CSIRO PUBLISHING

Australian Journal of Soil Research

Volume 37, 1999

A journal for the publication of original research
in all branches of soil science

www.publish.csiro.au/journals/ajsr

All enquiries and manuscripts should be directed to
Australian Journal of Soil Research
CSIRO PUBLISHING
PO Box 1139 (150 Oxford St)
Collingwood
Vic. 3066
Australia
Telephone: 61 3 9662 7628
Facsimile: 61 3 9662 7611
Email: jenny.fegent@publish.csiro.au

Published by **CSIRO** PUBLISHING
for CSIRO Australia and
the Australian Academy of Science

Aust. J. Soil Res., 1999, **37**, 983–91

Short rotation forestry for land treatment of effluent: a lysimeter study

J. K. F. Roygard[ABD], *S. R. Green*[A], *B. E. Clothier*[A], *R. E. H. Sims*[C], *and N. S. Bolan*[B]

[A] Environment and Risk Management Group, Hort Research, Palmerston North, New Zealand.
[B] Institute of Natural Resources, Massey University, Palmerston North, New Zealand.
[C] Institute of Technology and Engineering, Massey University, Palmerston North, New Zealand.
[D] Corresponsing author; email: jroygard@hort.cri.nz

Abstract

Land treatment of wastewater using short rotation forestry (SRF) has potential as a sustainable method for disposal of dairy-farm effluent. We compared 3 SRF species, 2 evergreen species of eucalypts (*Eucalyptus nitens*, *E. saligna*) and a deciduous willow (*Salix kinuyanagi*), in the land treatment of dairy-farm effluent. The trees were grown in lysimeters (1·8 m diameter, 1·0 m depth), and a bare soil treatment was used as a control. The application of dairy-farm oxidation-pond effluent totalled 218 g N/lysimeter (equivalent to 870 kg N/ha) over 2 irrigation seasons (December 1995–June 1996 and September 1996–April 1997). Effluent was applied weekly in summer at a rate of 18·9 mm/week. No effluent was applied during the winter period. The evapotranspiration (ET) rates of the trees, and the volumes and nitrogen contents of the leachates are compared for a winter period (4 weeks) and a summer period (5 weeks). The biomass accumulation and the uptake of nitrogen by the 3 tree species were also investigated.

The SRF trees improved the renovation levels of dairy-farm effluent and produced biomass suitable for energy conversion. Of the 3 tree species, only the *S. kinuyanagi* treatments maintained leachate nitrate concentrations below the New Zealand drinking water standard of 11·3 mg NO_3^--N/L throughout both the winter and summer periods. The *E. nitens* treatment produced significantly more oven-dry biomass (19·1 kg/tree) than the *E. saligna* trees (9·7 kg/tree) ($P = 0{\cdot}05$). The *S. kinuyanagi* treatment had intermediate production (13·3 kg/tree) and was not significantly different from the other 2 tree species ($P = 0{\cdot}05$). The nutrient accumulation was not significantly different among the species ($P = 0{\cdot}05$). *S. kinuyanagi* was considered the best overall performer for the land treatment of dairy-farm effluent, based on the concentrations of leachate moving beyond the root-zone.

Additional keywords: dairy-farm effluent, *Eucalyptus nitens*, *Eucalyptus saligna*, nitrate, *Salix kinuyanagi*.

Introduction

Dairy farming is a major producer of wastewater in New Zealand. Under the Resource Management Act (1991), New Zealand dairy farmers are required to dispose of dairy-farm effluent in a manner which has no adverse effect on the environment. Dairy-farm effluent in New Zealand is most commonly treated via 2-pond systems. The effluent from these pond systems may then be released into streams or rivers; however, nutrient removal by 2-pond systems is proving insufficient to protect the quality of receiving waters (Hickey *et al*. 1989). One further treatment option is to apply ponded effluent to soil growing trees. This system has the potential to meet the needs of regulatory agencies because the tree roots are able to strip the nutrients from wastewater as it percolates through

 10.1071/SR98067 0004-9573/99/050983$05.00

the soil. There are also economic incentives to utilise wastes containing nutrients for crop production. The fertiliser value of New Zealand's dairy-farm effluent, pig slurry, and poultry manure has been estimated in New Zealand to be NZ$36 million per year (Roberts *et al*. 1992).

