Forest Ecology and Management 257 (2009) 1363–1372

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Influence of pasture botanical composition and fertilization treatments on tree growth

M.L. López-Díaz [a], A. Rigueiro-Rodríguez [b], M.R. Mosquera-Losada [b,*]

[a] Dpto. Biología y Producción de los Vegetales, Centro Universitario de Plasencia, Univ. Extremadura, Avda. Virgen del Puerto, no. 2, 10600 Plasencia-Cáceres, Spain
[b] Dpto. Producción Vegetal, EPS Lugo, Univ. Santiago de Compostela, Campus Universitario s/n, 27002 Lugo, Spain

ARTICLE INFO

Article history:
Received 8 September 2008
Received in revised form 27 November 2008
Accepted 2 December 2008

Keywords:
Pasture
Orchardgrass
Clover
Potassium
Organic fertilizer
Pinus radiata

ABSTRACT

Silvopastoral systems, which combine tree and pasture production, are more complex ecosystems than exclusively agronomic systems. Good silvopasture management should seek to increase positive interactions (or synergies) and reduce negative interactions among system components (soil, trees, grass and cattle) to increase global system productivity. Tree growth and pasture production within such systems can be optimized through appropriate species selection and fertilization. The aim of the present study, carried out over the course of 3 years, was to compare how traditional fertilisation, sewage sludge dose, and potassium affect pasture-tree competition, botanic composition and tree growth in a silvopastoral system located on agricultural land during the early years of system development. The addition of potassium is recommended for improving tree growth in silvopastoral systems with slightly acidic soil, especially if the pasture has high legume content. White clover is a good choice of species for silvopastoral systems because it promotes tree growth. Our study revealed that pasture production improved when sewage sludge was used as a fertiliser, but annual production was still more strongly dependent on weather conditions.

1. Introduction

Silvopastoral systems are recognised as a sustainable means of increasing forest land through afforestation of agricultural land. Establishment of agroforestry systems is currently promoted by the new EU regulations through direct farmer payments (COUNCIL REGULATION on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) 15 September 2005). The impetus for promotion of the development of such systems was that, in many cases, silvopastoral systems can fulfil Agenda 21's economic (i.e. economic return in the short, medium and long terms), cultural (i.e. maintenance of traditional methods of land management) and social principles (i.e. favouring rural population stabilisation) better than pure forestry or agronomic systems (FAO, 1992; Eichhorn et al., 2006).

Between 1994 and 1999, about one million hectares of agricultural land were afforested in the EU Member States (EC, 2004) as a result of Regulation No. 2082/92 implementation. Silvopastoral systems may be a viable means to promote multi-purpose forest land use and obtain income from newly afforested areas in the short term, leading to enhanced rural development and reduced rural abandonment, an important problem that European policies need to address (Rois-Díaz et al., 2006). In some European areas, silvopastoral systems are promoted because they are a cheap way to reduce fire risk, compared to traditional clearance (Rigueiro-Rodríguez, 2000).

Silvopastoral systems are complex ecosystems in which wood production (with long- term economic return) and pasture production (with short-term economic return) are combined. They are characterised by interactions among three components: trees, pasture and animals, which poses management difficulties. Competition between trees and pasture for water and nutrients is high in the early stages of the development of silvopastoral systems established through afforestation (Etienne, 1996; Nair and Graetz, 2004). Therefore, the selection of tree and pasture species, as well as fertilization techniques, should look to optimize silvopastoral outputs.

Pinus radiata is a tree species that integrates well into silvopastoral systems in temperate areas like Australia, New Zealand or Chile. It is broadly used in the Atlantic biogeographic region of Spain. Fast-growing and possessing a very dense canopy, this tree species can limit pasture production if planted at a high density (Rigueiro-Rodríguez et al., 2005). Hence, it is important to use pasture species that persist well in shaded conditions, such as

* Corresponding author. Tel.: +34 982252231; fax: +34 982285926.
E-mail address: mrosa.mosquera.losada@usc.es (M.R. Mosquera-Losada).

0378-1127/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2008.12.001

Dactylis glomerata L. (Eason, 1991; Balocchi and Phillips, 1997; Mosquera-Losada et al., 2001, 2006a). *Trifolium repens* L. is a legume that can optimize pasture and tree growth because it improves soil nitrogen content and pasture production and quality, as has been described for fodder legume trees such as *Glyricidia sepium* and *Leucaena leucocephala* (Dulormne et al., 2003; Ibrahim et al., 2006).

Once the tree and pasture species selection is made, identification and application of optimal management practices are important to maximise complementary resource use between pasture and trees, thereby optimising overall system productivity (Wolstenholme et al., 1992).

Nitrogen fertilization is a cheap way to enhance pasture production, and therefore should be used when tree shade doesn't affect pasture production. Studies carried out in NW Spain have shown that inorganic fertilization enhances pasture production as well as tree growth in very acidic soils (López-Díaz et al., 2007), but reduces both in neutral soils (Mosquera-Losada et al., 2006a) in pastures mainly composed of grasses; however, no studies have yet been carried out in pastures with a high proportion of legumes.

In Europe, sewage sludge production has increased steadily since the early nineties (European Environment Agency, 2000,2002) in response to EU policy (European Directive 91/271/CEE) to enhance water quality. The most common means to dispose of sewage sludge have been incineration, disposal to surface waters (prohibited by European Directive 91/271/CEE), land-filling (restricted, depending on the organic matter content of the sludge (European Directive 31/1999/CEE)) and agricultural uses. Studies in several European countries on the use of sewage sludge as a fertilizer, as regulated by EU Directive 86/278/CEE (DOCE, 1986), have concluded that sewage sludge is a good fertilizer due to its high content of macronutrients—particularly N, and to a lesser extent of P, K, Ca and Mg. However, sewage sludge has disadvantages due to the high proportion of heavy metals introduced into the soil. In Spain, R.D. 1310/1990 and European Directive 86/278 limit the total heavy metal (Cd, Cr, Cu, Hg, Ni, Pb and Zn) concentration in soil and sewage sludge and the annual quantity that can be applied as a fertilizer in a soil (based on a 10-year mean). The dose rate that can safely be applied depends on the concentration of heavy metals in the sludge, as well as the nitrogen concentration and the proportion of the nitrogen that is readily mineralizable within the first year after application to the soil (Smith, 1996).

Importantly, the increase in fertilizer prices in the last few years as well as the high production of sewage sludge makes the use of sludge as a fertilizer an interesting option to promote pasture and tree growth.

To this end, the effect of sewage sludge on plant and tree growth, pasture botanical composition, in-soil macronutrient levels (N, P, K, Ca and Mg), and pasture quality (crude protein, P, K, Ca and Mg) in silvopastoral systems in very acidic soils in 5–8-year-old plantations has already been evaluated (López-Díaz et al., 2007; Rigueiro-Rodríguez et al., 2007). It was shown that sewage sludge application in acid soils initially increases soil pH, simultaneously reducing aluminium saturation in the interchange complex and increasing macronutrient availability (López-Díaz et al., 2007). This leads to an increase in sown grass species and, as a result, an improvement in pasture quality and productivity. Moreover, some authors have detected that sewage sludge applied to different tree species in forest soils increases their growth because the nutrients are released slowly and the trees are able to make use of them during the summer (Mosquera-Losada et al., 2006a; López-Díaz et al., 2007).

The aim of this study is to investigate the effects of different doses of sewage sludge (with or without potassium) and inorganic fertilizer on the competition between trees and pasture in a recently established silvopastoral system, constituted by legume and grass species and located on abandoned agricultural land.

