Application of Biosolids to Pine Plantations of the Swan Coastal Plain

Final Report of a Three Year Study

To

The Water Corporation of Western Australia

Ian Dumbrell
Dept Conservation and Land Management
Busselton, Western Australia.

In accordance with the Review of Environmental Factors associated with the trial application of Biosolids to the Myalup pine plantation, the following report fulfils the requirement for a final report at the end of the three year trial period. This report will cover results in tree growth, tree nutrition, water quality, nutrient and heavy metal concentrations in the soil and will examine operational constraints in the use of biosolids in pine plantations.

Summary

A trial evaluating the response of pines on the coastal sand plain to the application of biosolids was established in 1998. Anaerobically digested biosolids were applied to a 17 year-old *Pinus pinaster* plantation growing on deep Karrakatta sands within the Lake Preston groundwater sub-area. Treatments were a control, standard mineral fertiliser and biosolids applied at 17 and 34 dry tonne ha^{-1}.

Compared to the nil fertiliser control (C) treatment, the mineral fertiliser (MF), 17 dry tonnes biosolids (17B) and 34 dry tonnes biosolids (34B) treatments increased volume increment by 19%, 27% and 55% respectively over three years ($2m^3$ ha^{-1} yr^{-1}, $3m^3$ ha^{-1} yr^{-1}, $6m^3$ ha^{-1} yr^{-1}). The growth increase was significant ($p=0.02$) in the MF treatment and highly significant ($p < 0.01$) in the 17B and 34B treatments. When compared to the MF treatment, mean volume increment over three years in the 17B treatment was not significantly greater, however there was a significant ($p<0.01$) mean volume increment increase of 30% in the 34B treatment. Relative to the control treatment, the MF treatment produced the largest volume increment in the first year only. Relative volume increments in the biosolids treatments increased greatly in the second year and continued to increase in the third year while the response in the MF treatment plateaued then declined.

There was no difference in foliar nutrient concentrations across the site prior to treatment application. The 34B treatment significantly increased foliar concentrations of nitrogen (N), phosphorus (P), zinc (Zn) and manganese (Mn) above all other treatments over 3 years. The MF and 17B treatments significantly increased foliar concentrations of N for 2 years and P for 3 years above the C treatment but with no difference between them.

Analysis of surface soil (0-10cm) samples did not detect any pathogens (thermo-tolerant coliforms, salmonella) or pesticides from any treatment throughout the study and there was no change in pH. Some heavy metals were detected both prior to and after treatment application, however these detections were random and could not be related to any one treatment. In all cases concentrations of heavy metals were less than 1% of maximum allowable concentrations. Treatment applications did not affect either total N or P in the surface soil and when detected, nitrate concentrations were generally higher in the control treatment. The mineral fertiliser treatment was the only treatment to significantly ($p<0.05$) increase bicarbonate extractable (Bray) P in the surface soil after treatment.

Gravimetric soil moisture content was calculated from soil samples collected at the end of June 1999. Despite 440mm of rain falling in May and June of that year the soil profile remained relatively dry (mean moisture content 4.4%) below 25cm from the surface. Soil moisture profiles were similar to those from a nearby *P. pinaster* experimental site in McLarty plantation (which has the same soil type and structure, stand density, tree age and mineral fertiliser application), that was measured on a monthly basis for four years. The McLarty site showed no soil water recharge below 8.25m.

Groundwater nitrate concentrations remained unchanged in samples taken from bores within the plantation, however increased nitrate concentrations above acceptable limits for drinking water were detected in bore samples taken from beneath the stockpile area outside of the plantation. The excessive nitrate concentrations were recorded in May 2000 and January 2001 but were back within acceptable limits by August 2001. No other nutrient, heavy metal or pathogens were found above acceptable limits in the groundwater.

There were three major and two minor constraints identified from this study relating to the application of biosolids to pine plantations. The major constraints related to cost, storage provisions, and stockpiling and application time requirements. The minor constraints were related to the social aspects, such as odour and public access, and the required operational condition of the plantation.

Introduction

The Water Corporation of Western Australia owns and operates three wastewater treatment plants (WWTP) in Perth, Western Australia that produce approximately 13,800 dry tonne of biosolids annually. To date these biosolids have been used mainly in composting for garden mulch, and as a fertiliser replacement in agriculture. Since 1996 the Water Corporation has been actively pursuing a range of alternative markets for biosolids to allow flexibility of operations and to ensure adequate market availability for future expansion in production.

Forestry plantations represent a large potential market for biosolids. Biosolids applications to pine plantations have shown significantly improved growth rates in young and established plantations in the USA, New Zealand and Australia (Dixon *et al.* 1996, Henry and Van Ham 1996). In 1996, Sydney Water (NSW) applied approximately 10% (20,000 tonnes) of their total biosolids production to pine plantations (Hope and M^{c}Dougall 1996). There are 5500 ha of softwood plantations on the Swan Coastal Plain south of Perth in WA that could be suitable for the application of biosolids. Current fertiliser management in these coastal plantations usually includes application of nitrogenous and phosphatic inorganic fertilisers at various stages throughout the rotation.

The Swan Coastal Plain is comprised of a series of lineal sand dunes between the ocean and the Darling Ranges interspersed with a series of interconnecting lakes and wetlands. Myalup plantation is located on the Spearwood dune system that lies midway between the coast and ranges. The soils are generally highly permeable coarse-grained sands that range in depth from 5m to 30m. There are generally no impermeable layers to prevent the accession of leachate entering the groundwater, however limestone may affect drainage where it occurs. Therefore the potential for contamination of soil and groundwater with nutrients, heavy metals and pathogens were seen as the greatest obstacles to the widespread application of biosolids on the coastal sand plain.

Objectives

In 1996 the Water Corporation of WA approached the dept of Conservation and Land Management regarding the establishment of a trial to assess the potential for using biosolids from Perth's WWTP in plantations as a fertiliser replacement. The objectives of the trial were to:

1. Determine the growth response of *P. pinaster* to the application of biosolids and hence, assess the value of biosolids as a fertiliser replacement in plantations,
2. Assess the potential for movement of pathogens, nutrients and heavy metals from the applied biosolids into groundwater beneath the highly permeable coarse sands.
3. Determine operational constraints to the viability of routine biosolids applications.

Materials and Methods

Site

The trial was established in 1998 on the Swan Coastal Plain approximately 120 km south of Perth (S 33° 00'; E 115° 45') within the Lake Preston groundwater sub-area. The soil at the site is a Karrakatta sand, which is a uniform coarse podsolised siliceous sand, with a grey to pale brown topsoil and a yellow subsoil overlying limestone (M^{c}Arthur 1991). In general the soil was acidic (pH 4.5), non-saline and non-sodic, contained low levels of organic carbon (0.88%) and had very low fertility (total N 0.035%, available P <2.9 mg kg^{-1}). The Cation Exchange Capacity (meq 100g^{-1}) for the sands at this site were between 1.0 and 2.0 for the surface 10cm and less than 1.0 below 10cm, indicating that the soil had high potential for leaching throughout the profile. The trial involved the application of approximately 1100 tonnes (1,405m^{3}) of anaerobically digested dewatered biosolids to 11.6 ha of 17 year-old *P. pinaster* plantation using a tractor drawn manure spreader. The plantation was thinned a year earlier (8/97) from 800 stems per hectare (sph) to approximately 500 sph.

Biosolids

Cartage and stockpiling of biosolids commenced on 15/05/98 and was completed by 21/07/98. Spreading ran from 24/07/98 to 31/07/98. Fourteen batches of biosolids were sampled prior to leaving the Woodman Point WWTP and analysed for nutrients, heavy metals, pesticides and pathogens. Mean concentrations from this sampling are shown in table 1. Contaminant and pathogen grades are in accordance with current Western Australian Guidelines for Direct Land Application of Biosolids and Biosolids Products (Western Australian Biosolids Working Group 2002).

Table 1 Mean contaminant concentrations and contaminant grade of biosolids from Woodman Point wastewater treatment plant prior to transport.

Component	Mean (mg kg-1)	Biosolids Grade*
Arsenic	2.10	C1
Cadmium	3.06	C2
Total Chromium	304.00	C2
Copper	1646.67	C2
Lead	98.60	C1
Mercury	2.90	C2
Molybdenum	26.40	N/A
Nickel	73.87	C2
Selenium	3.49	C2
Zinc	1400.00	C2
DDD/DDE/DDT	0.02	C1
Aldrin	0.02	C1
Dieldrin	0.02	C1
Chlordane	0.02	C1
Heptachlor	0.02	C1
HCBs	0.02	C1
Lindane	0.02	C1
PCB	0.20	C1
Total Kjeldahl Nitrogen	38060.00	
Nitrate	48.07	
Nitrite	10.53	
Ammonium	9386.67	
Organic N	28673.33	
Total Phosphorus	12333.33	
Available Phosphorus	2590.00	
Total Solids (%)	26.53	
pH	7.23	
Faecal Coliforms (counts g-1)	1100.00	P3
Salmonella (counts 50 g-1)	368.78	P3

* Biosolids grades are defined in appendices 1 and 2.