Salix, *Eucalyptus*, and *Populus* species have recently been advocated in short rotation forestry (SRF) systems and their potential in land treatment systems is currently being investigated (Myers *et al*. 1996; Tungcul *et al*. 1996; Nicholas 1997; Nicholas *et al*. 1997). The fast initial growth-rate of SRF crops suggesting high water and nutrient uptake, as well as the coppicing abilities of SRF crops, are advantageous in land treatment systems (Nicholas *et al*. 1997), and biomass from SRF is suitable for energy conversion. SRF crops have been researched with municipal wastewater, meat processing effluent, and dairy-farm effluent (Myers *et al*. 1994, 1996; Nicholas 1997; Tungcul *et al*. 1996; Nicholas *et al*. 1997).

Vital to the successful design of an environmentally sustainable system of land-treatment is the evaluation of soil water and nutrient balances in the root-zone (Bond 1998). Nitrogen is the most important nutrient in the case of renovation of dairy-farm effluent by SRF crops. It is important to prevent nitrate concentrations building up in groundwater via leaching, as groundwater is widely used as a potable water source in many countries including New Zealand. Monitoring the quantity of nitrate leaching to groundwater is an essential part of ensuring a system is operating in an environmentally sustainable manner. In New Zealand, the drinking water standard or maximum permissible level (MPL) is $11 \cdot 3$ mg NO_3-N/L (Ministry of Health 1995).

Climatic conditions and the inputs of water and nitrogen change seasonally, as do the use and fate of water and nitrogen in land treatment systems. It might be expected that deciduous trees would have lower rates of water use in winter, in comparison with the evergreen trees which transpire throughout the whole year. The influence of the difference in the rates of water use by the deciduous and evergreen trees will effect both nutrient removal and nitrate leaching. Consequently, the objectives of this study were to understand better the key processes of tree water use and nitrogen leaching from the root-zone of 3 species, with a bare soil control, receiving dairy-farm effluent. For comparison a 4-week period in early winter (June–July) and a 5-week period in early summer (December-January) were studied. In addition, we compared the biomass production and nitrogen accumulation of the 3 species over $2 \cdot 5$ years. We hypothesised that bare soil is, on its own, not suitable for the land treatment of wastewater, but trees will improve the level of effluent treatment that can be achieved.

Methods

Twelve in-ground lysimeters containing 3 replicates of 3 tree species (*Eucalyptus nitens*, *E. saligna*, and *Salix kinuyanagi*), and 1 bare soil treatment, were established in a field at Aokautere, near Palmerston North, New Zealand. The lysimeters were $1 \cdot 8$ m in diameter and $1 \cdot 0$ m deep, and were filled with Manawatu fine sandy loam (weathered fluvial recent, Hewitt 1993; as described by Clothier *et al*. 1977). The soil was repacked into the lysimeters to the original bulk density. All lysimeters were left for a period of 1 year before data collection began. This delay allowed trees to establish and the soil to settle into the repacked lysimeters. A single tree was planted in each lysimeter, in November of 1994. The eucalypts (evergreen) were planted as 3-month-old seedlings, and the willows (deciduous) as unrooted cuttings. The control lysimeters contained bare soil only. Trees of the same species were planted around the lysimeters at a density of about 4000 stems/ha to create conditions approximating a small plantation. Dairy-farm effluent (secondary-pond treated) was applied weekly during the 2 irrigation seasons of December 1995–June 1996 and September 1996–April 1997. In the summer period, effluent was applied weekly at a rate of 18·9 mm/week, but no effluent was applied during the winter period. The total hydraulic loading was 720 mm/year, with a nitrogen loading of 218 g/lysimeter (approximately 870 kg N/ha). Data collection from the lysimeters began in December 1995 when the trees were 1 year old and continued through until September 1997. The above-ground biomass of the trees in lysimeters was harvested in April 1997. The rotation time of 2·5 years is within the range (2–10 years) expected to be used for SRF crops grown for land treatment of dairy-farm effluent.