2. Materials and methods

2.1. Characteristics of the study site

The experiment was carried out in Lugo (NW Spain; 7°20′N; 43°09′W; 450 m asl), between 1998 and 2000. The area belongs to the Atlantic biogeographic region (EEA, 2006) and has a total annual mean precipitation of 1083 mm. There is usually a period of drought in July and August, which is not favourable for tree growth and seriously limits pasture production. Low mean temperatures (<0 °C) in January also lead to minimal plant growth (Mosquera-Losada et al., 1999). Mean monthly precipitation and temperatures for 1998, 1999 and 2000, and for the previous 20 years are shown in Fig. 1; total annual rainfall was 942, 1239 and 1341 mm in 1998, 1999 and 2000, respectively.

The experiment was carried out in an agricultural land on a sandy loam soil of about 100 cm in depth. Initial soil analyses revealed a

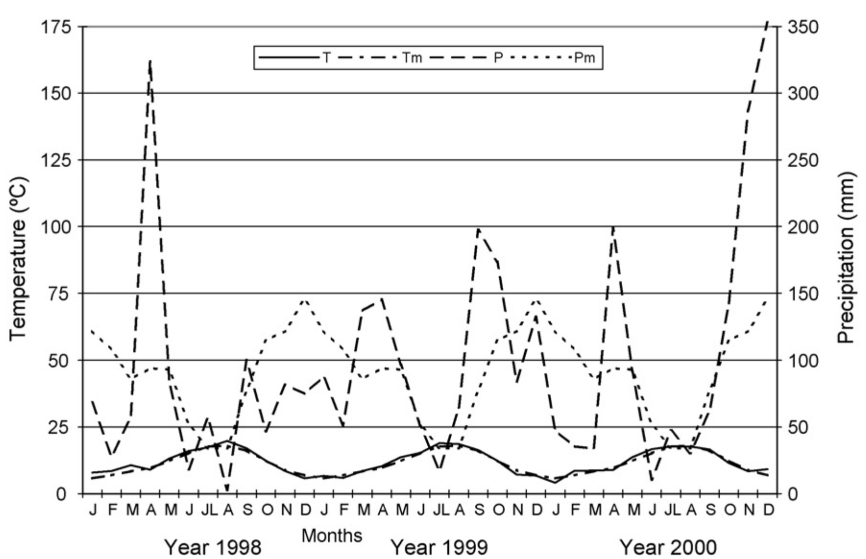

Fig. 1. Monthly precipitation and mean temperature for the study area in 1998, 1999 and 2000, and mean data for the last 20 years. T (—): temperature in 1998, 1999 and 2000; T_m (- - - -): mean temperature over the last 20 years; P (– – –): precipitation in 1998, 1999 and 2000; P_m (- - - -): mean precipitation over the last 30 years.

Table 1
Basic properties of the sewage sludge batches used in 1998, 1999 and 2000, showing dry matter concentration (DM, g kg^{-1}), pH in water, organic matter concentration (OM conc., g kg^{-1}), the carbon/nitrogen (C/N) ratio and the N, P, K, Ca, Mg and Na concentrations (conc.; g kg^{-1}).

Year	DM	pH	OM	N	C/N	P	K	Ca	Mg	Na
1998	25.00	6.94	49.00	3.21	8.85	0.93	0.25	0.67	0.54	0.08
1999	25.00	6.94	39.25	3.21	7.09	0.52	0.25	0.69	0.43	0.02
2000	23.54	6.94	44.12	4.23	6.05	1.65	0.26	0.65	0.65	0.14

slightly acidic pH of 6.3 (pH in water) and high soil organic matter (SOM: 45.8 g kg^{-1}) and nitrogen (2.3 g kg^{-1}) concentrations. Total phosphorus was high (0.03 g kg^{-1}). The total nitrogen (N) concentration was mainly in organic form, as mineral nitrogen forms included 308.6 mg N-NH_4^+ kg^{-1} and 5.4 mg N-NO_3^- kg^{-1}. All heavy metal concentrations in the soil (Table 1) were below the maximum thresholds for using sewage sludge as fertilizer, as specified by the European Union Directive 86/278/CEE (DOCE, 1986) and Spanish legislation under R.D. 1310/1990 (BOE, 1990).

2.2. Experimental design

The experimental design was a completely randomized block with three replicates. In January 1998, a plantation of *Pinus radiata* D. Don was established at a density of 1667 trees ha^{-1}, as is traditionally done in the area. Each plot consisted of a square of 5 × 5 trees with an area of 96 m^2. Pasture was established in autumn 1997 before tree planting, when each plot was sown with a mixture of 25 kg ha^{-1} of *Lolium perenne* L. cv. Brigantia (perennial ryegrass), 10 kg ha^{-1} of *Dactylis glomerata* L. cv. Artabro (cocksfoot) and 4 kg ha^{-1} of *Trifolium repens* L. cv. Huia (white clover) after ploughing. When the trees were planted, their diameters and heights ranged between 0.34–0.39 and 28.2–29.0 cm, respectively. Eight treatments were established consisting of three annual sewage sludge doses based on a total Nitrogen target dose (S1: 160 kg N total ha^{-1}; S2: 320 kg N total ha^{-1}; S3: 480 kg N total ha^{-1}), with (K: 200 kg K_2O ha^{-1} per year) or without potassium (NK: 0 kg K_2O ha^{-1}) in each case. Two control treatments were also included in the comparison: no fertilizer (NF) and the inorganic fertilizer usually used in the region (MIN). Mineral fertilization (MIN) consisted of the application of 80 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1} and 200 kg K_2O ha^{-1} split as 500 kg 8:24:16 ha^{-1} in March, and 40 kg N ha^{-1} and 120 kg K_2O ha^{-1} applied after the second harvest. All fertilization treatments were homogeneously distributed in the springs of 1998, 1999 and 2000. Sewage sludge doses were based on total N and mineral N concentrations, in line with the USA Environment Protection Agency recommendations (EPA, 1994), which assumes that around 25% total nitrogen with anaerobically digested sewage sludge will be released in the first year after application (Serna and Pomares, 1992).

2.3. Sewage sludge

Anaerobically digested municipal sewage sludge was produced in Lugo city. Heavy metal concentrations were below the Spanish legally permitted limits for use in agriculture (BOE, 1990). The composition of sewage sludge batches used in 1998, 1999 and 2000 is shown in Table 1, indicating a high-quality product, due to its low heavy metal concentration, compared with sewage sludge from other industrialized areas (Smith, 1996).

2.4. Field samplings

Basal diameter and total height measurements were taken in February 1998 (before fertilization treatments), 1999, 2000 and 2001 from the inner nine trees of each plot, to avoid a border effect.

Table 2
Zn, Cu and Cr sewage sludge concentration (mg kg^{-1} d.m.) in the years 1998, 1999 and 2000, and law limits established by EU European Directive 86/278 and Spain R.D. 1310/1990.

Year	Zn	Cu	Cr
1998	821	244	39
1999	746	154	141
2000	1320	241	74
Law limits	2500–4000	1000–1750	1000–1500

Limits depend on soil pH (minimum: soil pH < 7, maximum: soil pH > 7). Sewage sludge contains other heavy metals in lower proportions, which were not shown.

Plots were harvested eight times during the experiment: in May, June, July and November 1998 and 2000 and April, May, July and December in 1999. Before harvesting, four herbage samples (each of 0.09 m^2) were taken at a height of 2.5 cm from each plot using hand clippers and were hand-separated. Sown and native species proportions were estimated by hand-separation and their corresponding percentages were later estimated after oven drying at 80 °C (24 h). Tree cover was taken into account when determining the total pasture production per hectare.

