviation of K and Na through the soil profile because, in the last three months of 2002 and 2003, the registered precipitations were high in comparison with the mean precipitation for the previous 30 years. Na and K are the most soluble cations of the soil EEC ($\text{Na}^+ > \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{Al}^{3+}$) (Calvo et al., 1987; Álvarez et al., 1992).

A comparison of the effects of lime and sewage sludge on all soil variables shows that, initially, the effect of lime was greater than that of sewage sludge, which may be because the lime was responsible for higher inputs of Ca than sewage sludge (López-Díaz et al., 2007; Mosquera-Losada et al., 2011b). However, the effects of sewage sludge were similar to those observed by Mosquera-Losada et al. (2011c) in silvopastoral systems established with *P. radiata* D. Don in acidic soils (3.87) receiving much lower inputs of sewage sludge (50 and $100 \text{ kg total N ha}^{-1}$), which indicates that sewage has a higher residual effect than lime (EPA, 1994). The residual effects of the limed treatment gradually declined in the years after its application, as evidenced by the fact that, in the first years of the study (1998–2001), pasture production and tree growth were higher in the limed plots than in those not receiving

limed treatment (Mosquera-Losada et al., 2001; López-Díaz et al., 2007), which indicates that the nutrient uptake by the trees and the pasture was higher in the limed plots. Moreover, the limed plots had a higher proportion of *Dactylis glomerata* L. in the pasture than the unlimed plots (Mosquera-Losada et al., 2001). This species is more extractive than other grasses (Grime et al., 2007), which may have increased the cation soil extractions and reduced the residual effects of the lime. The positive effect of the lime on the soil pH, the EEC and the saturation percentage of Al could be attributed to the increase in the exchangeable Ca (Slattery et al., 1995), which tends to improve the physical and chemical properties of the soil by increasing the pH, EEC and microbial activity (Baley, 1995; Álvarez et al., 2009; Flower and Crabtree, 2011), causing organic mineralisation and, therefore, nutrient release (Wheeler, 1998). In comparison with the mineral fertiliser and the no fertilisation treatment, the application of sewage sludge also increased the soil pH and EEC and reduced the saturation percentage of Al. These results may be because the pH of the sewage sludge was higher than that of the soil, and the sludge added more Ca, Mg and micronutrients to the soil than the mineral fertiliser did (Smith, 1996; López-Díaz et al., 2007; Mosquera-Losada et al., 2010). Data on the effects of sewage sludge showed that, at the end of the experiment, the levels of the main variables under study in the plots fertilised with the high (S3: $480 \text{ kg total N ha}^{-1}$) doses of sewage sludge were similar across the limed and the unlimed plots. This finding is important because, due to the increase in the mineralisation rate, mineral fertilisation of the plots previously fertilised with sewage sludge probably favoured the incorporation of patches of sewage sludge in the soil observed in 2001 (López-Díaz et al., 2007). Once the sewage sludge was incorporated into the soil, the enhanced effect of the high dose of sewage sludge on the soil pH, the EEC and the main cations of the exchange complex (Ca and Al) between 1998 and 2000 could be explained by the higher total Ca input into the soil from the high dose ($692.4 \text{ kg CO}_3\text{Ca ha}^{-1}$) as compared with the low ($230 \text{ kg CO}_3\text{Ca ha}^{-1}$) dose and medium ($461.4 \text{ kg CO}_3\text{Ca ha}^{-1}$) dose of sewage sludge. In poplar silvopastoral systems established in the same area and fertilised with different doses of sewage sludge (200 and $400 \text{ kg total N ha}^{-1}$), the soil fertility of the plots fertilised with the high dose of sewage sludge showed greater improvement than the soil fertility of plots receiving the low dose (Rigueiro-Rodríguez et al., 2010b; Mosquera-Losada et al., 2011b). Finally, data on the saturation percentages of K and Mg show that, due to low K levels in the sludge, plots fertilised with minerals had a higher proportion of K in the soil exchange complex than those

fertilised with sewage sludge in 2003 (Mosquera-Losada et al., 2010). The saturation percentage of Mg and K tended to decrease in the treatments with more Ca due to the strong antagonism between Mg and Ca (O'Riordan et al., 1987; Vivekanandan et al., 1991; Ferreiro-Domínguez et al., 2011) and between K and Ca, with both Mg and K being preferentially leached (Barber, 1995; Ferreiro-Domínguez et al., 2011).