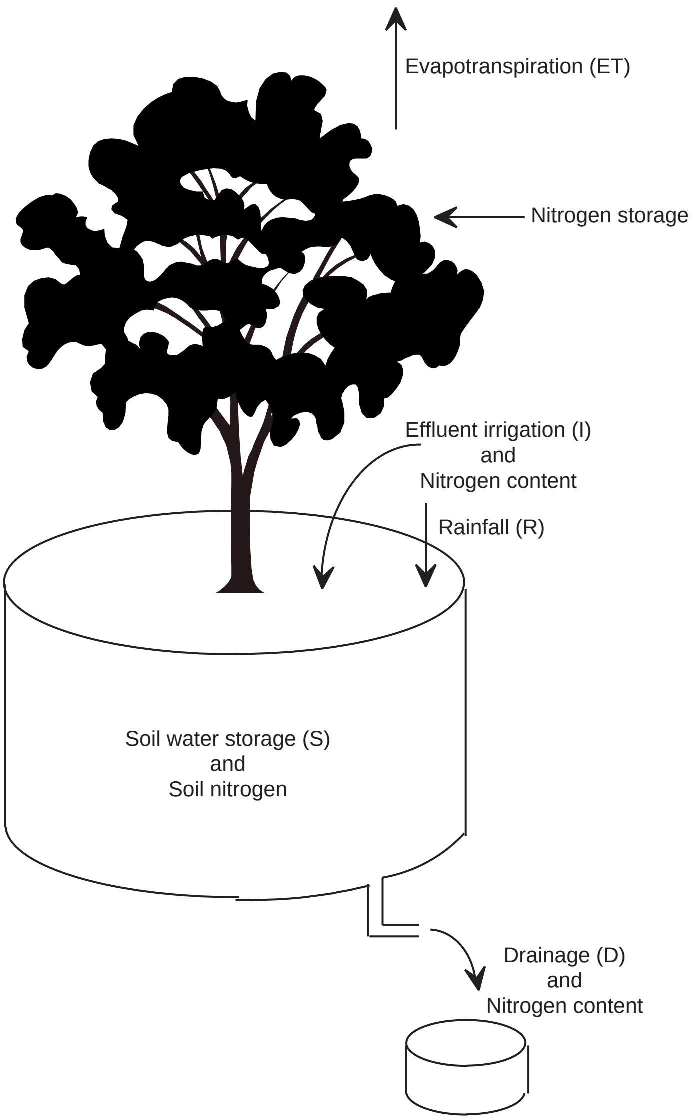

Fig. 1. Inputs and outputs of water and nitrogen in the lysimeter treatments.

The lysimeter facility (Fig. 1) enabled measurement of all inputs and outputs of water and nitrogen. Effluent application by microjets onto the individual lysimeters was controlled by a pump and solenoid valves. Rainfall was recorded on-site. Soil water storage was measured via Time Domain Reflectometry (TDR) using probes installed at 5 soil depths in each lysimeter. Two TDR probes were inserted vertically into the soil to depths of 100 mm and 250 mm. The other 3 TDR probes were inserted horizontally at depths of 250, 500, and 750 mm. Soil water storage was calculated from the TDR data that were collected at least 5 times per week. Leachate volumes were recorded manually during the winter period and by tipping-bucket flow-meters in the summer period. Evapotranspiration (ET) (mm) was calculated from a simple water balance equation:

$$ET = I + R - D - \Delta S$$

where I (mm) is effluent irrigation, R (mm) is effective rainfall, D (mm) is the drainage of leachate, and ΔS (mm) is the change in soil water storage.

Ammoniacal (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) nitrogen concentrations in the surface-applied effluent and drainage leachate were monitored regularly. Effluent samples were collected at the time of application, and then leachate samples were collected 3–7 times per week, depending on leachate volumes. Nitrogen concentration was determined by following the nitroprusside method for NH_4^+-N analysis (Weatherburn 1967) and a diazotisation coupling reaction (Griess-Ilosvay reaction) method for NO_2^--N and NO_3^--N analysis (Bremner and Mulvaney 1982). Biomass accumulation and nitrogen contents of plant components were measured at the time of harvest in April 1997. Biomass production was scaled up from the lysimeters based on a stocking density of 4000 stems/ha. Individual trees from each lysimeter were separated into biomass components following the methods of Young and Carpenter (1975). These components were then oven dried to determine the oven dry weight of the biomass produced. Kjeldahl N digestion (Markus *et al.* 1985) was used to determine the nitrogen contents of subsamples of the biomass components for each tree.