2.5. Statistical analysis

The results obtained were analysed by ANOVA (randomised block design). The models used were: $P_{ijk} = \mu + L_i + S_j + B_k + \delta_{ik} + (LS)_{ij} + \varepsilon_{ijk}$ for annual pasture production and tree height, diameter and volume; and $P_{ijklm} = \mu + L_i + S_j + B_k + \delta_{ik} + (LS)_{ij} + Y_l + H_m + \varepsilon_{ijklm}$ for botanic composition, with P_{ijklm}: the dependent variable; μ: the variable mean; L_i: i potassium fertilization; S_j: j sludge fertilization effect for block j; B_k: k block effect; Y_l: 1-year effect; H_m: m harvest effect; $(LS)_{ij}$: interaction between the i level of main-plot treatment and the j level of subplot treatment; and δ_{ik} and ε_{ijklm}: error components. The Duncan test was used for subsequent pair-wise comparisons ($p < 0.05$; $\alpha = 0.05$) if the ANOVA was significant. The statistical software package SAS (SAS, 2001) was used for all analyses. Only significant data are presented in this paper, based on the ANOVA results (Table 2).

3. Results

3.1. Tree diameter, height and volume

Tree height (Fig. 2) was significantly affected by fertilization treatments during the experiment (Table 3), with diameter and volume significantly modified since 2000 (Fig. 3) and 2001 (Fig. 4), respectively. In February 1999, tree height was significantly higher when a low dose of sewage sludge (S1: 41.3 cm) (data not presented), potassium and sewage sludge (K: 40.8 cm) or mineral fertilization (MIN: 41.8 cm) was applied compared to no-fertilization (NF: 37.2 cm) treatments (Fig. 2). However, since February 2000, only the lowest sewage sludge dose improved tree diameter and height (S1: 2.03 and 87.1 cm, respectively) with respect to no-fertilization treatment (1.69 and 73.2 cm, respectively). Finally, in February 2001, the greatest tree height and diameter were obtained when both potassium fertilization and sewage sludge were applied (K: 5.01 and 172.3 cm, respectively). Moreover, in this year, tree height was significantly increased by mineral fertilization (MIN: 168.9 cm) with respect to the control (NF: 147.9 cm).

Finally, tree volume was only significantly increased with low organic fertilization (S1: 1643 cm^3) with respect to no-fertilisation (NF: 1083 cm^3) in the last year of the study.

When sewage sludge was applied, potassium application over 3 years produced an increment of 20.1% for tree diameter, and

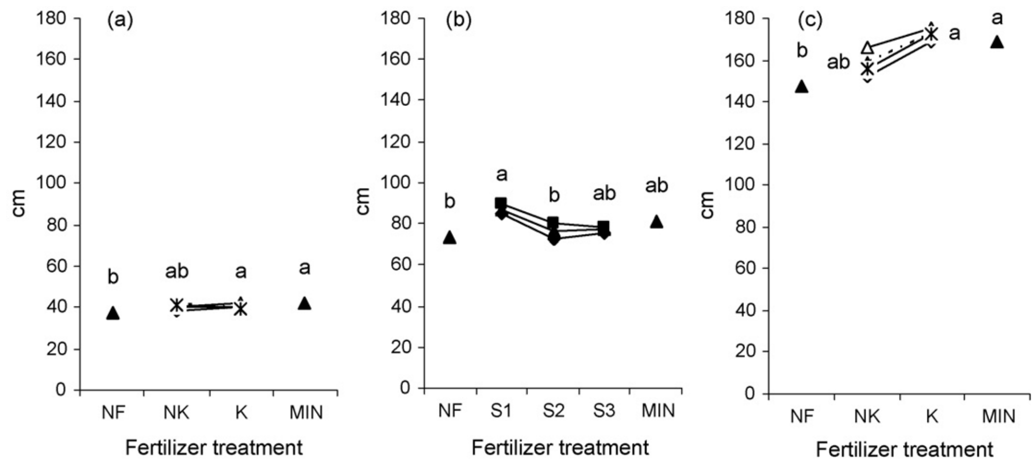

Fig. 2. Tree height (cm) under the different fertilizer treatments in February. (a) 1999, (b) 2000 and (c) 2001. NF: no-fertilizer treatment; S1: low sewage sludge application dose (160 kg total N ha^{-1}) (△); S2: medium sewage sludge dose (320 kg total N ha^{-1}) (◇); S3: high sewage sludge dose (480 kg total N ha^{-1}) (*); MIN: mineral fertilizer treatment; NK: 0 kg K_2O ha^{-1}(◆); K: 200 kg K_2O ha^{-1}(■). Different letters indicate significant differences between potassium (- -▲- -) and nitrogen fertilization treatments (▲). Means with the same letter do not differ significantly at $P = 0.05$.

Table 3
ANOVA of tree height, diameter and volume in February 1999, 2000 and 2001; annual pasture production in 1998, 1999 and 2000; *Trifolium repens* proportion in May, June, July and November 1998, May and July 1999 and May and June 2000; and sown grass proportion in May, June, July and November 1998, April, July and December 1999 and June 2000.

Date	BL	K	N	BL*K	BL*N	K*N
Height						
1999	ns	*	ns	ns	ns	ns
2000	ns	ns	*	ns	ns	ns
2001	ns	*	ns	ns	ns	ns
Diameter						
1999	ns	ns	ns	ns	ns	ns
2000	ns	ns	*	ns	ns	ns
2001	ns	*	ns	ns	ns	ns
Volume						
1999	ns	ns	ns	ns	ns	ns
2000	ns	ns	ns	ns	ns	ns
2001	ns	ns	*	ns	ns	ns
Pasture production						
1998	*	ns	*	*	ns	ns
1999	ns	ns	*	ns	ns	ns
2000	ns	ns	*	ns	ns	ns
Trifolium repens						
5/98	*	ns	ns	ns	ns	*
6/98	ns	ns	*	ns	ns	ns
7/98	ns	ns	*	ns	ns	**
11/98	ns	ns	**	ns	ns	ns
5/99	*	ns	**	ns	ns	ns
7/99	ns	ns	**	ns	ns	ns
5/00	ns	ns	ns	ns	ns	*
6/00	***	ns	ns	ns	*	*
Sown grasses						
5/98	*	*	ns	ns	ns	*
6/98	*	ns	*	ns	ns	ns
7/98	ns	ns	*	ns	ns	*
11/98	*	ns	*	ns	ns	ns
4/99	*	ns	*	ns	ns	ns
7/99	ns	ns	*	ns	ns	ns
12/99	ns	ns	ns	*	*	*
6/00	***	**	ns	ns	*	ns

BL: block; K: potassium fertilization; N: nitrogen fertilization. The symbol *, ** and *** indicates significant differences at a $p < 0.05$, $p < 0.01$ and $p < 0.01$ level.

14.9% and 16.5% for tree height in 1999 and 2001, respectively, compared to the no-fertilization treatment. The increase in tree height after inorganic fertilization (MIN), compared to the no-fertilization treatment condition, was about 12.3% and 14.2% in 1999 and 2001, respectively. The same trend was found in February 2000, but without a significant response of tree height to MIN treatment.

3.2. Pasture production

Annual pasture production with the different fertilization treatments in 1998, 1999 and 2000 can be observed in Fig. 5. Significant differences ($P = 0.0001$) were detected between years. The highest level of pasture production was found in 1999 (11.3–13.7 t DM ha^{-1}), while the lowest values were detected in 2000 (7.2–9.9 t DM ha^{-1}).

During the entire experiment, pasture production was significantly modified by sewage sludge application (Table 3), although in the first year treatment response depended on potassium application. In 1998, when no potassium was applied, pasture production was significantly increased by medium (L2) and high (L3) sewage sludge doses (10.7 and 11.3 t DM ha^{-1}, respectively), compared to 9.2 and 9.5 and t DM ha^{-1} with no-fertilization and mineral fertilization, respectively. However, no response was found to organic fertilizer application when potassium was added. In 1999, inorganic fertilization (MIN) produced the maximum annual pasture production (13.7 t DM ha^{-1}), but the outcome was similar to the case of the application of sewage sludge (12–13.5 t DM ha^{-1}, compared to 11.3 t DM ha^{-1} for the no-fertilization treatment condition).

