NUTRIENT BALANCE IN MONTEREY PINE STANDS TREATED WITH REPEATED APPLICATIONS OF SEWAGE SLUDGE

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1 INTRODUCTION

Fertilization and liming activities in forest plantations can help maintaining production and forest health in poor sites in which nutrient imbalances may occur. The addition of biosolids to forested land may recycle nutrients back to the soil, and decrease both disposal (Kimberley et al. 2004) and fertilization costs (when used in place of conventional fertilizers) (Wang et al. 2004; Kovanen, 2007). Nonetheless, the application of such wastes to forest soils should be restricted to (i) short-term rotation plantations, (ii) plantations destined for growing energy crops, and (iii) reforestation purposes where there is an extra input of nutrients. The growth responses of forest species to sludge amendments are often related to the N and P added with the sludge (Kimberley et al. 2004), and ratios of N to P in this waste are usually lower than required for crop growth (O'Connor et al., 2004). Here in this study, the foliar nutrient concentrations (Ca, Mg, K, P, N) of pine stands on acidic, sandy soils amended with repeated applications of sewage sludge, at different loading rates (2.4, 17 and 60 Mg ha^{-1}, DW equivalent, and control) was studied during 4 years.

2 MATERIALS AND METHODS

The soil is a Typic Endoaquept (Soil Survey Staff, 2006) developed from sandstones. The experimental design is a completely randomized design. Sludge was applied to 9 of the 12 established plots (8.1 x 8.6 m) at three different loading rates (2.4, 17 and 60 Mg ha^{-1}, DW sludge equivalent); there were three replicates per treatment and the remaining untreated plots were considered as controls. Vegetation consisted of a *Pinus radiata* D. Don. plantation, aged 22 months old at the start of experiment, and spaced at 2 × 3.5 m. The sludge was an anaerobic municipal sewage sludge (DW of ~23%), and was added at the above mentioned loading rates on three occasions: October 2001 (day 0), October 2002 (day 371), and October 2004 (day 1134), and the plots were monitored until September 2005. At these doses, European Union limits were exceeded for all of the metals, except for Pb (European Directive 86/278/EEC), and for N (European Directive 91/676/EEC) in the 60 Mg ha^{-1} $year^{-1}$ treatment, and for Cr, Zn, and N in the 17 Mg ha^{-1} $year^{-1}$ treatment. The present study was part of a project in which the presence of heavy metals and nitrates in leachates was investigated, and high doses of the sludge were applied so that cumulative metal and nitrate loading in the soil could be attained to simulate long-term applications. The mean organic C concentration in the biosolid applied to the plots was ~200 g kg^{-1}, total N 41.7 g kg^{-1}, P Olsen 556 mg kg^{-1}, C/N ratio 4.8, and pH 7.4. Concentrations of KCl-extractable NO_3^--N and NH_4^+-N in sludges were 33.9 and 2.7 mg kg^{-1}, respectively. Thus, most of the N in the sludge was present as organic N. Considering that the sludge was applied at loading rates of 2.4, 17, and 60 Mg ha^{-1} $year^{-1}$, the total N application rates were 101, 721, and 2544 kg ha^{-1}, respectively. Concentrations of Ca, Mg, K and Na, in the municipal sludge applied in 2001, 2002 and 2004 were between 35 and 49, 3.0 and 3.3, 2.0 and 3.4, and 1.4 and 1.7 g kg^{-1}, respectively. The chemical characterization of soils and leachates sampled throughout the experimental period are described by Egiarte et al. (2005; 2008; 2009). Concentrations of Ca, Mg, K, P of pine needles collected from lateral shoots, were measured with an ICP-OES and those of C, and N, with a LECO carbon analyzer.

3 RESULTS AND DISCUSSION

The distribution of mean Ca, Mg, K and P, N concentrations in current year pine needles taken at three sampling times (years 2002, 2004, 2005) are shown in Fig. 1 and Fig. 2, respectively. It was only in the fourth year of experiment, that the total mean concentrations of Ca in the 60 and 17 Mg ha^{-1} treatments were significantly higher ($P < 0.05$) than in the control plots (Fig. 1A). At any time, significant differences ($P < 0.05$) were detected between treatments for Mg (Fig. 1B). Nonetheless, there was a marked time effect at that time (2005), compared with previous sampling periods for Ca and Mg. The pattern of concentrations of Ca of pine needles in which there was an increase in this element with dose and time indicates either (i) that this element might be present in the sludge in non available forms, or (ii) that interactions with other nutrients and plant growth might occur, limiting the Ca uptake at low doses of sludge. On the other hand, subsurface lateral flow contributed to the flow of elements added with the sludge to the subsurface horizons of the control plots, and thus the pattern of the control samples should be interpreted with caution, especially for mobile ions. A significant decreasing trend ($P < 0.05$) in K concentrations in needles was observed over time, for all treatments (specifically, between years 2002 and 2004, except for the control). From that time on, the concentrations of K remained fairly constant (Fig. 1C). This decrease in K concentration could be mainly related to the effect of the aging of the forest stand; that is, when the stand is young, the amount of K available is high compared with the requirements of the stand (other variables being favourable).