Tree growth depends on the site quality, which is influenced by climate and by soil fertility. In accordance with the site quality curves of *P. radiata* D. Don in Galicia, the site in this study is of low quality. Therefore, despite Galicia's optimal climate for *P. radiata* D. Don development (Dans et al., 1999), the low soil fertility of the experiment site probably limited tree growth. The study found that the tree heights in 2001 and 2003 and the tree diameters in 2001 were higher in the no fertilisation plots with lime than they were in the no fertilisation plots without lime. This result could be explained by the input of Ca into the soil from liming, which probably increased the mineralisation rate of the soil organic matter and, therefore, the availability of nutrients. The pasture was not able to take up these nutrients for absorbance by trees because of the deeper root structure at that stage of development, which favoured tree growth (Mosquera-Losada et al., 2006). The positive effect of liming on tree growth was also observed by Balcar et al. (2011), who studied the growth of *Fagus sylvatica* L. and *Acer pseudoplatanus* L. over 15 years, and by Saarsalmi et al. (2011), who studied *Pinus sylvestris* L. where lime was applied to the soil surface. Finally, it is interesting to highlight that, in 2003, the tree diameters were not affected by the different experimental treatments. This was probably due to the high density of trees, which led to competition and resulted in limited growth, which make advisable to thin in order to ensure adequate development.

Applying lime improved soil fertility, leading to a higher cumulative phytomass production in the limed treatment plots due to an increased pasture production (Li et al., 2006; Álvarez et al., 2010). Moreover, tree growth and, therefore, needle production was higher in the limed plots than in the unlimed plots; this increase could be the cause of the increased cumulative phytomass production (Mosquera-Losada et al., 2009). In general, sewage sludge fertilisation together with limed treatment led to better soil fertility than that resulting from the no fertilisation or the mineral fertiliser treatments, which produced an increment of the levels of cumulative phytomass in the plots fertilized with sewage sludge. This result can be explained in part by the residual effect, as described by the EPA (1994), of organic fertilisers as compared with mineral fertilisers; it may also be because sewage sludge increases pasture macronutrient concentrations, while mineral fertilisation reduces these concentrations by reducing soil pH (Smith, 1996; López-Díaz et al., 2007). Moreover, in the last years of the study (2000–2003), the highest levels of cumulative phytomass production were found with limed treatment combined with a high dose of sewage sludge, possibly because this combined treatment caused an organic matter mineralisation increase and, therefore, higher nutrient availability in a very acidic soil (López-Díaz et al., 2007). Other researchers, such as Mosquera-Losada et al. (2011b) and Ferreiro-Domínguez et al. (2011), found that in silvopastoral systems fertilised with sewage sludge with inputs of 200 and 400 kg total N ha⁻¹ and 100, 200 and 400 kg total N ha⁻¹, respectively, phytomass production was higher with higher doses of sewage sludge.

5. Conclusion

Silvopastoral systems established with traditional tree densities in Galicia are a good way to maintain herbaceous pastures with low fire risk. Pasture production could be increased if trees are thinned,

which will also provide larger logs of trees. At the traditional densities established in our experiment, the application of lime and sewage sludge improves soil fertility, increasing the soil pH, the EEC and the saturation percentage of Ca, reducing the saturation percentage of Al and, thus, increasing the productivity of silvopastoral systems. Initially, the positive effect of lime on soil fertility was higher than the effect of sewage sludge. However, the effect of sewage sludge was found over time mainly when a high dose of sewage sludge was applied, which indicates that sewage sludge has a higher residual effect than lime. Therefore, the use of sewage sludge as a fertiliser in a silvopastoral system improves soil fertility in the long term while providing agronomic benefits.

Acknowledgements

We are grateful to FEDER, CICYT and XUNTA (Consolidation funds) for financial assistance and to Escuela Politécnica Superior for the use of their facilities. We also acknowledge José Javier Santiago-Freijanes, Divina Vázquez-Varela, Pablo Fernández Paradela and Teresa Piñeiro-López for their help with sample processing both in the laboratory and in the field. This research was funded, in part, by the Educational, Science and Technology Ministry (CICYT) and the autonomous regional government of Xunta de Galicia.

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