In the last year of the study (2000), pasture production was increased by a high dose of sewage sludge (8.1–9.4 t DM ha^{-1} compared to 7.2 t DM ha^{-1} with no-fertilization) and mineral (MIN: 8.9 t DM ha^{-1}). Moreover, in 2000, potassium application with sewage sludge (K) significantly increased forage production (8.3–9.9 t ha^{-1} compared to 7.2 t ha^{-1} with no fertilization (data not presented)).

3.3. Botanic composition

The weight proportion (% dry matter) of white clover (*Trifolium repens*) and sown grasses (*Dactylis glomerata* and *Lolium perenne*)

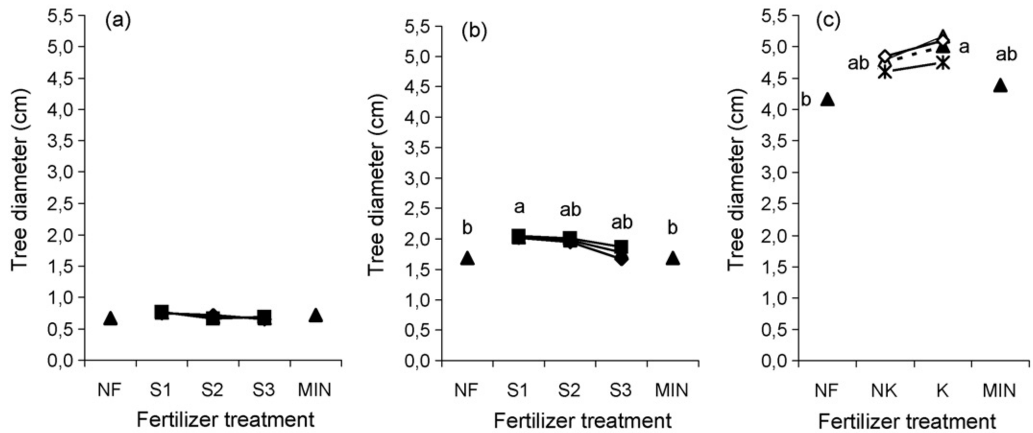

Fig. 3. Tree diameters (cm) under the different fertilizer treatment conditions in February. (a) 1999, (b) 2000 and (c) 2001. NF: no-fertilizer treatment; S1: low sewage sludge dose (160 kg total N ha^{-1}) (△); S2: medium sewage sludge dose (320 kg total N ha^{-1}) (◇); S3: high sewage sludge dose (480 kg total N ha^{-1}) (*); MIN: mineral fertilizer treatment; NK: 0 kg K_2O ha^{-1} (◆); K: 200 kg K_2O ha^{-1} (■). Different letters indicate significant differences between potassium (- -▲- -) and nitrogen fertilization treatment conditions (▲).

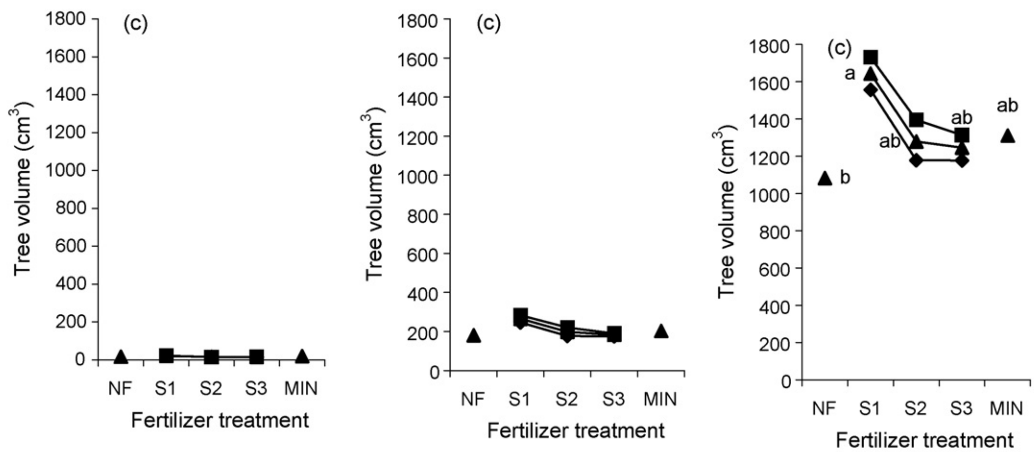

Fig. 4. Tree volumes (cm^3) under the different fertilizer treatment conditions in February. (a) 1999, (b) 2000 and (c) 2001. NF: no-fertilizer treatment; S1: low sewage sludge dose (160 kg total N ha^{-1}) (△); S2: medium sewage sludge dose (320 kg total N ha^{-1}) (◇); S3: high sewage sludge dose (480 kg total N ha^{-1}) (*); MIN: mineral fertilizer treatment; NK: 0 kg K_2O ha^{-1}(◆); K: 200 kg K_2O ha^{-1}(■). Different letters indicate significant differences between potassium (- -▲- -) and nitrogen fertilization treatment conditions (▲). Means with the same letter do not differ significantly at $P = 0.05$.

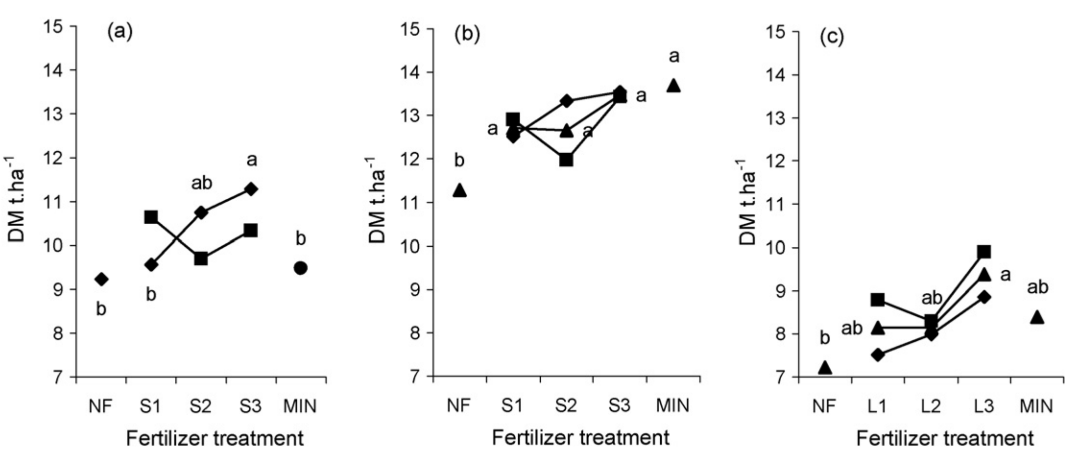

Fig. 5. Pasture production (DM t ha^{-1}) under the different fertilizer treatment conditions in (a) 1998, (b) 1999 and (c) 2000. NF: no-fertilizer treatment; S1: low sewage sludge dose (160 kg total N ha^{-1}) (△); S2: medium sewage sludge dose (320 kg total N ha^{-1}) (◇); S3: high sewage sludge dose (480 kg total N ha^{-1}) (*); MIN: mineral fertilizer treatment; NK: 0 kg K_2O ha^{-1}; K: 200 kg K_2O ha^{-1}; Different letters indicate significant differences between nitrogen fertilization treatments (◆: NK; ■: K) or the mean of both (▲). Means with the same letter do not differ significantly at $P = 0.05$.