Trial design

The trial was established as a randomised complete block with three replicates each of four treatments (table 2) giving a total of twelve plots. Mean treatment plot size was 1.92 ha.

Table 2 Applied treatments and nutrient loads.

Treatment		Total available N ha^{-1} €	Total available P ha^{-1}
Control	C	-	-
Mineral Fertiliser*	MF	200 kg	100 kg
17 dry t ha^{-1} Biosolids	17B	318 kg	94 kg
34 dry t ha^{-1} Biosolids	34B	636 kg	188 kg

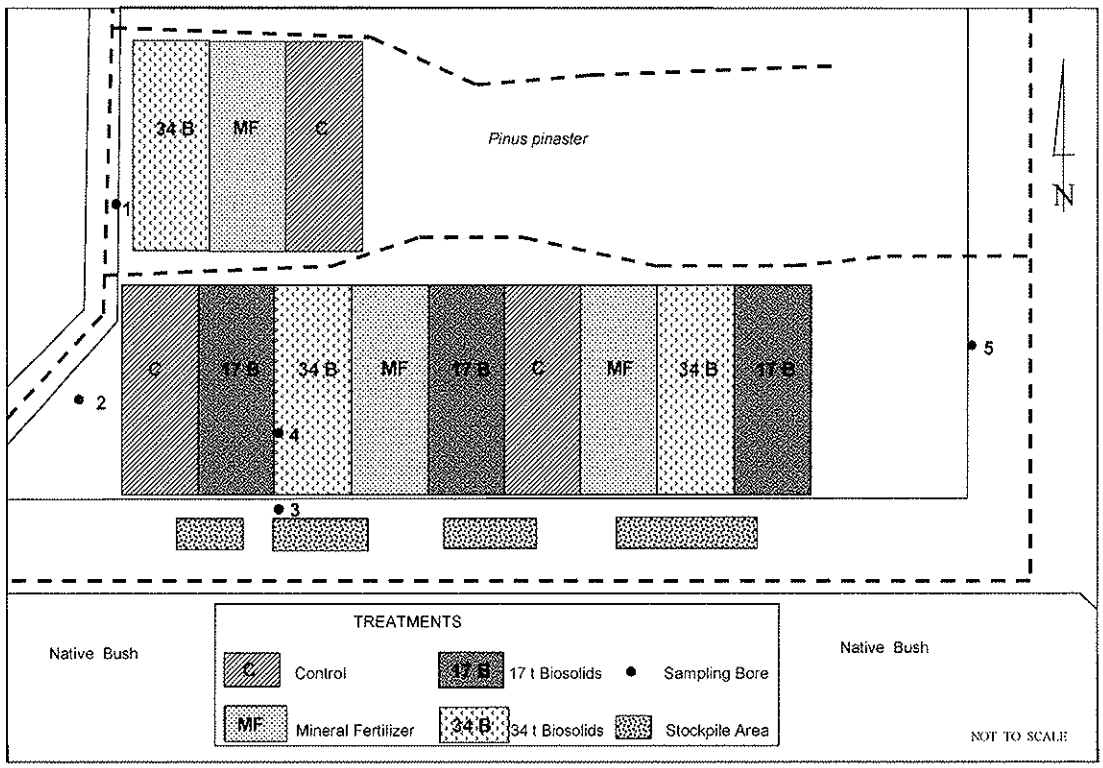
* Mineral Fertiliser applied as 500 kg ha^{-1} DAP + 250 kg ha^{-1} Urea

€ Total inputs of available N and P were calculated for three years, using a mineralisation rate of 15%. Total N also assumed that only 20% of the initial ammonium would be available due to volatilisation losses.

The highest biosolids application rate was designed to provide an equivalent amount of available N and P as the mineral fertiliser in the first year. The lower application rate was included to determine if tree growth could be enhanced with half the input of N and P. The mean total Kjeldahl nitrogen of the biosolids was 3.81%, of which 0.940% was in the form of ammonia and 0.0058% nitrate and nitrite. Total P was approximately 1.23%. At an estimated 15% mineralisation rate (NSW EPA 1997) inputs in the first year from the 34 dry tonnes ha^{-1} biosolids would approximate the initial N and 70% of the P input from the mineral fertiliser.

Figure 1 shows the plot and treatment layout as well as the stockpile areas and bore locations relative to the plots. Depth to water table in bores 1 and 2 was 11m, while in bores 3,4, and 5 it was 15m.

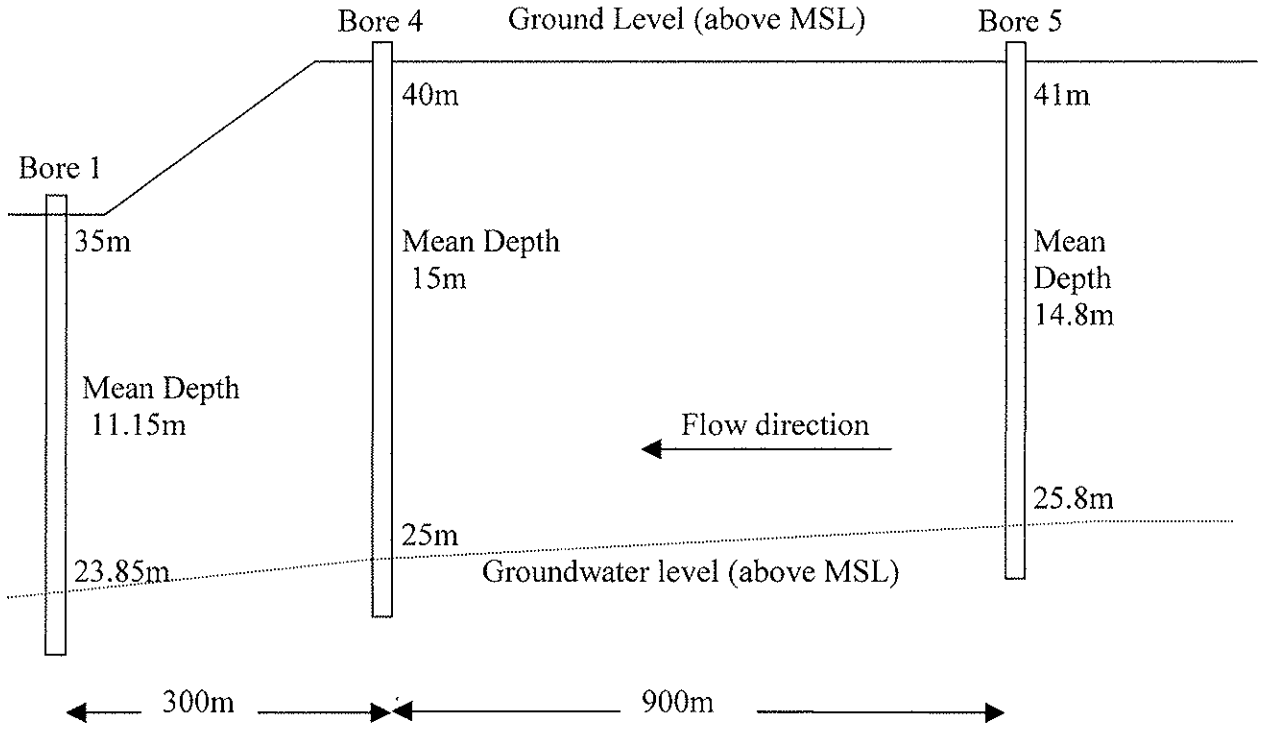
Figure 1 Trial layout showing plot and treatment configuration, sample bores and stockpile locations.



Groundwater flow

Figure 2 depicts a stylised cross-sectional diagram of the site from bore 1 (and 2) in the west through bore 4 (and 3) to bore 5 in the east. Groundwater flows from east to west and discharges into a series of saline lakes approximately 6km to the west of the trial site. These saline lakes are groundwater sinks, where groundwater input is balanced by evaporation (Commander 1984).

Figure 2 Site cross-sectional diagram from west to east showing ground and groundwater levels above mean sea level (MSL), and bore depths.