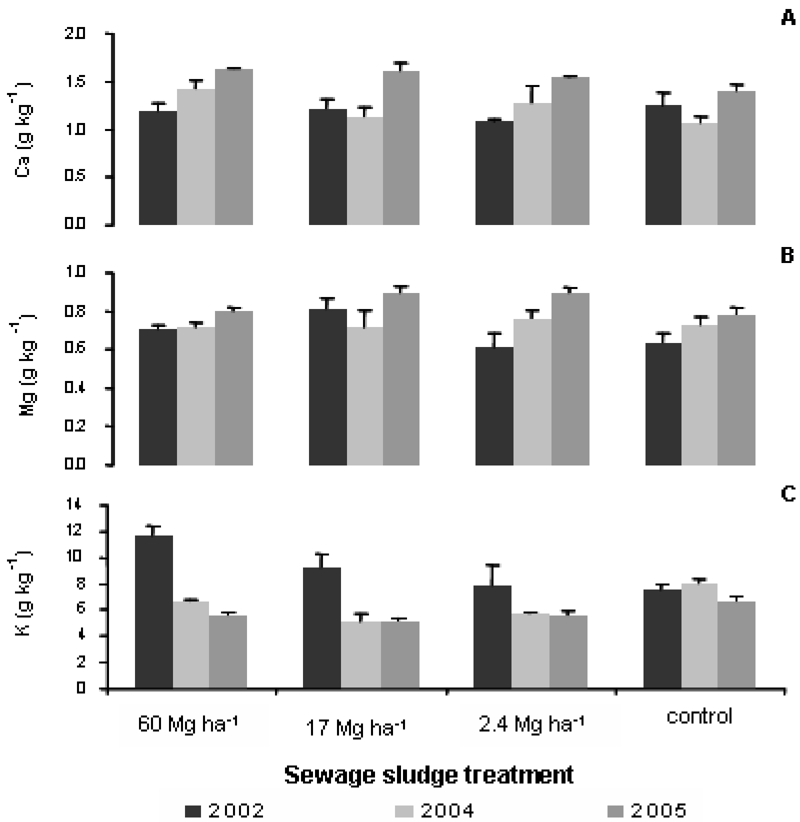

FIGURE 1 **Mean concentrations of Ca (A), Mg (B), and K (C) in current needles of Monterey pine, for each treatment (control, 2.4, 17, and 60 Mg ha^{-1} sludge addition), and at each of the sampling times: 2002, 2004, and 2005. Bars represent standard errors of the means (n = 3).**

Concentrations of P in pine needles generally followed increasing trend with dose and time (Fig. 2A). The low mobility of P enabled the detection of clear differences between the different treatments and the control, despite the existence of the subsurface lateral flow responsible for the cross-contamination of control plots with mobile elements. A decreasing trend with time was observed in concentrations of N in needles in all treatments, and was especially evident between 2002 and 2005 for 2.4 Mg ha^{-1} dose and control, although the differences were only significant ($P < 0.05$) for control soil (Fig. 2B). The initial flux of N concentrations in needles observed in the control plots may be related to this additional supply of N in very young pine stands, and the fact that other nutrients were scarce.