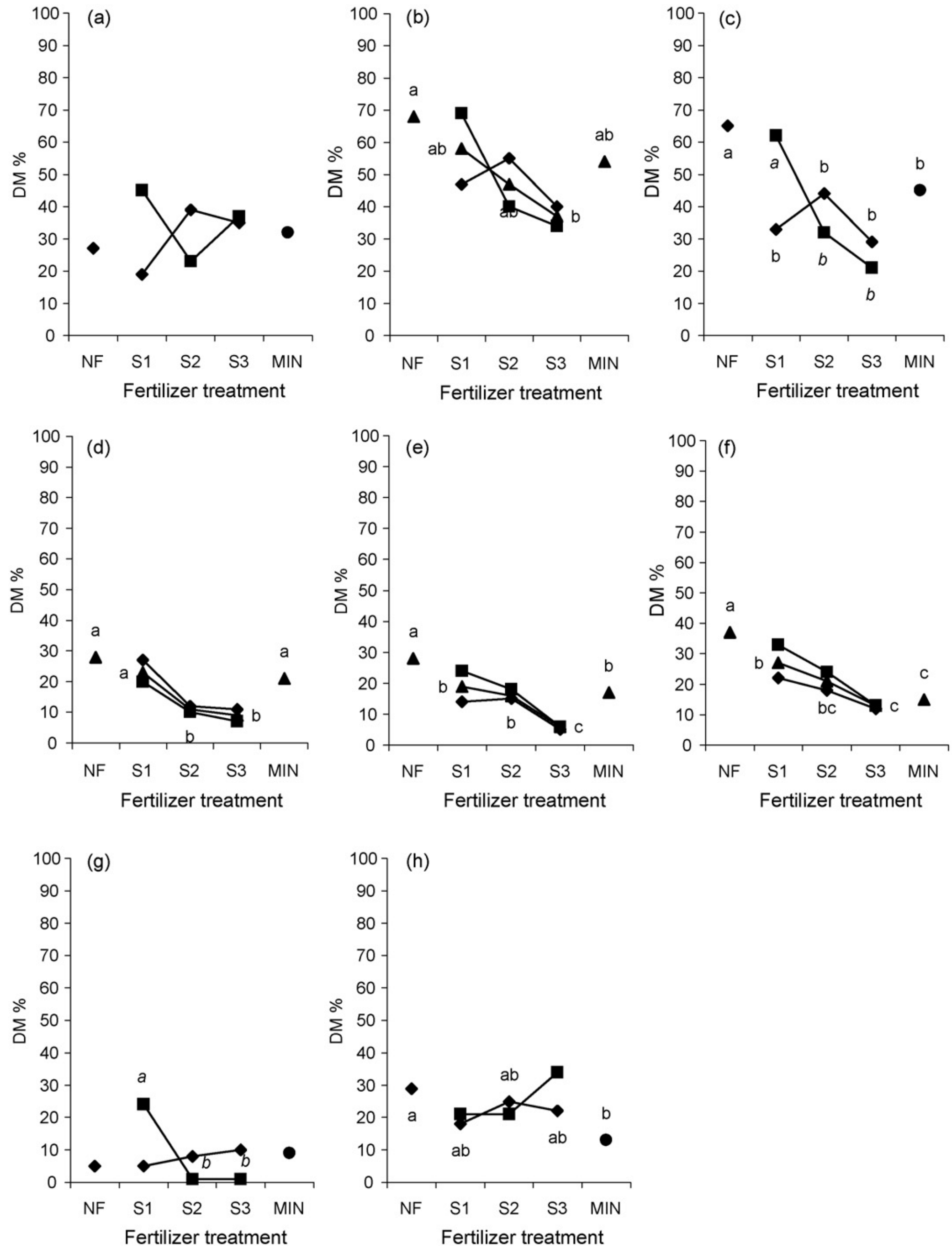

Fig. 6. Proportion in weight (% dry matter) of *Trifolium repens* on DM of all species in pasture under the different fertilizer treatment conditions in (a) May, (b) June, (c) July and (d) November 1998, (e) May and (f) July 1999 and (g) May and (h) June 2000. Different letters indicate significant differences between nitrogen fertilization treatments (◆: NK; ■: K) or the mean of both (▲). Means with the same letter do not differ significantly at $P = 0.05$.

on the total dry matter of all species in the pasture under different fertilizer treatments for all the harvests are shown in Figs. 6 and 7, respectively.

Other species detected in the pasture include other grasses (*Holcus lanatus* L., *Poa* sp., *Agrostis* sp., *Arrhenatherum elatius* (L.) Beauv., *Lolium multiflolum* Lam. and dicotiledoneous plants (*Rumex obtusifolius* L., *Plantago lanceolata* L., *Erodium* sp., *Taraxacum officinale* Webber et Wiggers), although their contribution was very low (<15% in most cases) and similar between the different treatments.

In general, the percentage of sown species was significantly affected by nitrogen application (Table 3) in some samplings (May and July 1998 and May and June 1999 for clover, and May 1998 and December 1999 for grasses), and depended on the response to potassium.

In 1998 and 1999, treatments that increased clover proportion generally also decreased sown grass proportion, probably because of mutual competition. In May and July 1998 and in May 2000, clover proportion was increased with potassium fertilisation (45%, 62% and 24% with respect to 19%, 33% and 5% with no potassium) for the lowest sewage sludge dose (S1) condition. Conversely, the proportion of sown grass was reduced by the same treatments (S1 and potassium) (39% and 22% with respect to 63% and 42% with no