Average linear groundwater velocity (V) = ki/n

Where k = hydraulic conductivity

i = hydraulic gradient

n = soil porosity

Hydraulic Gradient = Δht/distance

Bore 5 – 4: I = 0.0011

Bore 4 – 2: I = 0.0038

Typical hydraulic conductivity for Karrakatta sands is 20m day^{-1} with a porosity of 0.3 (Commander pers. comm.). Using the estimated k and n, and the calculated i values, lateral linear groundwater flow was estimated to be 25m $year^{-1}$ from bore 5 to bore 4, and 95m $year^{-1}$ from bore 4 to bore 2 in a westerly direction.

Monitoring

Monitoring of the trial included tree growth measurements, foliar, soil and groundwater sampling. Tree growth was assessed by measuring the height and diameter at breast height over bark (DBHOB) of 30 -50 trees per plot. Foliage samples for nutrient analysis were taken from five trees per plot just prior to treatment application and in early spring each year for three years.

Soil samples for nutrient and heavy metal analysis were collected prior to treatment application (03/06/98) and twice after treatment during the first year (27/11/98, 29/06/99). Samples were scheduled to be taken in Feb/Mar 1999, however this was not possible due to the dry soil conditions. Samples were taken in winter for the second and third years. Samples were collected (where possible) from 0-10 cm, 25 cm, 50 cm, 75 cm, 100 cm, 150 cm, 200 cm and 300 cm.

Groundwater samples for nutrient, heavy metal and pathogen analysis were collected from 5 bores within and around the site. Sampling commenced 4 months prior to treatment application in March 1998, then three times after treatment application during the first year (15/10/98, 06/01/99, and 22/06/99). Samples were collected in winter in the second and third years. An extra sample was collected in January 2001 to monitor the high nitrate concentrations in bore 3. All bores were purged in accordance with guidelines (Barber and Davis 1996) prior to sampling.

Soil and water samples were analysed by Australian Environmental Laboratories[1]. Elements analysed, limits of detection and analytical methods are outlined in appendices 3 and 4. Foliar nutrient analyses were conducted by the Department of Conservation and Land Management's laboratory, Kensington. Foliar analysis of total nitrogen was by the Kjeldahl method (M^{c}Kenzie and Wallace 1954), and analysis of total potassium was by flame photometer following acid digests. Foliar phosphorus was analysed colorimetrically using a spectrophotometer (Kitson and Mellon 1944) following acid digest (Piper 1942).

Statistical Analysis

Analysis of Variance using Systat software was used for the statistical analysis of mean treatment differences.

[1] Australian Environmental Laboratories, 52 Murray Rd Welshpool, Western Australia.

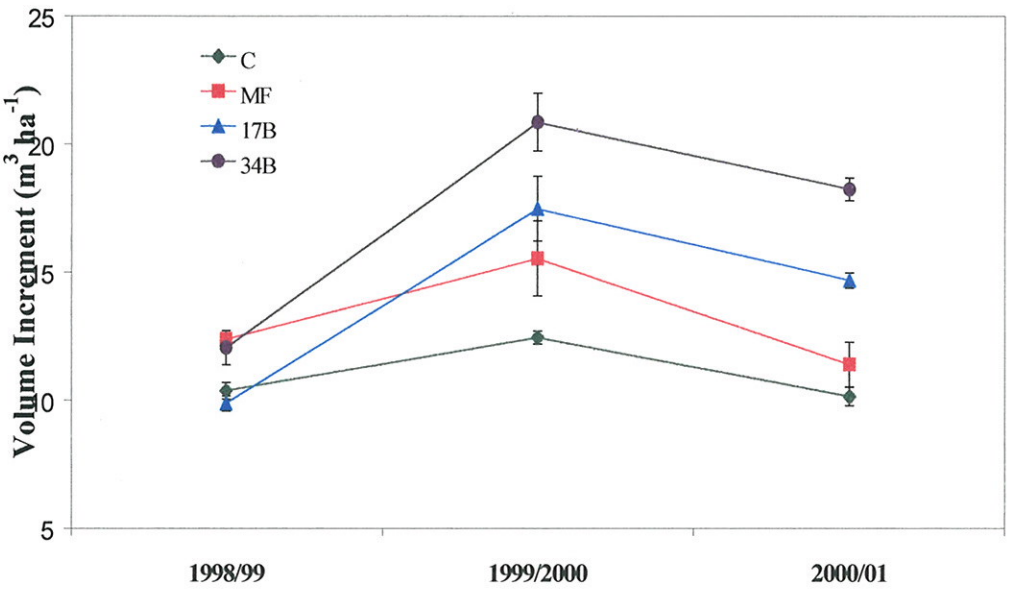
Results

Tree Growth

Compared to the control (C) treatment, the mineral fertiliser (MF), the 17 dry tonne biosolids (17B) and the 34 dry tonne biosolids (34B) increased volume increment by 19%, 27% and 55% respectively over three years ($2m^3\ ha^{-1}\ yr^{-1}$, $3m^3\ ha^{-1}\ yr^{-1}$, $6m^3\ ha^{-1}\ yr^{-1}$). The growth increase was significant ($p=0.02$) in the MF treatment and highly significant ($p < 0.01$) in the 17B and 34B treatments.

In comparison with the MF treatment, the 17B treatment did not significantly increase mean volume increment, whereas the 34B treatment did significantly ($p<0.01$) increase mean volume increment by 30% over three years ($4m^3\ ha^{-1}\ yr^{-1}$). However in the third growing season (2000/01) greater separation occurred in volume increments between the fertilised treatments. The 34B treatment maintained a significantly greater ($p < 0.01$) volume increment than any other treatment, and the 17B treatment was now significantly greater ($p < 0.01$) than the MF treatment, which decreased greatly to be no different to the control treatment (Fig 3). The significant volume increases were due to increases in both height and basal area increments in the biosolids treatments.

Figure 3 Influence of mineral fertiliser and biosolids application on volume increments ($m^3\ ha^{-1}$) over the three growing seasons after treatment application.

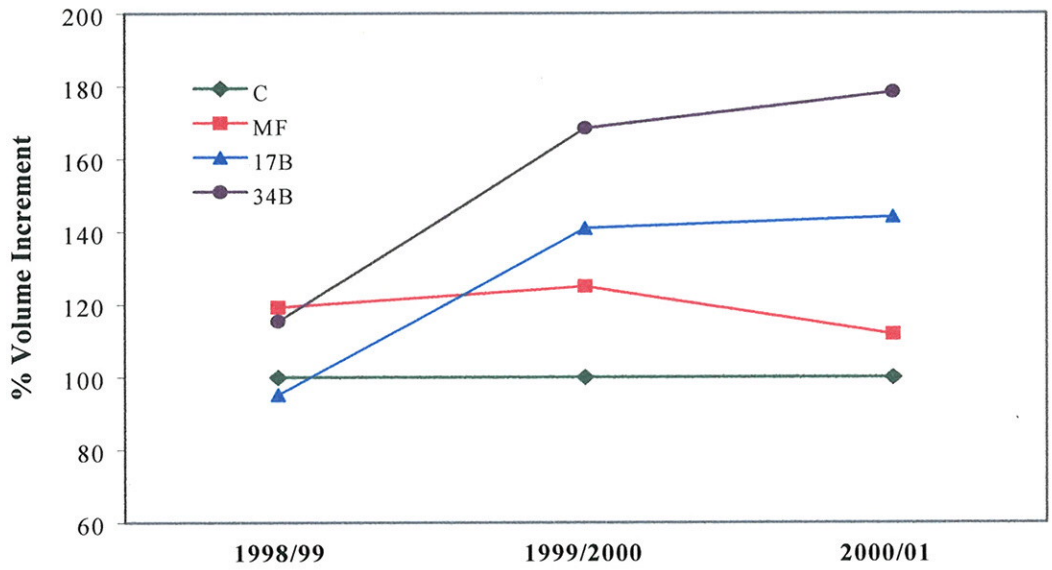


The actual mean volume increments mask the trends in relative volume increases on an annual basis. This examines the relative change in increment (as a percentage) when one value is kept constant. In this case the C treatment has been kept constant at 100% and the other treatments are expressed as a percentage of (above) the C treatment. The purpose of presenting growth data in relative terms is to remove differences in growth due to environmental factors and allow a comparison of treatment effects only.

Figure 4 shows volume increments expressed as a percentage of the control treatment. Relative to the control treatment, the response to biosolids in the first year (17B – 95%; 34B 115%) was less than the MF treatment (119%). However in the second and third years volume increments relative to the control treatment were much greater in the biosolids treatments (17B 141% and 144%; 34B 168% and 178%) than the MF treatment (125% and 112%).

While the MF treatment produced the greatest growth increase in the first year it could not sustain the growth. The two biosolids treatments continued to increase tree growth relative to the control in the second and third years.