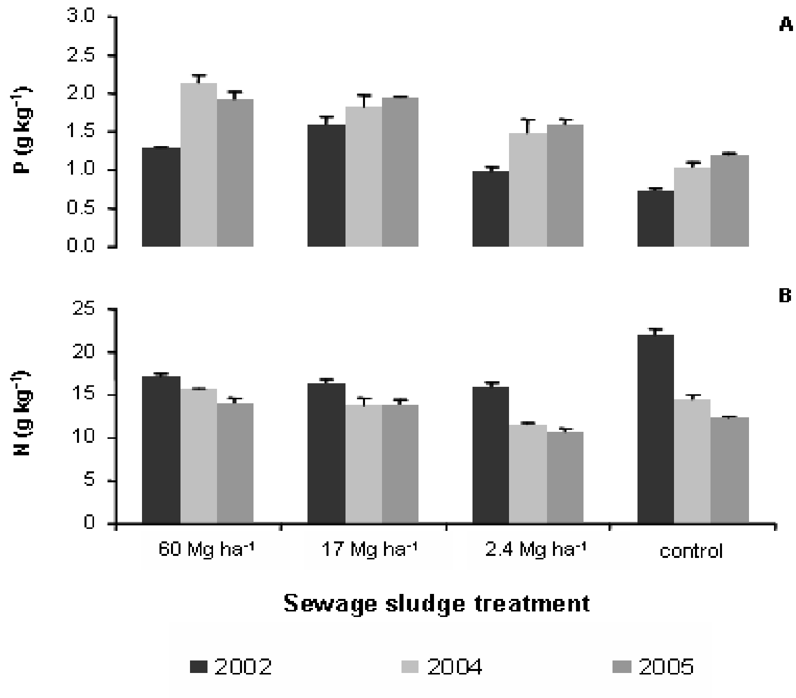

FIGURE 2 **Mean concentrations of P (A), N (B), in current needles of Monterey pine, for each treatment (control, 2.4, 17, and 60 Mg ha^{-1} sludge addition), and at each of the sampling times: 2002, 2004, and 2005. Bars represent standard errors of the means (n = 3).**

TABLE 1 **Mean N/P, K/N, N/Mg, and N/Ca ratios in current needles of Monterey pine after repeated applications of sewage sludge. Comparison between plots treated with sewage sludge at three different loading doses (2.4, 17, and 60 Mg ha^{-1}, DW equivalent) and control.**

Dose	N/P (g g^{-1})			K/N (g g^{-1})			N/Mg (g g^{-1})		
	Year 2002	Year 2004	Year 2005	Year 2002	Year 2004	Year 2005	Year 2002	Year 2004	Year 2005
Sewage sludge at 60 Mg ha^{-1}									
X	13.3ba	7.3aa	7.4aa	0.7aa	0.4aa	0.4aa	24.5aa	22.2aa	17.8aa
S.D.	0.6	0.5	0.2	0.10	0.01	0.03	1.8	1.7	1.6
Sewage sludge at 17 Mg ha^{-1}									
X	10.4ba	7.5aa	7.1aa	0.6aa	0.4aa	0.4aa	20.4aa	19.5aa	15.6aa
S.D.	1.6	0.3	0.5	0.13	0.04	0.03	2.7	3.5	1.4
Sewage sludge at 2.4 Mg ha^{-1}									
X	16.1aba	8.0aab	6.7ab	0.5aa	0.5aa	0.5aa	26.9aa	15.3aa	12.0aa
S.D.	0.9	1.4	0.7	0.14	0.04	0.04	4.7	2.1	0.1
Control									
X	29.5a	13.8aab	10.2ab	0.3aa	0.6aa	0.5aa	34.9aa	19.9aa	15.8aa
S.D.	1.5	0.6	0.5	0.03	0.07	0.03	4.2	2.3	1.9

n=3 for each treatment. Similarities and significant differences (P< 0.05) are indicated by letters for each element.

The Ca/Al molar ratios in foliage - used as an indicator of Al stress in trees - ranged between 1.7 and 2.6, which suggests risk of Al toxicity (data not shown). The foliar N/Mg ratios corresponding to the different treatments ranged between 20 and 35 g g^{-1} in 2002, between 15 and 22 g g^{-1} in 2004, and between 12 and 18 g g^{-1} in 2005, i.e. there was a decreasing trend over time (Table 1), which indicates critical Mg nutrition in relation to N nutrition. Moreover, the foliar N/Mg and K/N ratios did not differ significantly ($P < 0.05$) among treatments (including control), or among sampled years (Table 1). The K/N ratios obtained from the needles sampled in this experiment (Table 1) indicate that they were generally below the foliar ratio considered to be related to marginal nutrition (0.65).

The foliar levels of N/P for all treatments except for the 60 and 2.4 Mg ha^{-1} in year 2002 (Table 1) were below 12.5, which is indicative of optimal P nutrition, whereas in the control plots, this condition was only fulfilled at the final sampling time.

4 CONCLUSIONS

Under acidic and dystrophic conditions, these amended pine stands with repeated application of sewage sludge tend to be deficient in P and other nutrients (e.g., Ca, Mg). Moreover, other drawbacks related to nutrient imbalance (e.g., K) or antagonistic effects (e.g., Ca against Mg) may be the limiting factors for the optimum growth of pine stands, as suggested by the concentrations of these elements in the needles of the forest stands under study. Given the strong acidification in the plots amended with the highest dose of sludge mainly attributed to strong nitrification a negative impact is expected on the whole ecosystem in the long term. For this reason, the use of other types of sludge with a higher acid buffering capacity and greater stabilization of the organic fraction of this waste is strongly encouraged in very acid soils such as the present ones. In addition, balancing the wastes with those nutrients in which they are deficient is fully recommended in order to avoid imbalances in plant nutrients.

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