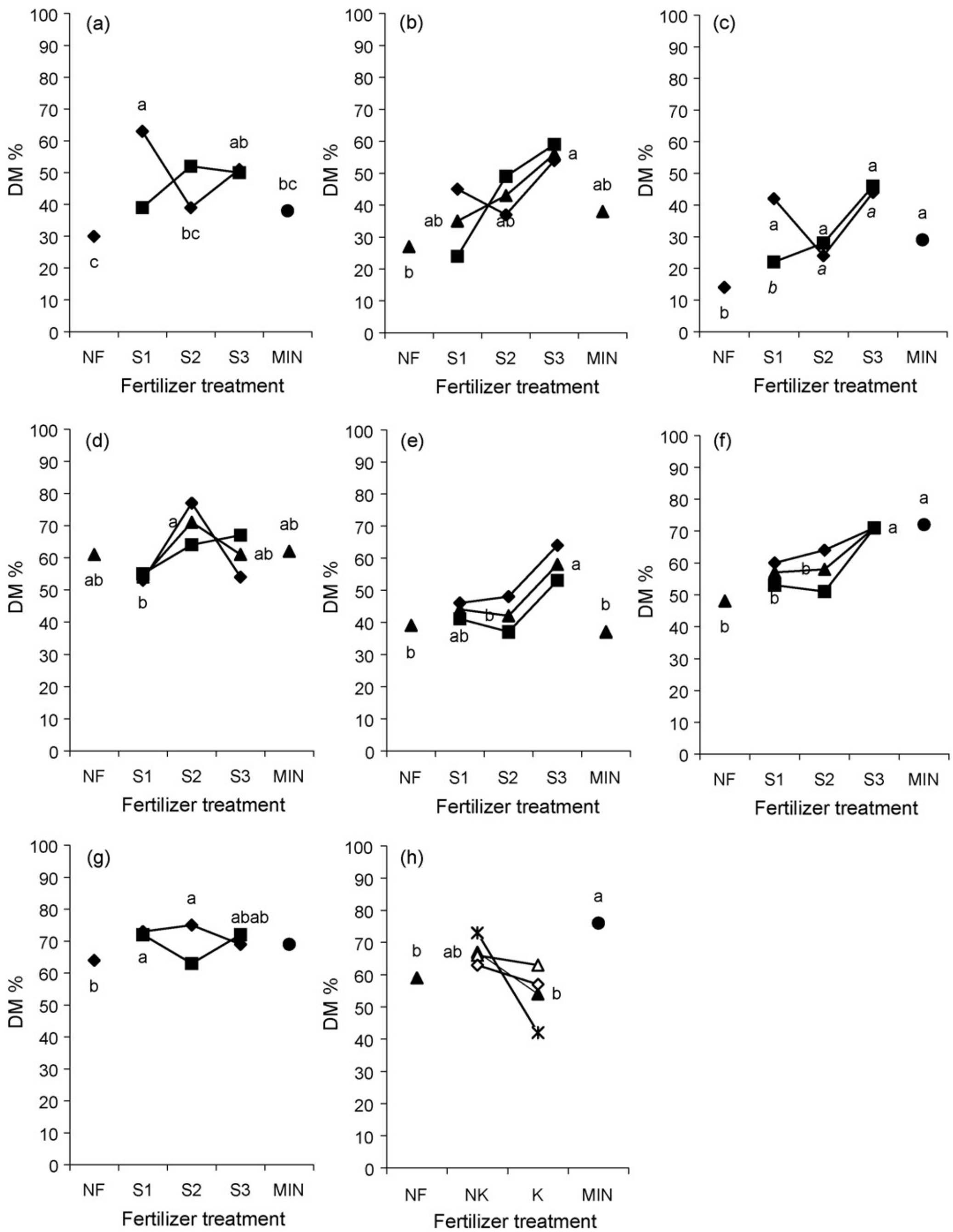

Fig. 7. Proportion in weight (% dry matter) of sown grasses *(Dactylis glomerata* and *Lolium perenne)* on DM of all species in pasture under the different fertilizer treatment conditions in (a) May, (b) June, (c) July and (d) November 1998, (e) May, (f) July and (g) December 1999 and (h) June 2000. Different letters indicate significant differences between potassium (–▲–) or nitrogen fertilization treatments (◆: NK; ■: K) or the mean of both (▲). Means with the same letter do not differ significantly at $P = 0.05$.

potassium) in May and July 1998. This tendency was also found in 1999.

In general, medium and high doses of sewage sludge reduced clover and increased the sown grass contribution to the pasture in different samplings from 1998 and 1999. In July (when potassium was applied) and November 1998 and May and July 1999, clover proportion was lower with the S2–S3 treatment (32–21%, 11–9%, 16–6% and 21–13%, respectively) than the no-fertilization treatment (65%, 28%, 28% and 37%). However, the presence of *Trifolium repens* with S1 was similar to the no-fertilization treatment. Moreover, in spring 2000 (May) when potassium was applied, the clover proportion was higher at the lowest sewage sludge dose (S1: 24%) than for the S2 and S3 treatments (1% for both).

In the first 2 years, the botanic composition with mineral fertilizer depended on the harvest period. In general, clover proportion under inorganic fertilization improved in the spring, yielding observed values that were similar to the no-fertilization or S1 treatments, i.e. May, June and November 1998 and May 1999 (32%, 54%, 21% and 17% with MIN compared to 27%, 68%, 28% and 28% with NF), but subsequently decreased in the summers of 1998 and 1999 (45% and 15% less respect to 65% and 37% with no fertilization).

In June 2000, the maximum percentage of sown grass was observed for the mineral fertilizer condition (76% compared to 59% with NF); at that time, 71% of the total pasture was *Dactylis glomerata* and only 5% was *Lolium perenne* (data not presented).

4. Discussion

The pine height reached by the end of the experiment (3 years) was higher than the predicted tree height based on production tables established for *Pinus radiata* (Sánchez-Rodríguez, 2000) in NW Spain; thus it is not possible to determine the index site. However, the tree heights obtained in this trial were similar to the values observed by Mosquera-Losada et al. (2006a) in soils with an initial water pH of 6.8, probably due to the high precipitation rate from the year of planting, which significantly increased initial tree growth.

Annual pasture production levels fell in the high part of the interval defined by Mosquera-Losada et al. (1999) in Galicia (6–12 t DM ha^{-1}). In 1999, production was higher than that attained by these authors (Mosquera-Losada et al., 1999) when organic or mineral fertilization was applied in our experiment, because the pasture was well-established and the values given by Mosquera-Losada et al. (1999) included data from permanent pastures. Variability between pasture production sites depends on the specific weather conditions for the year of measurement, and is mainly explained by the variability in summer precipitation (Mosquera and González, 1999). The high precipitation found in Summer 1999 (320 mm) extended the growth period and, therefore, increased annual pasture production. However, the drought in February, March and June 2000 (with 35, 34 and 10 mm, respectively, compared to values of 108, 86 and 52 mm for the mean precipitation over the last 30 years) could explain the lower production in 2000 compared to the other 2 years.

Throughout the experiment pasture production was significantly improved by sewage sludge application, mainly with the highest dose (S3), as was previously found by Mosquera-Losada et al. (2001), López-Díaz et al. (2007) in forest soils and Mosquera-Losada et al. (2006a) in agrarian soils in Galicia. Organic fertilization caused an increase in annual pasture production similar to the effects of MIN treatment (traditional management in the region) in the two last years; however, inorganic fertilization offered an improvement only over the 1999 results for the no fertilization condition. If the P and K soil availability is sufficient to allow white clover growth, *Rhizobium* nitrogen fixation can mask a positive fertilization effect on pasture production (Green et al., 1999). This could explain the high pasture production for no-fertilization treatments, which consisted of around 65%, 39% and 29% of *Trifolium repens* in July 1998, 1999 and 2000. However, the proportion of white clover for the inorganic fertilization condition was 45%, 15% and 13% for the same consecutive years.

Once the type of pasture and tree is chosen in a specific climatic area, the initial sustainability of the tree-pasture relationships depends on soil fertility and fertilization management. Moreover, it has been observed that different fertilization treatments in different contexts can enhance pasture production over tree growth, tree growth over pasture production, tree and pasture production together, or even reduce tree and pasture production (Mosquera-Losada et al., 2006a; López-Díaz et al., 2007). Foresters in humid temperate areas usually avoid competition through the use of herbicides or yearly clearances at the initial stages of tree and pasture development, but this can cause damage to the environment by reducing tree growth in very dry environments, and is one of the most costly management practices during the life of the stand.

Knowledge about tree-pasture relationships will enable us to recommend better management practices to enhance possible synergies for more optimal tree and pasture development, and may also allow us to preserve understory biodiversity, preserve understory cover to avoid erosion, and make better use of understory species to enhance multiple-output activities from the forests. In the case of Galicia, better understanding on tree-pasture management will allow us to maintain an herbaceous layer to avoid fire risk. Fertilization is not a practice usually linked to tree management after afforestation because it is costly, but tree growth can benefit if they are grown with other crops that are fertilized to enhance land productivity (Dupraz et al., 2005).

Tree response to fertilization depends on tree-pasture relationships, which are also affected by soil conditions (Campbell et al., 1994; Rigueiro-Rodríguez et al., 2000; Rigueiro-Rodríguez et al., 2001). Tree growth was enhanced in this study by a low dose of sewage sludge fertilizer, but not by the high dose of sewage sludge fertilizer. Rigueiro-Rodríguez et al. (2000) observed a similar response in initial tree growth in young afforested stands, in silvopastoral systems developed with *Pinus radiata* in sandy agricultural soils with pH 6.8, and in those fertilized by dairy sludge with a dose of nitrogen similar to the S1 dose. This was due to the improvement of humidity retention in the soil caused by organic fertilization, which increased the tree growth period. However, tree diameter and height were significantly reduced by inorganic fertilization compared to no fertilization or organic fertilization cases from that experiment (Mosquera-Losada et al., 2006a). In our experiment, we obtained the same results in the first year due the strong competition established between the pasture and the trees with S3 treatment. Therefore, high nitrogen doses resulted in enhanced competition between pasture and trees, reduced tree growth in the early development stages, and reduced tree height. Moreover, the precipitation that happened in 1999 likely reduced the tree growth advantage in reducing drought stress gained from sewage sludge, which resulted in similar tree growth outcomes in MIN and S1 as measured by tree height; this variable is more sensitive to treatments in the early planting stages. After 3 years of afforestation, MIN application did not reduce tree growth, as was found by Mosquera-Losada et al. (2006a) because the root zones for the pasture and trees were different and the competition between these two silvopastoral system components was therefore less important.