Figure 4 Influence of mineral fertiliser and biosolids application on percentage volume increments relative to the control treatment (where control equals 100%) over the three growing seasons after treatment application.



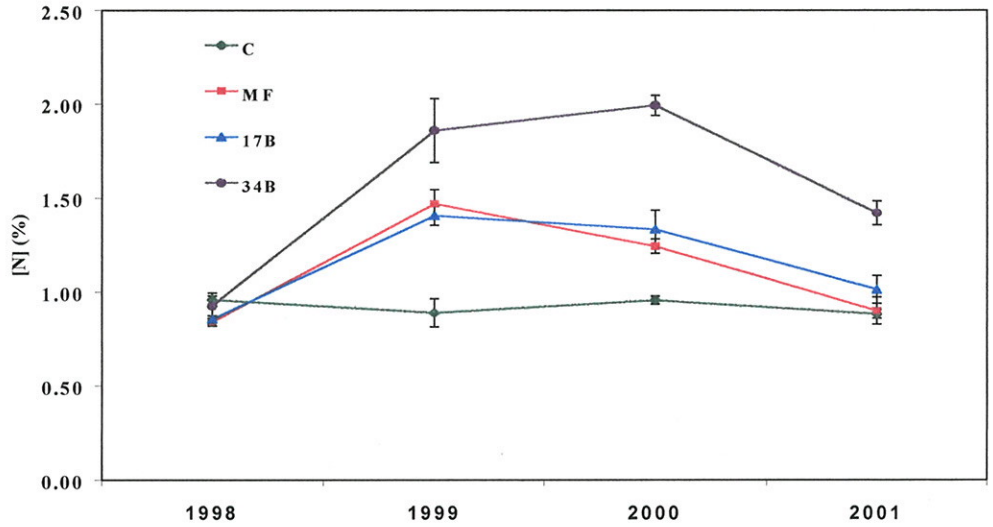
Tree Nutrient Status

There were no differences in foliar nutrient concentrations across the site prior to treatment application. Critical foliar nutrient concentrations published by Reuter and Robinson (1997) give these adequate values for mature *P. pinaster*; N 0.6%, P 0.08%, K 0.25%, Cu 4 mg kg^{-1}, Zn 10 mg kg^{-1}, Mn 14 mg kg^{-1}. Mean foliage concentrations of P (0.065%), in all treatments, was therefore deficient prior to treatment application in 1998 (Fig 5b) while concentrations of N, K, Cu, Zn and Mn were all adequate and remained so for the duration of the study.

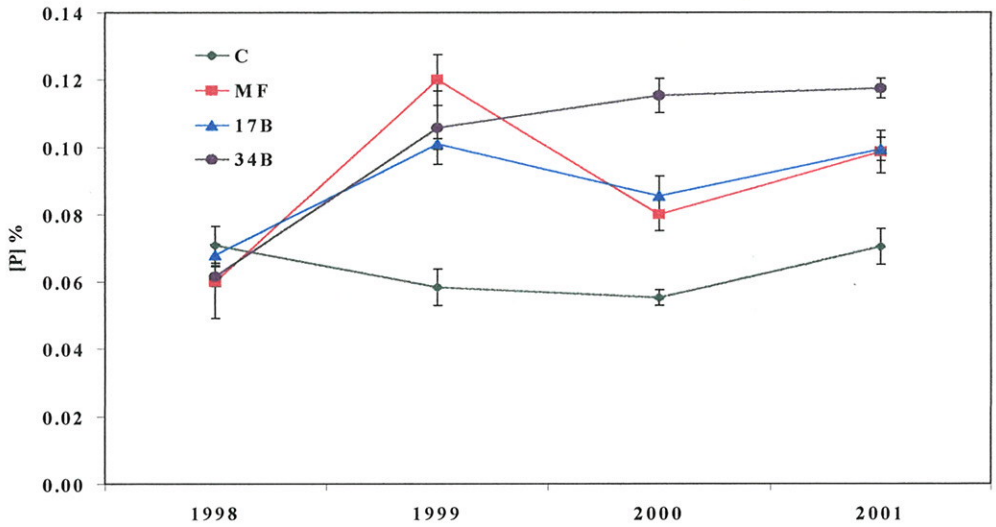
Foliage concentrations of P in the unfertilised control treatment remained below critical concentrations for the duration of the study. The 34B treatment significantly increased foliage concentrations of N, P, Zn and Mn above all other treatments and maintained adequate concentrations of N and P over the 3 years after treatment application. The MF and 17B treatments significantly increased foliar concentrations of N for 2 years and P for at least 3 years above the C treatment but with no difference between each other (Fig 5a and b).

Figure 5 Influence of mineral fertiliser and biosolids application on foliar nutrient concentrations of nitrogen (a) and phosphorus (b) prior to treatment application and for three years after.

a.



b.



Soil Analysis

Soils remained slightly acidic (treatment means pH 5.2 – 5.7) over the three year trial period. There were fluctuations in surface soil pH across all treatments, however the application of biosolids and mineral fertilisers did not change the pH compared to either the control treatment or their initial pH. There were also no changes in pH down the profile in any treatment.

No pesticides were detected in soils beneath any of the treatments over the three-year trial period. Parameters analysed and limits of detection are given in appendix 3.

The heavy metals, arsenic, chromium, copper, nickel, lead and zinc were detected at various depths and locations across the site prior to the application of treatments.

Chromium and zinc were detected in almost all soil samples prior to and after treatment and it would appear that this has been caused by contamination from the hard facing material on the sampling augers. Other metals detected after treatment application were arsenic, copper, nickel and lead. Mean concentrations in the surface soil of these contaminants and the date of detection for each treatment are shown in table 3.

Arsenic was detected in the 34B treatment only in 6/98, but was later intermittently detected in low concentrations in both the 17B and C treatments.

Copper was found across the site in all treatments equally prior to treatment application. Following treatment application, detection was again intermittent and concentrations were lower than pre-treatment values (except the 17B treatment where copper was detected every year and concentrations were higher in the final year).

Nickel was only detected in the MF treatment in 6/98 but was detected in all treatments, including the control, one year later in 6/99.

Lead was detected in all treatments in 6/98 and again in 11/98 and 7/00. It was not detected from any treatment in either 6/99 or 7/01. Concentrations of lead detected after treatment application were higher than pre-treatment concentrations, including the control treatment.

In all cases, mean concentrations of heavy metals detected in the soil were less than 1% of the allowable soil contaminant concentrations as stated in the current Western Australian Guidelines for Direct Land Application of Biosolids and Biosolids Products (Western Australian Biosolids Working Group 2002).

Table 3 Mean concentrations of heavy metal contaminants found in the surface soil (0 – 10cm) prior to- and up to three years after treatment application.

		Mean Concentrations (mg kg^{-1})				
Metal	Treatment	6/98	11/98	6/99	7/00	7/01
arsenic	C	-	-	0.3	-	0.2
	MF	-	-	-	-	-
	17B	-	0.2	0.2	-	-
	34B	0.2	-	-	-	-
copper	C	0.7	-	-	0.2	-
	MF	0.8	-	0.2	-	0.3
	17B	0.7	0.2	0.2	0.6	1.3
	34B	0.7	-	0.2	0.5	0.7
nickel	C	-	-	0.2	-	-
	MF	0.2	-	0.2	-	-
	17B	-	0.2	0.6	-	-
	34B	-	-	0.3	0.2	-
lead	C	0.2	0.4	-	0.5	-
	MF	0.4	0.6	-	0.5	-
	17B	0.4	0.4	-	0.5	-
	34B	0.2	0.7	-	0.7	-

Treatments were applied in 7/98.

Mean total P prior to treatment application (June 1998) was 24 mg kg^{-1}. Mean total P in the control treatment for 2000 and 2001 remained at 24 mg kg^{-1}. Compared to the control treatment the biosolids treatments did not increase total P in the surface soil after three years. Mean values for 2000 and 2001 were 24 mg kg^{-1} and 26 mg kg^{-1} for the 17B and 34B treatments respectively. Mean total P concentration in the MF treatment for 2000 and 2001 was 30 mg kg^{-1}. Due to large variances in the samples, there were no significant differences either between or within treatments before and after treatment application. Total P was not analysed in 1999.

In the three years following treatment application, mean bicarbonate extractable (Bray) P in either of the biosolids treatments was not significantly different to the control treatment (C 0.9 mg kg^{-1}, 17B 1.4 mg kg^{-1}, 34B 0.8 mg kg^{-1}). The application of inorganic fertiliser (MF) increased mean Bray P (2.8 mg kg^{-1}) significantly ($p<0.05$) above the control and 34B values in the same period.