One *E. saligna* and 1 bare soil replicate were not included in the analysis due to faults in their tipping bucket flow meters. Minitab was used for all statistical analysis. ANOVA tests were used to compare the treatments. No statistical effect was found among replicates.

Results

The average daily rainfalls recorded in the winter (3·1 mm/day) and the summer periods (2·8 mm/day) were similar.

Evapotranspiration

ET of the trees during summer (means between 4·59 and 5·71 L/day) was significantly higher ($P < 0{\cdot}05$) than the evaporation losses from the bare soil (mean 1·85 L/day) due to the high transpiration rate of the trees (Table 1). ET values for the 3 tree species in the summer period were not significantly different ($P > 0{\cdot}05$). Winter ET values from the evergreen trees were significantly higher than from the bare soil treatment ($P < 0{\cdot}05$). In winter, the ET of *S. kinuyanagi* (deciduous, 1·10 L/day) was significantly ($P < 0{\cdot}05$) lower than of *E. nitens* (2·49 L/day) and not significantly different from *E. saligna* (1·93 L/day) and the bare soil (0·68 L/day) ($P > 0{\cdot}05$).

Leachate volume

Because evaporation from the bare soil was much less than the ET of the trees, there was a significantly greater volume of leachate ($P < 0{\cdot}05$), in both winter and summer (Table 1). In winter, leachate volumes for the 2 evergreen *Eucalyptus* species were significantly less ($P < 0{\cdot}05$) than from deciduous *S. kinuyanagi* treatment. Neither *S. kinuyanagi* nor *E. nitens* treatments leached during the summer period. Leachate was collected from *E. saligna* treatments after some summer rainfall, and effluent application events (Table 1).

Table 1. Water and nitrogen balance from the lysimeter study

ET, evapotranspiration; L_v, leachate volume; M_L, mass of nitrogen leached. Within each row, means followed by the same letter are not significantly different at $P = 0 \cdot 05$

Month	Bare soil	*E. nitens*	*E. saligna*	*S. kinuyanagi*
		ET (mm/day)		
Winter	0·68a	2·49b	1·93bc	1·10ac
Summer	1·86e	5·51f	5·71f	4·59f
		L_v (mm/day)		
Winter	2·75g	0·66h	1·06h	2·27i
Summer	3·29j	0·00k	0·02k	0·00k
		M_L (kg N/ha.day)		
Winter	1·11l	0·26m	0·43m	0·21m
Summer	2·70n	0·0o	0·02o	0·0o

Leachate N concentration

Fig. 2 shows the winter-time concentration of nitrogen in the leachate compared with the MPL of 11·3 mg NO_3^--N/L allowed for in drinking water. Each of the bare soil, *E. nitens*, and *E. saligna* treatments recorded leachate concentrations above the MPL throughout the winter period. Meanwhile the *S. kinuyanagi* treatments were very close to the MPL throughout the winter period.

Biomass production

The average quantity of biomass harvested from the 2·5-year-old trees varied between tree species. *E. nitens* gave the highest dry matter yield (19·1 kg/tree), followed by *S. kinuyanagi* (13·3 kg/tree), and with *E. saligna* yielding the lowest (9·7 kg/tree). The *E. nitens* produced significantly ($P < 0 \cdot 05$) more biomass than *E. saligna*. The *S. kinuyanagi* had an intermediate biomass yield, not significantly different ($P > 0 \cdot 05$) from the other 2 species. For a forest planted at 4000 stems/ha, the mean annual yield increment of these species would be equivalent to: *E. nitens* 30·6 oven-dry tonnes (odt)/ha.year, *S. kinuyanagi* 21·3 odt/ha.year, and for *E. saligna* 15·6 odt/ha.year. The trees were grown in lysimeters; therefore, approximation to biomass yields in field plantations should be treated with caution.