A different response was also found for *Pinus radiata* in very acid soils: tree growth (height, diameter and volume) was increased by similar mineral treatment to S1 treatment (Pinto et al., 1996; Neilsen et al., 1992; López-Díaz et al., 2007). In this case, inorganic fertilizer notably reduced water pH (below 4), so pasture production was very low and the herbaceous component was not able to develop properly, thereby enabling tree growth as a result of the added inorganic fertilizer.

Tree-pasture competition also depends on the botanic composition of the pasture. The combination of similar pasture production (compared to the no-fertilisation conditions in 1998 and 2000) and high clover presence in 1998 could also explain the increment in tree growth observed when a low sewage sludge dose (S1) treatment was applied. It can be concluded that the *Trifolium repens*-tree competition was less intense than the grass-tree competition, as was also previously observed by Green et al. (1999).

Regarding potassium treatments, in our experiment trees responded favourably to the addition despite the soil's initial medium-K levels, a condition that normally makes it inadvisable to add this potassium. This result could be explained in several ways. First, the soil where the experiment was established was sandy, which means that the exchange complex capacity was small, and potassium could have been easily lost by leaching (due to high precipitation in this area) and by crop and tree extractions. Second, sewage sludge used in the present experiment had low levels of potassium (Rigueiro-Rodríguez et al., 2002), which did not compensate the extractions made by the crops and therefore made it advisable to add potassium to the soil. Finally, the presence of legumes in the pasture enhanced K depletion, as legumes extract substantial amounts of K (Mosquera-Losada et al., 2004). We

observed this phenomenon in the first year of the experiment (Mosquera-Losada et al., 2006b). As expected, high N doses further reduced K availability in soil because N input increased pasture production and, therefore, K extraction (Simpson, 1986; Guerrero, 1996). The lack of K for tree growth can reduce tree development as well as increase the incidence of some illnesses, such as disease caused by *Dothistroma pini*, which can be found as high as Bará-Temes (1998). *Pinus radiata* resistance to low temperatures, frost and salinity can be enhanced by potassium addition (Ouro et al., 2001).

As the system evolves, tree development can modify pasture production. Therefore, the pasture production reduction observed in the last year could have been caused by competition with trees that were 147.92–175.16 cm in height and had a basal diameter of 4.19–5.17 cm, as light interception by the trees could potentially limit pasture development (Rigueiro-Rodríguez et al., 2008). After three consecutive years of sewage sludge application, López-Díaz et al. (2007) observed that shade caused by 8-year-old trees (*Pinus radiata*) limited the effects of fertilisation (Balocchi and Phillips, 1997) and mineralization rate (López-Díaz et al., 2007) on pasture production. In order to limit the deceleration of pasture production on time, it is important to delay crown closure. This can be accomplished by reducing tree density or pruning trees in order to improve light intensity reaching the soil (Mosquera-Losada et al., 2006a). In the Atlantic region of interest to this study, shade coverage greater than 55% reduces pasture production and quality (Rigueiro-Rodríguez et al., 2007). The optimum initial tree density depends on the relative importance of each product of the silvopastoral system: the timber, pasture, and then livestock. A wide initial tree spacing would enhance forage production and at the same time, the production of quality timber (Rigueiro-Rodríguez et al., 2007). Appropriate silvopastoral system management should combine production of both to optimize the profitability of these systems.

In conclusion, tree-pasture development was found to be dependent on the effects of various fertilization treatments on the different tree-pasture components. Nitrogen doses near 40 kg N ha^{-1} (S1) did not improve pasture production in a silvopastoral system compared with a no-fertilization treatment condition. However, the presence of clover in the low nitrogen dose treatment (S1) condition along with addition of K improved tree growth compared to the no-fertilisation treatments. Moreover, the addition of potassium is recommended for improving tree growth in silvopastoral systems established on slightly acid soil, especially for pastures with high legume content. White clover is an appropriate species for silvopastoral systems because it competes less with trees than with grasses, thereby allowing the preservation of an herbaceous layer that averts fire risk. Pasture production was improved by the addition of sewage sludge, but the effects were strongly weather-dependent.

References

Balocchi, O.A., Phillips, C.J.C., 1997. Grazing and fertilizer management for establishment of *Lotus uliginosus* and *Trifolium subterraneum* under *Pinus radiata* in southern Chile. Agroforest. Syst. 37, 1–14.

Bará-Temes, S., 1998. Fertilización forestal (Forestry fertility). Consellería de Agricultura, Gandería e Política Agroalimentaria. Xunta de Galicia, Santiago de Compostela, Spain (in Spanish).

BOE (Spanish Official Bolletin) 01/11/1990. Real Decreto 1310/1990 29 de Octubre de 1990, que regula la utilización de los lodos de depuración (Royal Decree 1310/1990 29th October 1990, that regulates the use of sewage sludge. Ministerio Agricultura, Pesca y Alimentación, Madrid, Spain (in Spanish).

Campbell, C.D., Atkinson, D., Jarvis, P.G., Newbould, P., 1994. Effects of nitrogen fertiliser on tree/pasture competition during the establishment phase of a silvopastoral system. Ann. Appl. Biol. 124, 83–96.

DOCE no. L 181 04/07/1986. Council Directive 86/278/CEE of 12 June 1986 on the protection of the environment and, in particular of the soil, when sewage sludge is used in agriculture. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31986L0278:ES:HTML.

DOCE no. L 135 del 30/05/1991. Council Directive 91/271/CEE of 21 May 1991 concerning urban waste-water treatment. http://aragon.ugt.org/mambiente/Normativa/pdf/aguas/aguas_eu_91-271.pdf.

DOCE no. L 128 16/07/1999. Council Directive 1999/31/EC of 26 of April 1999 on the landfill of waste. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0031:EN:HTML.

Dulormne, M., Sierra, J., Nygren, P., Cruz, P., 2003. Nitrogen-fixation dynamics in a cut-and-carry silvopsatoral system in the subhumid conditions of Guadeloupe—French Antilles. Agroforest. Syst. 59, 121–129.

Dupraz, C., Burgess, P., Gavaland, A., Graves, A., Herzog, F., Incoll, L.D., Jackson, N., Keesman, K., Lawson, G., Lecomte, I., Liagre, F., Matzanas, K., Mayus, M., Moreno, G., Palma, J., Papanastasis, V., Paris, P., Pilbeam, D.J., Reisner, Y., Van Noordwijk, M., Vincent, G., Wert Van der, W., 2005. Quality life and management of living resources. Silvoarable Agroforestry for Europe. European Research Contract QLK5-CT-2001-00560.

Eason, W.R., 1991. The effect of tree leaf litter on sward botanical composition and growth. For. Ecol. Manage. 45, 165–172.

EC, 2004. In support of the Communication from the Commission to the Council and the European Parliament in the implementation of the EU Forestry Strategy. Draft Commision Staff Working Document.

Eichhorn, M.P., Paris, P., Herzog, F., Incoll, L.D., Liagre, F., Mantzanas, K., Mayus, M., Moreno, G., Papanastasis, V.P., Pilbeam, D.J., Pisanelli, A., Dupraz, C., 2006. Silvoarable systems in Europe—past, present and future prospects. Agroforest. Syst. 67, 29–50.

Environment Protection Agency, 1994. Land application of sewage sludge. A Guide for Land Appliers on the Requirements of the Federal Standards for the Use of Disposal of Sewage Sludge, 40 CFR Part 503.