Mean total (Kjeldahl) N across the site prior to treatment application was 227 mg kg^{-1} and there were no significant differences between treatments. There was no significant variation in total N of the surface soil either between or within any treatment for the three-year period following treatment application. Mean values for this period for each treatment were 254 mg kg^{-1} (C), 297 mg kg^{-1} (MF), 329 mg kg^{-1} (17B), and 327 mg kg^{-1} (34B).

Nitrate was not analysed prior to treatment application or below the surface 10cm from subsequent samples after treatment application. One year after treatment application (June 1999) nitrate was not detected in any surface soil samples across the range of treatments, however after two years (July 2000) nitrate was detected in the control treatment only (mean 18 mg kg^{-1}). In July 2001 nitrate was detected in the control (mean 14 mg kg^{-1}), 17B (9 mg kg^{-1}) and 34B (10 mg kg^{-1}) treatments.

Soil Moisture

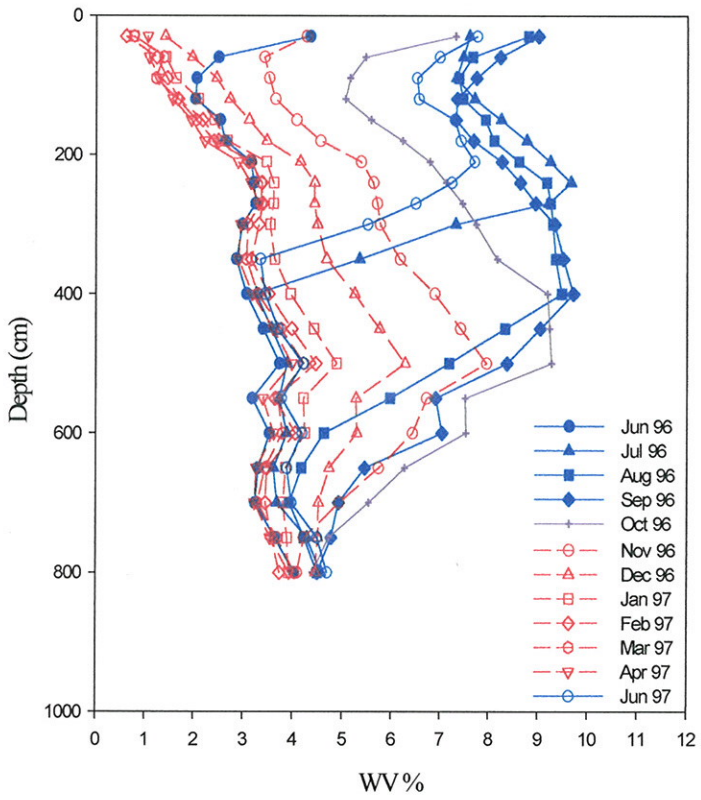
Gravimetric soil moisture contents calculated from samples taken in June 1999, one year after treatment application, showed that dry soil conditions persisted beneath the surface 25 cm (Table 4).

Table 4 Mean gravimetric soil moisture contents beneath the four treatments as measured in June 1999.

	Gravimetric Soil Moisture Content (%)			
Depth (cm)	**C**	**MF**	**17B**	**34B**
25	6.3	4.4	6.8	5.1
50	3.8	3.8	4.3	3.8
100	4.4	4.7	5.0	4.1
200	4.2	5.2	5.6	3.4
300	4.3	4.6	4.5	4.2

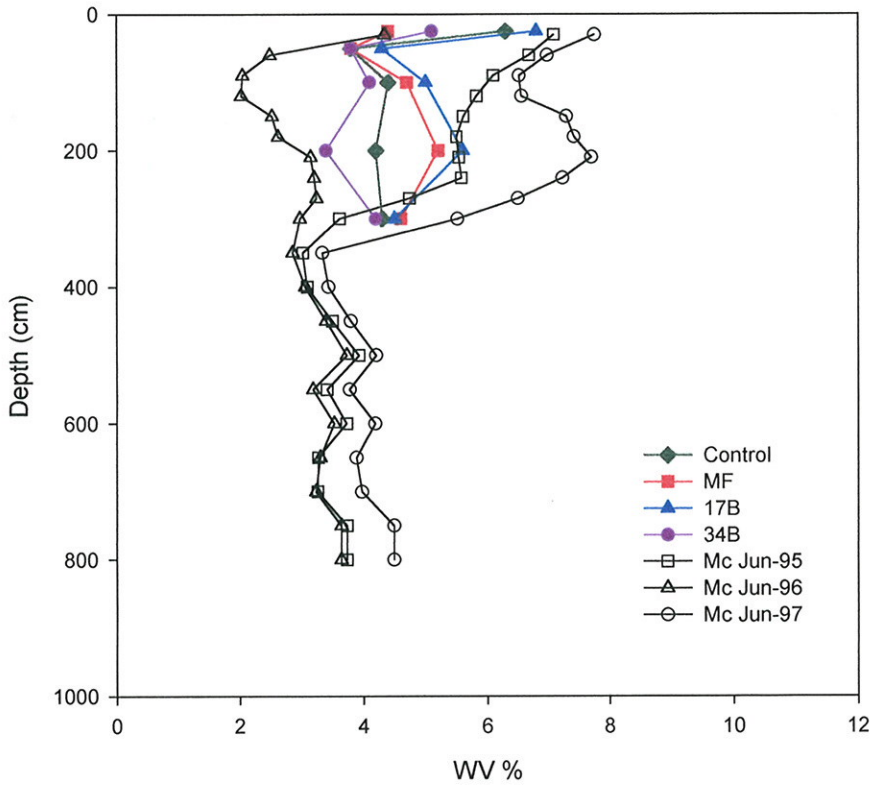
Soil moisture contents to 8m were measured on a monthly basis between 1994 and 1997 (inclusive) at a nearby research trial (McLarty plantation) using a neutron probe moisture meter. The sites are comparable in that the soils, stand density, tree age, and rates and type of mineral fertiliser applied are the same. Figure 6 shows the wetting (June96–Sept96), drying (Nov96–April 97), wetting (June97) cycle for the McLarty site. October 96 shows the profile continuing to wet below 5m but beginning to dry out above 4m due to water extraction by tree roots. In all months the soil remains dry at 8m and there is no water movement below this depth. Hence, it can then be assumed there is no movement of water or solutes into the groundwater beneath this plantation.

Figure 6 Monthly soil moisture profiles beneath a 500 sph fertilised *P. pinaster* plantation at McLarty.



A comparison of the June 1999 soil moisture profiles for the various treatments in this study to the June 1995, 1996 and 1997 soil moisture profiles at McLarty is shown in figure 7. June soil moisture profiles may vary considerably from year to year (depending on the break of season) as evidenced at McLarty in the 1996 and 1997 profiles. However there is generally little change at depth (below 3m) at this time of year.

Figure 7 June soil moisture profiles beneath a 500 sph fertilised *P. pinaster* plantation at McLarty (1995, 1996 and 1997) and the four treatments applied in this study (1999).



Rainfall for Myalup/McLarty plantations in May and June 1995, 1996, 1997 and 1999 are shown in table 3. Soil moisture measurements in 1996 were taken on the 12th June, and rainfall figures are up to this date only, while in the other years recordings were taken on 28th, 26th, and 29th June for 95, 97 and 99 respectively. Low rainfall in 1996 is reflected in the drier soil profile in this year.

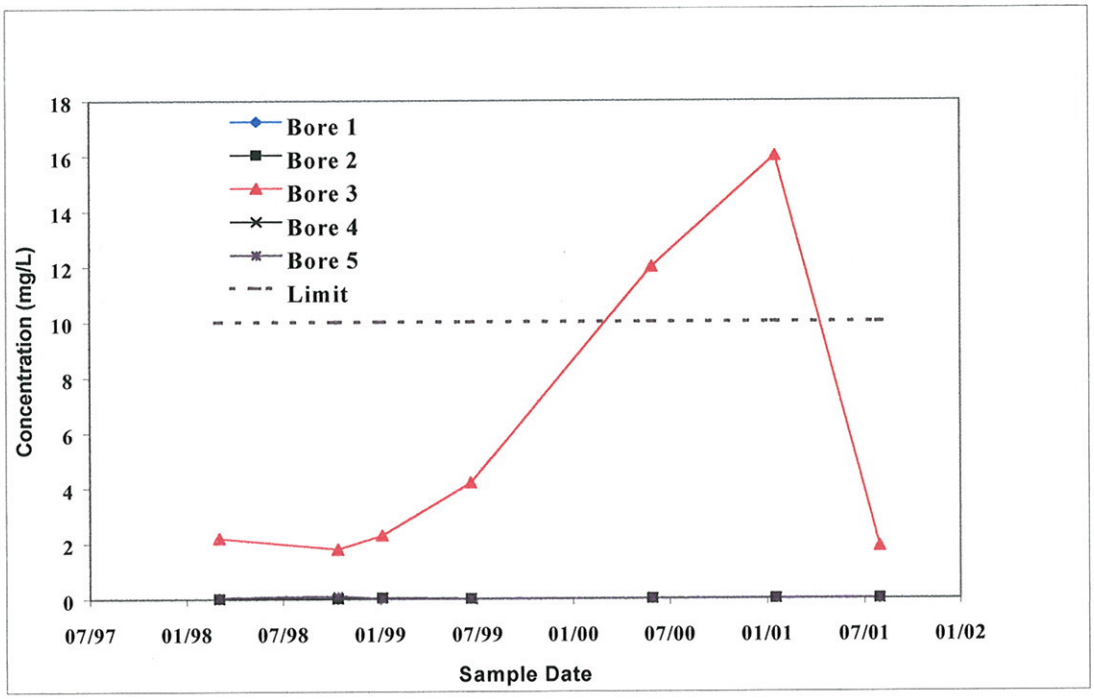
Table 5 Rainfall recordings for Myalup/McLarty plantations for May and June in 1995,1996, 1997, and 1999.