Nitrogen accumulation

The above-ground biomass of *E. nitens* treatments contained some 116 g N/tree. This equates to about 53% of the nitrogen applied. *S. kinuyanagi* treatments stored 122 g N/tree (56%), and *E. saligna* stored 71 g N/tree (33%). N accumulation was not significantly different ($P > 0 \cdot 05$) between tree species because of the large variation between the trees within the treatments.

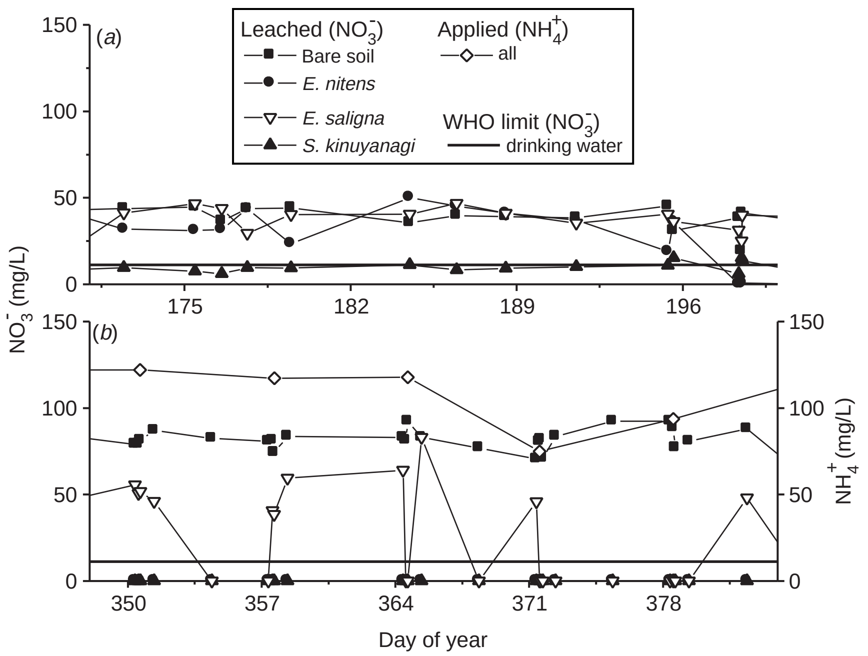

Fig. 2. Nitrogen concentrations of the effluent pond (NH_4^+) and the leachates (NO_3^-) compared with the maximum permissible level (MPL): (*a*) winter with no effluent; (*b*) summer with effluent.

Discussion

In our study, dairy-shed effluent contained 75–125 mg NH_4^+-N/L, which is similar to the average value of 87 mg NH_4^+-N/L measured by Hickey *et al.* (1989) in a survey of dairy-effluent ponds in the Manawatu province in New Zealand. This concentration is 6–11 times greater than the MPL (Fig. 2), and would require extra treatment prior to discharge.

Further treatment of the effluent can be achieved using SRF trees in a land treatment system. The trees in the present study were able to remove 33–56% of applied nitrogen, thereby preventing the nitrogen leaching into waterways or groundwater. Hopmans *et al.* (1990) measured nitrogen uptake rates of *E. saligna*, *E. grandis*, *E. camadulensis*, *Populus deltoides*, *P. deltoides*×*P. nigra*, *Casuarina cunninghamiana*, and *Pinus radiata* receiving municipal effluent at Wodonga, Australia. Effluent application added the equivalent of 400 kg N/ha.year over a 44-month period. Hopmans *et al.* (1990) found no significant difference in nitrogen uptake among the tree species, and N uptake averaged only 19%, with a maximum N uptake of 28%. The trees in the Wodonga experiment appear to be less efficient at taking up nitrogen than were the trees in this experiment. One possible explanation for this is that larger quantities of water were applied at Wodonga than in our study, possibly increasing nitrogen leaching and concomitantly decreasing uptake by trees at Wodonga.

