Tree nutrition and chemical properties of a sandy soil in a pine plantation receiving repeated biosolids applications

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Abstract
Biosolids are rich in organic carbon and nutrients and are commonly used as a fertiliser and soil amendment. Since the mid-1990s, a *Pinus radiata* (D. Don) plantation growing on a sandy, low fertility soil at Rabbit Island near Nelson, New Zealand, has received aerobically digested liquid biosolids. An experimental research trial was established on the site in 1997 to investigate the effects of biosolids applications on tree growth, nutrition, and soil quality. Biosolids have been applied to the trial site every three years since 1997, at three application rates: 0 (Control), 300 (Low) and 600 kg N/ha (High). Tree nutrition status is monitored annually. Soil samples were taken in August 2007 to assess the effects of the repeated biosolids application on soil chemical properties. Biosolids application increased N concentration in pine foliage. Forest litter and soil analysis indicates that the High biosolids treatment has significantly increased concentrations of soil available P and organic C, but reduced soil pH. The High biosolids treatment has also increased concentrations of total soil Cu, Pb and Zn, although overall concentrations are considered to be very low for a soil. The Low biosolids treatment had no significant effect on soil chemical properties. Our results show that repeated application of biosolids to a plantation forest can significantly improve tree nutrition and site productivity. However, the biosolids-derived heavy metals are strongly retained by the litter layer. The long term effects of these litter-retained metals need to be evaluated.

Key Words
Sewage sludge, plantation forest, low fertility, soil quality.

Introduction
Using biosolids (i.e., treated sewage sludge) as a fertiliser and soil amendment is one of the most common options for biosolids management (Magesan and Wang 2003). Compared with applying biosolids to agricultural land, forest land application can reduce the risk of contaminants entering the human food chain, and can also increase tree growth and subsequent economic returns (Kimberley *et al.* 2004). The regional wastewater treatment plant in Nelson, New Zealand, originally established in 1983, was upgraded to incorporate the handling of biosolids in 1995/96. After treatment, biosolids from the scheme are applied to a 1000-ha *Pinus radiata* D. Don forest plantation at Rabbit Island near Nelson City. A long-term trial was established in 1997 to monitor the environmental effects of the repeated application of biosolids on the plantation, and to determine sustainable application rates. Since then tree growth and nutrition and wood properties have been assessed along with a number of environmental variables, such as soil and groundwater quality (Wang *et al.* 2004; 2006). The objective of this study was to investigate the effects of repeated applications of biosolids on tree nutrition and soil chemical properties.

Materials and methods
The research trial was established in 1997 in a 6-year-old stand of *Pinus radiata* in the Rabbit Island plantation. The soil consists of coarse coastal dune sands, classified as a sandy raw soil (Hewitt 1998), which provides free rooting access to the shallow groundwater 2.0 to 4.2 m below the surface. Three biosolids treatments were applied in a split-plot, randomised block design with four replicates. The treatments consisted of a Control (no biosolids), a Low treatment (target application of 300 kg N/ha) and a High treatment (at a target rate of 600 kg N/ha). Each main-plot contained three stocking density treatments (subplots) at 300, 450 and 600 stems/ha. There were 36 subplots in total (4 replicates × 3 biosolids rates × 3 stocking densities), each plot measuring 25 m × 25 m, plus 5 m buffer zones, so that the whole site covered an area of approximately 4 ha. The biosolids were applied in October 1997 and reapplied at the same rates to the same plots in November 2000, October 2003, and October 2006. The biosolids contained high concentrations of nitrogen (approximately 10% N with about 40% in ammonium form). Concentrations of contaminants such as pathogens and heavy metals in the biosolids were low and well below the New Zealand

guidelines for land application (NZWWA 2003), and therefore would not limit beneficial use through land application. Details about properties of the biosolids applied and method of application were given by Wang *et al.* (2004).

To assess changes in tree nutrition due to biosolids application, foliage samples (present year's secondary foliage in top third of crown) have been collected from selected trees in each plot annually in summer since 1998. The impact of biosolids applications on soil chemical properties was assessed from samples taken from the litter layer, topsoil (0–0.25 m depth) and subsoil (0.25–0.5 m depth) in August 2007. Samples were taken from all subplots within each biosolids treatment main-plot and bulked, resulting in four replicate samples per biosolids treatment. The foliage and litter were oven-dried (70^{o}C) and ground for chemical analysis. Soil samples were air-dried and ground to pass a 2-mm sieve. Soil pH was measured at a soil:water ratio of 1:2. Total N in soil, tree foliage and understorey samples, and total C in soil were determined by dry combustion using a Leco CNS 2000 machine. Concentrations of soil exchangeable Ca, Mg, K, and Na were measured using the ammonium acetate method (Blakemore *et al.* 1987). Extractable soil P was determined using the Olsen P method. Acid digestion was used to extract heavy metals in biosolids and soil samples (ASTM International 1999). Flame atomic absorption spectrometry was used to determine As, Cd, Cr, Cu, Pb, Ni, and Zn in the acid digestion and groundwater samples. Mercury was analysed using cold vapour atomic absorption spectrometry (APHA 1995). Foliage and litter samples were digested with concentrated HNO_3/H_2O_2, and concentration of nutrients and heavy metals in the digest were determined using the inductively coupled plasma optical emission spectrometry (ICP-OES, Perkin Elmer Optima 3000DV).