	Rainfall (mm)			
	1995	1996	1997	1999
MAY	159.0	69.4	135.8	207.6
JUNE	127.0	28.2	196.2	232.5
TOTAL	**286.0**	**97.6**	**332.0**	**440.1**

Groundwater Analysis

Nitrate concentrations in groundwater sampled from beneath the stockpile area (bore number 3) increased from 2.20 mg L^{-1} prior to the stockpiling of biosolids to 4.20 mg L^{-1} one year later (June 99). Concentrations continued to increase and two years after biosolids were applied (June 00) nitrate concentrations were 12.0 mg L^{-1} and peaked at 16.0 mg L^{-1} two and a half years after stockpiling (Jan 01). Nitrate concentrations in the groundwater were back to 1.90 mg L^{-1} one year later (Aug 01) (Fig. 8). Concentrations of nitrate above 10.0 mg L^{-1} are in excess of the acceptable limit for drinking water (ANZECC 1992). Nitrate was not detected in water samples from any of the bores within the plantation or immediately adjacent to the plantation away from the stockpile area. Analysis of water samples from all bores found no other elements, pesticides or pathogens exceeded acceptable limits (ANZECC 1992) during this study. Parameters analysed and limits of detection are given in appendix 4.

Figure 8 Nitrate concentrations in groundwater sampled from five bores in and around the plantation, 3 months prior to, and 3 years after fertiliser treatment application.



Operational Constraints:

There were three major and two minor constraints identified from this study concerning further applications of biosolids to pine plantations. The major constraints related to cost, storage provisions, and stockpiling and application time requirements. The minor constraints were related to the social aspects, such as odour and public access, and the required operational condition of the plantation. This discussion will not include any aspects of the research trial that would not be repeated in a future routine operation.

Major Constraints

Cost – Based on this trial the cost to supply and spread an average of 22.5 (dry) t ha^{-1} of biosolids was \$2900 ha^{-1}. This is over 8 times the cost to purchase, transport and spread mineral fertiliser of \$350 ha^{-1}. If the biosolids rate was increased to an average of 30 t ha^{-1} the cost difference would be even greater. Plantation managers would not be able to justify the purchase of biosolids unless increased yields (tree volume m^3 ha^{-1}) were proportionate to cost (ie at least 8 times greater than that of mineral fertiliser).

Storage – Approximately 1400 m^3 of biosolids were required to cover an area of 12 ha at an average rate of 22.5 dry t ha^{-1}. To store this volume, an area of approximately 900 m^2 was prepared with a hard base and retaining banks. Large areas such as this may not always be available within close proximity to the spreading site. It should be noted that the further the storage area is from the application site the greater the spreading costs will be. In addition, an area of 12 ha is not quite 2% of the annual average fertiliser program of 700 ha for the coastal plantations. To fertilise 12 ha with mineral fertiliser would require approximately 3 tonnes of fertiliser which would be stored in one "leg bin" covering an area of about 15 m^2 that could be placed at any roadside. A central storage facility should be investigated to enable cartage and spreading to occur simultaneously negating the need for large on-site storage facilities.

Time – Transportation of 1400 m^3 of biosolids was conducted over a 10 week period and the application using a tractor drawn manure spreader, an excavator, and two operators added a further week. To transport and apply mineral fertiliser over a similar area would take one day with one operator, a tractor and spreader. Having the biosolids stockpiled prior to cartage on-site would greatly reduce the time of the operation.

Minor Constraints

Social Impacts – Biosolids have potential health risks associated with handling, both during and after application. Site access to the storage area and application site needs to be restricted. Plantations are public access areas and restricting access is sometimes difficult to implement.
The strong ammonia odour in the early stages of storage and application can cause problems when large volumes need to be stored or applied close to adjoining properties.

Plantation Preparation – The machinery required for spreading biosolids is larger than that required to spread mineral fertiliser and would therefore require larger turn-around areas in the plantation. In addition, a 3 tonne fertiliser spreader should cover approximately 9 ha whereas a 10 tonne manure spreader would only cover approximately ⅓ ha. This potentially means that a fertiliser spreader could travel up to 1500 m before having to turn around, whereas a manure spreader could travel only 100 m (assuming an application swathe width of 30 m for mineral fertiliser and 20 m for biosolids and they both spread out and back). This means more frequent turn-around points are needed to efficiently spread biosolids. In this trial the manure spreader had to travel 200m (the length of the plot) before turning around, which meant that several passes over the same ground were required to achieve the desired biosolids application rate.

Discussion

In the seasonally dry Mediterranean environment in Western Australia mid-rotation growth responses to fertilisation by *P. pinaster* are limited by water availability and are thus generally restricted to thinned stands (Butcher and Havel 1976, Butcher 1977). The plantation in this study was recently thinned from 800 sph to approximately 500 sph, and had very low soil nutrient concentrations (N 0.035% and bicarbonate extractable P <2.9 mg kg^{-1}). Foliar analysis prior to treatment application showed that the trees had marginal concentrations of N and less than adequate concentrations of P (Reuter and Robinson 1997) and indicated that trees on this site would be responsive to fertiliser applications, in particular N and P.

The first year after treatment application biosolids did not increase tree volume relative to the control treatment as much as the mineral fertiliser did. However in subsequent years both of the biosolids treatments significantly increased volume increments relative to the control while the response in the MF treatment plateaued before declining.

Rainfall in the first two growing seasons (August to July) was close to the long term average of 920mm, however rainfall in the third growing season was only 572mm (62% of average). Actual volume increments in all the fertilised treatments declined in the third year, which indicated that there was some limitation due to reduced water availability. However, the increased volume growth in both of the biosolids treatments above the MF and control treatments suggested that water availability was not the sole limitation to growth.

Mineralisation of organic N and P in the biosolids over the duration of this study maintained an adequate supply of nutrients to the trees. The application rates of biosolids were based on the highest rate (34B) providing similar quantities of plant available N and P (70% only) as the mineral fertiliser in the first year. This meant that in the first year the MF treatment received 200 kg N ha^{-1} and 90 kg P ha^{-1}, the 17B treatment 106 kg N ha^{-1} and 31 kg P ha^{-1} and the 34B treatment 212kg N ha^{-1} and 63 kg P ha^{-1}. However, over the three years of the study the MF treatment received only the initial 200 kg N ha^{-1} and 90 kg P ha^{-1}, while through ongoing mineralisation, the 17B treatment would have received a total of approximately 318 kg N ha^{-1} and 93 kg P $ha^{-1}$and the 34B treatment 636 kg N ha^{-1} and 188 kg P ha^{-1}.

Data from this study (not shown here) showed a strong positive linear relationship between foliar N (r^2 0.84) and P (r^2 0.55) concentrations and annual relative volume growth increments. It is not surprising then that the biosolids treatments showed less relative growth than the MF treatment in the first year, but continued to increase in subsequent years while the response in the MF treatment plateaued before declining.

Foliar N and P concentrations of trees in the biosolids treatments remained above critical levels for the duration of the study and the continual input of nutrients from mineralisation of the biosolids maintained the relative volume increases above the control and MF treatments.

The real value of the increased volume growth from the application of biosolids will depend on how long it can sustain the responses seen so far. As yet this has not been determined.

Surface soil concentrations of 0.75 mg kg^{-1} bicarbonate extractable (Bray) P was determined to be sufficient for adequate growth of juvenile *P. pinaster* growing on the coarse sands of the coastal plain (Dumbrell and M^{c}Grath in press). Despite the low concentrations of Bray P in the surface soil after treatment application, values above 0.75 mg kg^{-1} were maintained across all treatments.