Etienne, M., 1996. Research on temperate and tropical silvopastoral systems: a review. In: Etienne, M. (Ed.), Western European Silvopastoral Systems. INRA, París, France, pp. 5–22.

European Environment Agency, 2000. Information about waste management facilities in EEA member countries.

European Environment Agency, 2002. Review of selected waste streams: sewage sludge, construction and demolition waste, waste oils, waste from coal-fired power plants and biodegradable municipal waste. Technical Report, p. 69.

European Environment Agency, 2006. European forest types: categories and types for sustainable forest management reporting and policy. EEA Technical Report No. 9, Copenhagen, Denmark.

FAO, 1992. Agenda 21. http://www.un.org/esa/sustdev/documents/agenda21/english/agenda21toc.htm.

Green, J.J., Alifragis, D., Baddeley, J.A., Bagnaresi, U., Bohne, H., Bulfin, M., 1999. Impact of understorey vegetation on tree production in European agrofororestry systems. In: Papanastasis, V.P., Frame, J., Nastis, A.S. (Eds.), Grassland and woody plants in Europe. European Grassland Federation. Grassland science in Europe, vol. 4. pp. 171–176.

Guerrero, A., 1996. El suelo, los abonos y la fertilización de los cultivos (Soils, fertilizers and farming fertilizer). Mundi-Prensa, Madrid, Spain (in Spanish).

Ibrahim, M., Villanueva, C., Mora, J., 2006. Traditional and improved silvopastoral systems and their importance in sustainability of livestock farms. In: Mosquera-Losada, M.R., McAdam, J., Rigueiro-Rodríguez, A. (Eds.), Silvopastoralism and Sustainable Land Management. CABI Publishing, Wallinford, pp. 13–18.

López-Díaz, M.L., Mosquera-Losada, M.R., Rigueiro-Rodríguez, A., 2007. Lime, sewage sludge and mineral fertilization in a silvopastoral system developed in very acid soils. Agroforest. Syst. 70 (1), 91–101.

Mosquera, M.R., González, A., 1999. Pasture production in Northern Spain dairy system. N. Z. J. Agric. Res. 42, 125–132.

Mosquera-Losada, M.R., González-Rodríguez, A., Rigueiro-Rodríguez, A., 1999. Ecología y manejo de praderas (Pastures ecology and management). Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain (in Spanish).

Mosquera-Losada, M.R., López-Díaz, M.L., Rigueiro-Rodríguez, A., 2001. Sewage sludge fertiliser of a silvopastoral system with pines in northwestern Spain. Agroforest. Syst. 53, 1–10.

Mosquera-Losada, M.R., González-Rodríguez, A., Rigueiro-Rodríguez, A., 2004. Fertilization with N and K pastures in temperate areas. J. Range Manage. 57, 280–290.

Mosquera-Losada, M.R., Fernández-Núñez, E., Rigueiro-Rodríguez, A., 2006a. Pasture, tree and soil evolution in silvopastoral systems of Atlantic Europe. For. Ecol. Manage. 232, 135–145.

Mosquera-Losada, M.R., López-Díaz, M.L., Rigueiro-Rodríguez, A., 2006b. Soil and pasture potassium content evolution after sewage sludge application. Grassland Sci. Europe 11, 125–127.

Nair, V.D., Graetz, D.A., 2004. Agroforestry as an approach to minimizing nutrient loss from heavily fertilized soils: the Florida experience. Agroforest. Syst. 61, 269–279.

Neilsen, W.A., Pataczek, W., Lynch, T., Pyrke, R., 1992. Growth response of *Pinus radiata* to multiple applications of nitrogen fertilizer and evaluation of the quantity of added nitrogen remaining in the forest system. Plant Soil 144, 207–217.

Official Journal of the European Union, 2005. Council regulation (EC) No. 1698/2005 of 20 September 2005 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD).

Ouro, G., Pérez-Batallón, P., Merino, A., 2001. Effects of selvicultural practices on nutrient status in a *Pinus radiata* plantation: nutrient export by tree removal and nutrient dynamics in decomposing logging residues. Ann. Forest Sci. 58, 411–422.

Pinto, M., Rodríguez, M., Besga, G., Virgel, S., Echeandia, A., Domingo, M., 1996. Fertiliser and grass species mixtures in a silvopastoral system. Grassland Sci. Europe 1, 133–137.

Rigueiro-Rodríguez, A., 2000. Sistemas silvopastorales en la Iberia Atlántica (Silvopastoral systems in Atlantic Iberian). XL Reunión Científica de la Sociedad Española para el Estudio de los Pastos 649–658 (in Spanish).

Rigueiro-Rodríguez, A., Mosquera-Losada, M.R., Gatica-Trabanini, E., 2000. Pasture production and tree growth in a young pine plantation fertilized with inorganic fertilizers and milk sewage in northwestern Spain. Agroforest. Syst. 48, 245–256.

Rigueiro-Rodríguez, A., Mosquera-Losada, M.R., López-Díaz, M.L., 2001. Crecimiento del arbolado y producción de pasto en un sistema silvopastoral fertilizado con lodos de depuradora urbana en una zona agrícola abandonada en Galicia (Tree growth and pasture production in a silvopastoral system fertilized with sewage sludge in an abandoned agricultural land in Galicia). III Congreso Forestal Español, Granada, Spain, pp. 703–707 (in Spanish).

Rigueiro-Rodríguez, A., Amador-García, A., Mosquera-Losada, M.R., 2002. In: Villalobos, J., Testi, L. (Eds.), Characterisation of dairy and municipal sewage sludge as fertilisers. VII European Society for Agronomy Congress, Córdoba, Spain, pp. 399–400.

Rigueiro-Rodríguez, A., Mosquera-Losada, M.R., Romero-Franco, R., González-Rodríguez, M.P., Villarino-Urtiaga, J.J., 2005. Silvopastoral systems as a forest fire prevention technique. In: Mosquera-Losada, M.R., McAdam, J., Rigueiro-Rodríguez, A. (Eds.), Silvopastoralism and Sustainable Land Management. CABI Publishing, Wallinford, pp. 380–387.

Rigueiro-Rodríguez, A., Mosquera-Losada, M.R., López-Díaz, M.L., 2007. Soil and Forage N, P, K, Ca and Mg concentrations in a Pinus radiate silvopastoral system in North West Spain after sewage sludge and lime application. Grass Forage 62 (2), 208–224.

Rigueiro-Rodríguez, A., Mosquera-Losada, M.R., López-Díaz, M.L., 2008. Effect of sewage sludge and liming on productivity during the establishment of a Silvopastoral system in North-West Spain. N. Z. J. Agric. Res. 51 (2), 199–207.

Rois-Díaz, M., Mosquera-Losada, R., Rigueiro-Rodriguez, A., 2006. Biodiversity Indicators on Silvopsatoralism across Europe. European Forest Institute, Joensuu, Finland.

Sánchez-Rodríguez, F., 2000. Crecimiento y producción de *Pinus radiata* en Galicia (Growth and productivity of *Pinus radiata* in Galicia). Thesis. University of Santiago de Compostela, Spain (in Spanish).

SAS, 2001. User's Guide, Statistics. SAS Institute Inc., Cary NC, USA.

Serna, M.D., Pomares, F., 1992. Nitrogen mineralization of sludge-amended soil. Bioresource Technol. 39 (3), 285–290.

Simpson, K., 1986. Abonos y estiercoles (Mineral and organic fertilizers). Acribia, S.A, Zaragoza, Spain, in Spanish.

Smith, S.R., 1996. Agricultural Recycling of Sewage Sludge and the Environment. CAB International, Wallingford, UK.

Wolstenholme, R., Dutch, J., Monat, A., Bayes, C.D., Taylor, C.M.A., 1992. A manual of good practice for the use of sewage sludge in forestry. Forestry Commission. Bulletin 107. HMSO, London.