Analysis of variance (ANOVA) and least significant difference (LSD) tests were used to determine the statistical significance of the biosolids treatment effects on tree nutrition over time and soil properties using the SAS/STAT Version [9] GLM procedure.

Results and discussion

Effect of biosolids application on tree nutrition

Annual foliage analyses have shown that foliar concentrations of all nutrients except N have remained in the "satisfactory" range of tree nutrition and indicate that none of these nutrients are limiting tree growth (Will 1985). However, they have consistently shown that natural soil N supply in the Rabbit Island *P. radiata* forest is low, with foliar N concentration of the Control treatment averaging 1.2% N since monitoring began (Figure 1), well under the 1.5% N, threshold below which *P. radiata* may benefit from nitrogen fertiliser (Will 1985). Both biosolids treatments have produced significant ($P < 0.05$) elevations in foliar N with the Low treatment averaging 1.4% N and the High treatment 1.5% N.

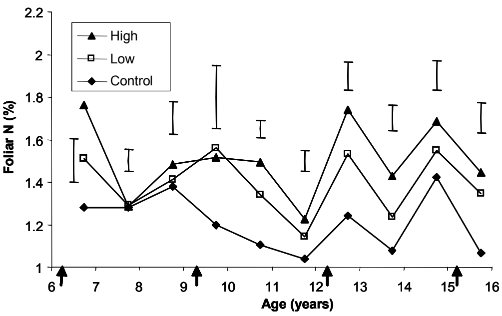

Figure 1. Effect of biosolids application on concentrations of nitrogen in foliage. Arrows indicate time of biosolids application. Error bars show least significant differences (*P* = 0.05) and can be used to determine the significance of treatment differences.

Effect of biosolids application on forest litter and soil chemistry

Analysis of the forest litter layer samples collected in 2007 show that both of the biosolids treatments significantly ($P < 0.05$) increased C/N ratios and concentrations of total P and Mg (Table 1). The High biosolids treatment significantly ($P < 0.05$) increased concentrations of total N and Fe, whereas the Low biosolids treatment significantly ($P < 0.05$) increased concentrations of total Na and B in the litter. Litter Mn concentration in the High biosolids treatment was significantly ($P < 0.05$) lower than the Control (Table 1). These changes in litter elemental concentration can be attributed to the initial litter chemical composition and retention of biosolids-derived elements. For example, significantly lower Mn concentrations in foliage samples were observed (Wang *et al.* 2004).

Table 1. Effect of biosolids application on litter chemical properties (sampled in August 2007)*

Treatment	C	N	P	K	Ca	Mg	Na	C/N	B	Mn	Fe
				%						mg/kg	
Control	47.0 a	1.02 a	0.055 a	0.079 a	0.36 a	0.17 a	0.029 a	47 a	10 a	445 a	1100 a
Low	44.0 a	1.28 ab	0.069 b	0.097 a	0.41 a	0.19 b	0.043 b	35 b	14 b	375 ab	1665 ab
High	47.9 a	1.47 b	0.071 b	0.079 a	0.40 a	0.19 b	0.038 ab	34 b	11 ab	318 b	2313 b

*Values within a column followed by the same letter do not differ significantly (LSD test, $P = 0.05$; number of replications per treatment = 4).

Analysis of soil samples show significantly ($P < 0.05$) increased soil organic C and available P (Olsen P), and reduced soil pH in the top soil layer (0–0.25 m) in the High treatment. Biosolids treatments had no significant effect on concentrations of total soil N and exchangeable Mg, K, and Na, but significantly increased soil exchangeable Ca in the Low treatment (Table 2). The significantly ($P < 0.05$) higher soil P concentration in the 0-0.25 m and 0.25–0.5 m layers (Table 2) suggests that the High rate biosolids application has not only resulted in accumulation in the topsoil but also caused some P movement down the soil profile. This agrees with findings of Lu and O'Connor (2001) who reported that biosolids-derived P may be susceptible to leaching through sandy soils, due to the low soil P-sorbing capacity. Biosolids treatments significantly ($P < 0.05$) increased the soil C/N ratios in the 0.25-0.5 m layer. This was due to the increase of total C with biosolids treatments, which may be caused by the downward movement of organic C in the soil profile. Analysis of deeper soil layers has been proposed to verify the P and organic C movement in the soil profile.

