Agriculture, Ecosystems and Environment 161 (2012) 165–173

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

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

# 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% $P_2O_5$ – 16% $K_2O$) 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.



## 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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0167-8809/$ – see front matter © 2012 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.agee.2012.08.001

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% $P_2O_5$–16% $K_2O$) 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 m$^2$, 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 $P_2O_5$ ha$^{-1}$ and 200 kg $K_2O$ 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 $CaCO_3$ 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% $P_2O_5$ – 16% $K_2O$ 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 0.6 N $BaCl_2$ 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