Not all the nitrogen was, however, taken up by the trees in our study. Nitrate did pass beyond the root-zone where it would be expected to continue its passage downwards to contaminate the groundwater. The amount of N leached from each tree treatment was similar. In winter the leaching ranged between $0 \cdot 2$ and $0 \cdot 4$ kg N/ha.day. There were no losses in the summer, except for a small amount from the *E. saligna* trees ($0 \cdot 02$ kg N/ha.day). In all cases, the trees significantly ($P < 0 \cdot 05$) decreased nitrogen leaching losses in comparison with the bare soil treatment. N leaching losses from the bare soil treatment totalled $1 \cdot 1$ kg N/ha.day in the winter, and $2 \cdot 5$ kg N/ha.day in summer. The amount was higher in the summer as this was when the effluent was applied.

The differing water use by the *S. kinuyanagi* enhanced the quality of the water leaching beyond the root-zone. The *S. kinuyanagi* (deciduous) treatments had significantly more winter leachate volume than the evergreen *Eucalyptus* trees ($P < 0 \cdot 05$). This results from lower water use by the deciduous trees during winter. Also, interception of rainfall by the canopy would be greater for the evergreen trees than for the deciduous trees, further increasing the hydraulic loading. The deciduous treatments leached a similar mass of nitrogen, but the concentration was diluted by the larger leachate volume. This dilution had the favourable result of lowering the N concentration to below the MPL.

Tree water uptake rates in our study were moderately less than the rates reported in Australian plantations. The *E. saligna*, *E. nitens*, and *S. kinuyanagi* treatments summer ET rates were $5 \cdot 71$, $5 \cdot 51$, and $4 \cdot 59$ mm/day, respectively. Australian reports of the rates of water use by effluent irrigated plantations vary. Dunin and Aston (1984) reported a maximum water-use of 7 mm/day in summer for a native eucalypt forest with non-limiting soil water availability in coastal New South Wales, Australia. Myers *et al*. (1996) reported maximum daily water use rates of $8 \cdot 0$ mm/day for 3-year-old *E. grandis* trial plots irrigated with municipal effluent at Wagga Wagga, NSW, Australia. Tungcul *et al*. (1996) reported values ranging from $3 \cdot 8$ mm/day to $9 \cdot 65$ mm/day for *Salix* species receiving effluent application at Aokautere, New Zealand, on a cloud-free day in summer. The lower rates in our study are likely due to restricted water availability. Water inputs totalled $5 \cdot 5$ mm/day during summer, not accounting for rainfall interception. Thus the *E. nitens* and *E. saligna* were utilising all applied water and some from the soil's water storage. The willow was likely using all the water that it was receiving, as the water content of the soil averaged $10 \cdot 4\%$ during this period. Low ET in comparison with other studies may be a consequence of this limited availability of water.

A useful by-product of SRF effluent treatment crops is the production of woody biomass that can be used as an energy source. Our biomass production (scaled up from lysimeter measurements) yielded approximately 30 odt/ha.year at a plantation density of 4000 stems/ha. This compares well with one of the highest biomass production values recorded for *E. nitens* in Rotorua, New Zealand. In Rotorua, *E. nitens* planted at 2200 stems/ha without effluent applied produced 28 odt/ha.year for 6-year-old trees (Nicholas *et al*. 1997).

In our study, trees improved effluent treatment because higher evapotranspiration rates reduced the volume of leachate passing beyond the root-zone. Uptake of nitrogen by the trees further reduced the quantities of nitrogen available for leaching. In this study, *S. kinuyanagi* was the most suitable of the 4 treatments evaluated for land treatment. The low leachate nitrogen concentration is the key criterion in determining suitability of a tree species for land treatment of effluent.

The biomass production and tendency for nitrogen accumulation are secondary criteria.

Acknowledgments

This project is supported by the Foundation for Research, Science and Technology (Contract CO6618). The principal author also acknowledges the C. Alma Baker Trust, the New Zealand Large Herds Association, the MacMillian Brown Agricultural Research Scholarship, the Leonard Condell Farming Scholarship and Helen E. Akers Scholarship, for PhD stipend support. We thank Dexter McGee and Gerard Harrigan for their assistance.

References

Bond, W. J. (1998). Effluent irrigation—an environmental challenge for soil science. *Australian Journal of Soil Research* **36**, 543–55.

Bremner, J. M., and Mulvaney, C. S. (1982). Nitrogen—total. *In* 'Methods of Soil Analysis, Part 2'. (Ed. A. L. Page.) pp. 595–624. (American Society Agronomy: Madison, WI.)