Table 2. Effect of biosolids application on soil chemical properties (sampled in August 2007)*

Depth	Treatment	pH	C	N	C/N	Olsen P	K	Ca	Mg	Na
			%			mg/kg		cmol$_c$/kg		
0-0.25m	Control	5.30 a	0.55 a	0.03 a	18.4 a	29.1 a	0.09 a	0.95 a	1.11 a	0.07 a
	Low	5.18 ab	0.74 ab	0.04 a	18.8 a	36.7 a	0.10 a	1.05 b	1.13 a	0.08 a
	High	4.93 b	0.89 b	0.05 a	20.3 a	56.3 b	0.11 a	1.03 ab	0.99 a	0.08 a
0.25-0.5m	Control	5.80 a	0.25 a	0.03 a	8.9 a	21.5 a	0.07 a	0.75 a	1.02 a	0.04 a
	Low	5.70 a	0.26 a	0.03 a	9.4 b	21.5 a	0.07 a	0.75 a	1.06 a	0.07 a
	High	5.33 a	0.36 a	0.03 a	11.8 b	32.8 b	0.08 a	0.68 a	0.95 a	0.07 a

*For each depth, values within a column followed by the same letter do not differ significantly (LSD test, $P = 0.05$; number of replications per treatment = 4).

Biosolids applications significantly ($P < 0.05$) increased total concentrations of all eight heavy metals measured in the litter layer, except for Pb and Ni in the Low treatment (Table 3), which implies that a large proportion of the biosolids-derived metals are strongly retained by the litter layer. High metal retention capacity by forest litter was also reported by McLaren *et al.* (2007) who found that concentration of heavy metals in the litter layer was greatly elevated even a few years after biosolids were applied.

Table 3. Effect of biosolids application on concentrations of heavy metals in litter and soil (sampled in August 2007)*.

Depth	Treatment	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
					mg/kg				
Litter	Control	0.6 a	0.02 a	2.5 a	4.5 a	3.4 a	0.05 a	4.0 a	19.0 a
	Low	0.8 b	0.09 b	5.2 b	13.3 b	4.8 ab	0.08 b	5.5 ab	37.5 b
	High	1.2 b	0.22 c	10.5 c	61.3 c	8.8 b	0.16 c	11.9 b	69.8 c
0-0.25m	Control	2.6 a	<0.05 a	21.5 a	3.9 a	3.9 a	<0.05 a	28.5 a	26.0 a
	Low	2.3 a	<0.05 a	20.8 a	4.7 ab	4.0 ab	<0.05 a	27.8 a	26.5 a
	High	2.1 a	<0.05 a	21.6 a	6.3 b	4.3 b	<0.05 a	25.8 a	30.5 b
0.25-0.5m	Control	2.9 a	<0.05 a	24.3 a	4.3 a	4.0 a	<0.05 a	43.8 a	27.3 a
	Low	3.0 a	<0.05 a	23.8 a	4.5 ab	4.0 a	<0.05 a	41.8 a	27.3 a
	High	3.5 a	<0.05 a	24.8 a	4.9 b	4.0 a	<0.05 a	44.5 a	29.3 a

*For each depth, values within a column followed by the same letter do not differ significantly (LSD test, p=0.05; number of replications per treatment=4).

Although concentrations of heavy metals in underlying soils showed less obvious changes in response to biosolids application than in the litter layer, the High biosolids treatment had significantly ($P < 0.05$)

increased concentrations of soil Pb and Zn in the 0–0.25 m layer, and significantly increased soil Cu concentrations in both 0–0.25 m and 0.25–0.5 m layers (Table 3). The increased Cu concentration in soils receiving biosolids applications (Table 3) did not result in increased *P. radiata* foliage Cu concentration (data not shown), indicating a low bioavailability of the biosolids-derived Cu. The relatively higher concentrations of Cr and Ni in the 0.25-0.5 m layer than in the 0-0.25 m layer were due to the natural soil conditions, and were not affected by the biosolids applications. Generally, heavy metal concentrations (Table 3), with or without biosolids application, were low and well below the soil contaminant limits defined by the guidelines for the safe application of biosolids to land in New Zealand (NZWWA 2003). Overall, repeated application of biosolids improved soil fertility and appeared to have no significant detrimental effect on soil quality at Rabbit Island.

Conclusions

Repeated application of biosolids to a *P. radiata* plantation on a low fertility sandy soil on Rabbit Island has significantly enhanced N supply to meet tree growth demands. The High biosolids treatment significantly increased concentrations of soil available P and organic C, but it resulted in a reduced soil pH. Although the High biosolids treatment increased the concentration of total soil Cu, Pb and Zn, overall concentrations of these heavy metals are considered to be very low for a soil. The Low biosolids treatment had no significant effect on soil chemistry. However, the biosolids-derived heavy metals are strongly retained by the litter layer. The long term effects of these litter-retained metals will be further assessed in future studies.

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