As a comparison of the relative growth increases achieved by the biosolids treatments the annual volume increments in the control and MF treatments were compared to that found in two other nearby *P. pinaster* experiments growing on the same deep sands with similar fertiliser applications, stand age, stocking and thinning history. The trees in this study were found to be responding to inorganic fertiliser in a similar pattern to that shown previously in these other thinned plantations growing on deep porous coastal sands. It can be assumed then that further biosolids applications would produce similar growth increases on other sites on the Swan Coastal Plain.

Groundwater flow beneath this site is in a westerly direction and discharges into a series of saline lakes approximately 6km to the west of the trial site. These saline lakes are groundwater sinks, where groundwater input is balanced by evaporation (Commander 1984).

Increased nitrate concentrations to above acceptable limits were detected from water samples taken from a sample bore (number 3) located 5m south of the plantation and adjacent to the stockpile area. Nitrate was not detected from any of the bores within or to the west of the plantation. This suggests that trees within the plantation are either utilising all available nitrate within the soil profile or completely drying the soil profile so as to prevent recharge and nitrate movement to the groundwater. No attempt had been made to quantify total nutrient uptake by the trees.

Soil water profile data from a nearby experiment showed that a similarly stocked plantation of *P. pinaster* greatly restricted both infiltration and movement of water below 8m from the surface (M^{c}Grath *et al.* In prep). Two studies (Henry 1996, Robinson and Polglase 1996) examining nitrate leaching from biosolids applied to plantations at 47 and 30 dry t ha^{-1} showed nitrate concentrations in soil water in excess of 10 mg L^{-1} within one year after application. The samples that showed these high concentrations were taken from shallow (50cm) lysimeters and did not report any subsequent contamination of groundwater.

The detection of nitrate in the groundwater from samples collected from bore 3 indicated that there was both sufficient time and rainfall to facilitate its movement from surface to groundwater within the study period.

The low Cation Exchange Capacity of the soil at this site indicated that there was little buffering capacity to prevent leaching. There was no indication of increased nitrate concentrations in the groundwater samples taken from bore number 4 (15m to groundwater), and bore number 1 (11m to groundwater), both of which are located in or adjacent to a 34B plot. This would indicate that on these porous sands, while

maintaining a plantation density at or above 500 sph, applying biosolids at the heaviest rate does not pose a threat to groundwater contamination. However, care needs to be taken with the stockpiling of biosolids prior to spreading.

Heavy metals are difficult to remove from soils because they are strongly held on cation-exchange sites. The concentrations in solution are therefore low and leaching is relatively ineffective for removing them from the soil. However, plants can be effective in removing significant quantities, provided they are not in toxic concentrations (Troeh and Thompson 1993). Cadmium is more mobile in soil and more easily adsorbed by plants than most other heavy metals. Accordingly it's potential to leach into groundwater is also higher (Stevenson and Cole 1999). To date none of the heavy metals monitored have been detected in groundwater samples, but monitoring will continue for several years.

Conclusions

Significant tree volume growth increases above both the control treatment and the standard mineral fertiliser application have shown that biosolids, as a nutrient source and hence a fertiliser replacement in plantations, is a viable option. The longevity of the increased growth in these coastal plantations is yet to be determined and therefore the true value of biosolids is also yet to be determined. The trial will be monitored on an annual basis until tree volume increments between the treatments are no longer significant.

As evidenced by soil water profiles and the lack of contamination of groundwater after three years beneath plantations on these coastal sands, applying biosolids to these plantations does not pose a threat to groundwater quality.

Acknowledgments

I would like to thank The Water Corporation of WA for providing the majority of the funding, Nancy Penney (Water Corporation of WA) for, helping to initiate this project, organising the provision, transport and spreading of the biosolids, and analysis of soil and water samples. Keith Mungham and Beth Copeland for sample and data collection, and Beth Copeland for statistical analysis. I would also like to thank the Forests Products Commission of Western Australia for contributing funds for the maintenance and monitoring of the project and John McGrath, Nancy Penney and Ray Fremlin for their technical inputs and comments on earlier drafts of this report.

References

ANZECC. (1992). *Australian Water Quality Guidelines for Fresh and Marine Waters*. Chapter 4 Raw Water for Drinking Water Supply. Australian and New Zealand Environmental and Conservation Council, Canberra, A.C.T.

Barber, C. and Davis, G.B. (1996). Monitoring and Sampling Methods. Ch 18 *Fundamentals of Groundwater Science, Technology and Management.* Centre for Groundwater Studies, 15th Australian Groundwater School, Melbourne, November 1996.

Butcher, T.B. (1977). Impact of moisture relationships on the management of *Pinus pinaster* AIT. plantations in Western Australia. *Forest Ecology and Management*. **1**: 97-107.

Butcher, T.B. and Havel, J.J. (1976). Influence of moisture relationships on thinning practice. *Journal of Forest Science*. **6**: 158-170.

Commander, D.P. (1984). Geology and hydrogeology of the superficial formations and coastal lakes between Harvey and Leschenault inlets. Hydrogeology Report N° 2605, Geological Survey of Western Australia series. Geological Survey, Perth Western Australia. pp1-49.

Dixon, L.L., Turner, J. and Lambert, M.J. (1996). Biosolids utilisation in NSW State Forests: progress of the last five years. In *Land Application of Wastes in Australia and New Zealand: Research and Practice.* (Eds P.J. Polglase and W.M. Tunningley) pp 7-12. Proceedings of 14th Land Treatment Collective Conference, Canberra. CSIRO Forestry and Forest Products, Canberra.

Dumbrell, I.C. and McGrath, J.F. (in press) Growth and nutrient relationships of juvenile *Pinus pinaster* grown on ex-farmland in Western Australia. *Australian Forestry* (accepted July 2002).

Henry, C.L. and Van Ham, M.D. (1996). Biosolids management in the Pacific northwest: an overview of land application programs. In *Land Application of Wastes in Australia and New Zealand: Research and Practice.* (Eds P.J. Polglase and W.M. Tunningley) pp 7-12. Proceedings of 14th Land Treatment Collective Conference, Canberra. CSIRO Forestry and Forest Products, Canberra.

Henry, C.L. (1996). Biosolids and nitrogen management in forest ecosystems. In *Land Application of Wastes in Australia and New Zealand: Research and Practice.* (Eds P.J. Polglase and W.M. Tunningley) pp 7-12. Proceedings of 14th Land Treatment Collective Conference, Canberra. CSIRO Forestry and Forest Products, Canberra.

Hope, P.S. and M^{c}Dougall, C.R. (1996). The biosolids revolution in Sydney Water: the land application program. In *Land Application of Wastes in Australia and New Zealand: Research and Practice.* (Eds P.J. Polglase and W.M. Tunningley) pp 7-12. Proceedings of 14th Land Treatment Collective Conference, Canberra. CSIRO Forestry and Forest Products, Canberra.

Kitson, R.E. and Mellon, M.G. (1944) Calorimetric estimation of phosphorus as Molybdovanadophospheric acid. *Industrial and Engineering Chemistry Analytical Edition* **16**, 379.

M^{c}Arthur, W.M. (1991). *Reference Soils of South-western Australia.* Dept of Agriculture, Western Australia and Australian Society of Soil Science Incorporated (WA Branch). Perth, Western Australia.

M^{c}Kenzie, H.A. and Wallace, H.S. (1954) The Kjeldahl determination of nitrogen; a critical study of digestion conditions – temperature, catalyst and oxidising agent. *Australian Journal of Chemistry* **7**, 55-70.

M^{c}Grath, J.F., Crombie, D.S., Dumbrell, I.C. and Mungham, K. (in prep). Comparative water use and water relations of *Pinus radiata* and *Pinus pinaster* in a Mediterranean climate.

New South Wales E.P.A. (1997). *Environmental Guidelines: Use and disposal of biosolids products.* New South Wales Environmental Protection Authority.

Piper, C.S. (1942) *Soil and Plant Analysis.* University of Adelaide. 1942.

Reuter, D.J. and Robinson, J.B. (Eds.)(1997). *Plant Analysis: an interpretation manual.* 2nd edition. CSIRO Publishing, Collingwood, Australia.

Robinson, M.B. and Polglase, P.J. (1996). Release and leaching of nitrogen from biosolids applied to a pine plantation. In *Land Application of Wastes in Australia and New Zealand: Research and Practice.* (Eds P.J. Polglase and W.M. Tunningley) pp 7-12. Proceedings of 14th Land Treatment Collective Conference, Canberra. CSIRO Forestry and Forest Products, Canberra.