Clothier, B. E., Scotter, D. R., and Kerr, J. P. (1977). Water retention in soil underlain by a coarse-textured layer: theory and a field application. *Soil Science* **123**, 392–9.

Dunin, F. X., and Aston, A. R. (1984). The development and proving of models of large scale evapotranspiration: an Australian study. *Agricultural Water Management* **8**, 305–23.

Hewitt, A. E. (1993). 'New Zealand Soil Classification.' (Landcare Research New Zealand Ltd: Lincoln, NZ.)

Hickey, C. W., Quinn, J. M., and Davis-Colley, J. (1989). Effluent characteristics of dairy shed oxidation ponds and their potential impacts on rivers. *New Zealand Journal of Marine and Freshwater Research* **23**, 569–84.

Hopmans, P., Stewart, H. T. L., Flinn, D. W., and Hillman, T. J. (1990). Growth, biomass production and nutrient accumulation by seven tree species irrigated with municipal effluent at Wodonga, Australia. *Forest Ecology and Management* **30**, 203–11.

Markus, D. K., McKinnon, J. P., and Buccafuri, A. F. (1985). Automated analysis of nitrite, nitrate and ammonium nitrogen in soils. *Soil Science Society of America Journal* **49**, 1208–15.

Ministry of Health (1995). 'Drinking Water Standards for New Zealand.' (Ministry of Health: Wellington, NZ.) pp. 1–87.

Myers, B. J., Bond, W. J., Falkiner, R. A., O'Brien, N. D., Polglase, P. J., Smith, C. J., and Theiveyanathan, S. (1994). Wagga effluent plantation project—Technical Report. CSIRO Division of Forestry, User Series No. 17, 123 pp.

Myers, B. J., Theiveyanathan, S., O'Brien, N. D., and Bond, W. J. (1996). Growth and water use of effluent-irrigated *Eucalyptus grandis* and *Pinus radiata* plantations. *Tree Physiology* **16**, 211–19.

Nicholas, I. D. (1997). Hardwoods in land treatment schemes: current status of New Zealand and Australian research. *In* 'Land Application of Biosolids'. New Zealand Land Treatment Collective Technical Session No. 15. (Eds H. Wang and J. M. Carnus.) Nelson, April 1997. pp. 34–5. (NZ Forest Research Institute: Rotorua, NZ.) pp. 34–5.

Nicholas, I. D., Carnus, J. M., and Oliver, G. R. (1997). Comparative performance of tree species in New Zealand wastewater irrigation systems. *In* 'Proceedings of Land Treatment and Wetland Workshop'. (Eds H. Wang and J. M. Carnus.) pp. 45–52. (New Zealand Waste Water Association and New Zealand Land Treatment Collective, NZ Forest Research Institute: Rotorua, NZ.)

Roberts, A. H. C., O' Connor, M. B., and Longhurst, R. D. (1992). Wastes as plant nutrient sources: issues and options. *In* 'The Use of Wastes and By-products and Fertilisers as Soil Amendments for Pastures and Crops'. (Eds P. E. H. Gregg and L. D. Currie.) pp. 44–55. Occasional Report No. 6. (Fertiliser and Lime Research Centre, Massey University: Palmerston North, NZ.)

Tungcul, R. O., Sims, R. E. H., and Mason, I. G. (1996). Response of short rotation forestry to dairy-farm pond effluent irrigation. *In* 'Proceedings of the 7th National Bioenergy

Conference.' South Eastern USA Regional Biomass Program. 15–20 September, Nashville, Tennessee, USA. pp. 793–9.

Weatherburn, M. W. (1967). Phenol–hypoclorite reaction for determination of nitrogen. *Analytical Chemistry* **39**, 971–4.

Young, H. E., and Carpenter, P. N. (1975). Sampling variation of nutrient element content within and among trees of the same species. *In* 'Oslo Biomass Studies International Union of Forest Research Organisations S4·01 Mensuration, Growth and Yield. Working Party on the Mensuration of the Forest Biomass'. (College of Life Sciences and Agriculture, University of Maine: Orono, USA.)

Manuscript received 22 July 1998, accepted 3 May 1999