Stevenson, F.J. and Cole, M.A. (1999). *Cycles of Soil* 2nd Ed. John Wiley and Sons, New York. 1999.

Troeh, F.R. and Thompson, L.M. (1993). *Soils and Soil Fertility.* (5th Ed.) Oxford University Press,New York.

Western Australian Biosolids Working Group (2002). *Western Australian Guidelines for direct land application of biosolids and biosolids products.* Biosolids Working Group – Dept Environmental Protection, Waters and Rivers Commission and Dept of Health. February 2002.

APPENDIX 1 - Biosolids contaminant acceptance concentration thresholds

Contaminant	Grade C1* (mg kg^{-1})	Grade C2* (mg kg^{-1})	Grade C3
Arsenic	20	60	Untested or greater than grade C2
Cadmium	3	20	Untested or greater than grade C2
Chromium	100	500	Untested or greater than grade C2
Copper	100	2500	Untested or greater than grade C2
Lead	150	420	Untested or greater than grade C2
Mercury	1	15	Untested or greater than grade C2
Nickel	60	270	Untested or greater than grade C2
Selenium	3	50	Untested or greater than grade C2
Zinc	200	2500	Untested or greater than grade C2
DDT/DDD/DDE	0.5 (total)	1 (total)	Untested or greater than grade C2
Aldrin	.02	0.5	Untested or greater than grade C2
Dieldrin	.02	0.5	Untested or greater than grade C2
Chlordane	.02	0.5	Untested or greater than grade C2
Heptachlor	.02	0.5	Untested or greater than grade C2
HCB	.02	0.5	Untested or greater than grade C2
Lindane	.02	0.5	Untested or greater than grade C2
PHC	.02	0.5	Untested or greater than grade C2
PCB's	0.3	0.5	Untested or greater than grade C2

* All values are dry weight.

APPENDIX 2 - Pathogen Grading Requirements

Pathogen Grade	Max Pathogen Levels	Treatment methods to achieve required pathogen levels
P1	Salmonella - <1 count per 50g dry product **AND** Thermo-tolerant Coliforms - <100 counts per gram of dry product	Digested then composted in a vessel, heated at >55°C for a three day period. **OR** Composted in a windrow, turned 5 times and maintained at >55°C for a 15 day period. **OR** Maintained at pH>12 for a 3 day period, heated at >53°C for a 12 hour period, and dried to >50% solids. **OR** Heated to >80°C and dried to >90% solids and the product kept dry until used. **OR** Digested and dried to solids >10% and then stored for >3 years.
P2	Salmonella - <10 count per 50g dry product **AND** Thermo-tolerant Coliforms - <1000 counts per gram of dry product	Composted at >53°C for a 5 day period. **OR** Composted at >55°C for a 3 day period. **OR** Heated to 70°C for 1 hour and then dried to >90% solids. **OR** Digested, heated to 70°C for 1 hour and then dried to >75% solids. **OR** Aerobic thermophilic digestion (55-60°C for a 10 day period), with a volatile solids reduction of >38% and total solids reduction of >50%.
P3	Thermo-tolerant Coliforms - <2,000,000 counts per gram of dry product	Anaerobic digestion at 35°C for 20 days with a volatile solids reduction of >38% **OR** Anaerobic digestion at 15°C for 60 days with a volatile solids reduction of >38% **OR** Aerobic digestion at 20°C for 40 days with a volatile solids reduction of >38% **OR** Aerobic digestion at 15°C for 60 days with a volatile solids reduction of >38% **OR** Aerobic digestion at >40°C for 5 days including a period of at least 4 hours at >55°C.
P4	Thermo-tolerant Coliforms - >2,000,000 counts per gram of dry product	Untreated or inadequately treated.

APPENDIX 3 - Soil Analysis

METALS	UNITS	LOR[a]	METHOD
Arsenic	mg kg^{-1}	0.5	USEPA 3550
Cadmium	mg kg^{-1}	0.5	USEPA 3550
Chromium	mg kg^{-1}	0.5	USEPA 3550
Copper	mg kg^{-1}	0.5	USEPA 3550
Mercury	mg kg^{-1}	0.2	USEPA 3550
Molybdenum	mg kg^{-1}	1	USEPA 3550
Nickel	mg kg^{-1}	0.5	USEPA 3550
Lead	mg kg^{-1}	0.5	USEPA 3550
Selenium	mg kg^{-1}	0.5	USEPA 3550
Zinc	mg kg^{-1}	0.5	USEPA 3550
Silver	mg kg^{-1}	0.5	USEPA 3550
ORGANOCHLORINE PESTICIDES			
HCB	mg kg^{-1}	0.02	USEPA 8080, 3550
Lindane	mg kg^{-1}	0.02	USEPA 8080, 3550
Heptachlor	mg kg^{-1}	0.02	USEPA 8080, 3550
Aldrin	mg kg^{-1}	0.02	USEPA 8080, 3550
γ-Chlordane	mg kg^{-1}	0.02	USEPA 8080, 3550
α-Chlordane	mg kg^{-1}	0.02	USEPA 8080, 3550
pp-DDE	mg kg^{-1}	0.02	USEPA 8080, 3550
Dieldrin	mg kg^{-1}	0.02	USEPA 8080, 3550
pp-DDT	mg kg^{-1}	0.02	USEPA 8080, 3550
pp-DDD	mg kg^{-1}	0.02	USEPA 8080, 3550
Arochlor 1016	mg kg^{-1}	0.2	USEPA 8080, 3550
Arochlor 1221	mg kg^{-1}	0.2	USEPA 8080, 3550
Arochlor 1232	mg kg^{-1}	0.2	USEPA 8080, 3550
Arochlor 1242	mg kg^{-1}	0.2	USEPA 8080, 3550
Arochlor 1248	mg kg^{-1}	0.2	USEPA 8080, 3550
Arochlor 1254	mg kg^{-1}	0.2	USEPA 8080, 3550
Arochlor 1260	mg kg^{-1}	0.2	USEPA 8080, 3550
PLANT NUTRIENTS			
Total (Kjeldahl) Nitrogen, N	mg kg^{-1}	20	APHA4500 Norg BNH3 PLUS 4500 NO3-E or 4110-B
Ammoniacal Nitrogen, NH_3-N	mg kg^{-1}	20	APHA 4500 NH3 B+C
Nitrate, NO_3	mg kg^{-1}	5	APHA 4110-B
Nitrite, NO_2	mg kg^{-1}	2	APHA 4110-B
Total Phosphorus, P	mg kg^{-1}	5	APHA 4500P-B
Bray P	mg kg^{-1}	5	
Potassium, K (exchangeable)	meq $100g^{-1}$	0.01	USEPA 3050
Calcium, Ca (exchangeable)	meq $100g^{-1}$	0.01	USEPA 3050
Aluminium, Al (exchangeable)	meq $100g^{-1}$	0.1	USEPA 3050
Sodium, Na (exchangeable)	meq $100g^{-1}$	0.01	USEPA 3050
PHYSICAL CHARACTERISTICS			
pH	Units	0.1	1:5 $CaCl_2$
Electrical Conductivity	µS cm^{-1}	5	APHA 2510-B

a. Limit Of Reporting

APHA – American Public Health Association, 20th Edition, 1998.

USEPA – United States Environmental Protection Agency.

APPENDIX 4 - Groundwater analysis

Test Parameter	Units	LOR[a]	Method
pH	pH units	0.1	APHA 4500-H+
Electrical Conductivity	$\mu S\ cm^{-1}$	1	APHA 2510-B
Cadmium	$mg\ L^{-1}$	0.005	APHA 3113-B
Copper	$mg\ L^{-1}$	0.05	APHA 3111-B
Zinc	$mg\ L^{-1}$	0.05	APHA 3111-B
Total (Kjeldahl) Nitrogen, N	$mg\ L^{-1}$	0.2	APHA4500 Norg BNH3 PLUS 4500 NO3-E or 4110-B
Ammoniacal Nitrogen, NH_3-N	$mg\ L^{-1}$	0.1	APHA 4500 NH3 B+C
Nitrate, NO_3	$mg\ L^{-1}$	0.2	APHA 4110-B
Nitrite, NO_2	$mg\ L^{-1}$	0.05	APHA 4110-B
Total Phosphorus, P	$mg\ L^{-1}$	0.05	APHA 4500P-B
Orthophosphate, PO_4-P	$mg\ L^{-1}$	0.05	APHA4500P-E
Thermotolerant Faecal Coliforms	CFU/100m L	0	AS4276.7
Salmonella	Counts	0	AS4276.14

a Limit Of Reporting

APHA – American Public Health Association, 20th Edition, 1998.

AS – Australian Standard.