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ABSTRACT

Land application of wastewater in New Zealand is becoming more common due to resource management legislation and the cultural preferences of the indigenous people. Impacts of municipal wastewater irrigation on some physical properties of two sandy soils under *Pinus radiata* D. Don forest were measured on a site of sand-dune origin (Waitarere) and one of volcanic origin (Whakarewarewa) which received primary-treated and tertiary-treated wastewater, respectively, at a rate of 60 mm/week. Intact soil cores were collected at 0–100 mm and 100–200 mm from wastewater-irrigated and non-irrigated control sites after 4 years of irrigation.

At the Waitarere site, irrigation with primary-treated wastewater significantly decreased the bulk and particle densities and unsaturated hydraulic conductivity, but increased total porosity and macroporosity. However, there was no change in saturated hydraulic conductivity. At the Whakarewarewa site, irrigation with tertiary-treated wastewater did not change bulk and particle densities, total porosity, water retention, and hydraulic conductivity but significantly increased soil macroporosity. Wastewater quality and, possibly, soil origin appear to play important roles in the changes in soil physical properties observed under wastewater irrigation.

Keywords: municipal wastewater; soil physical properties; irrigation; volcanic soil; sand dune soil.

INTRODUCTION

Large quantities of municipal, industrial, and agricultural wastewater are generated worldwide every year, and most of these wastewaters are treated and recycled back into the environment. Because discharging wastewater to waterways (e.g., rivers, lakes) can degrade their quality and result in depletion of dissolved oxygen and eutrophication, land application is becoming popular as an effective management option for the treatment of wastewater (Feigin *et al.* 1991). In New Zealand, resource management legislation and the cultural preferences of the indigenous Maori people also contribute toward this practice.

The objective of land treatment of wastewater is to utilise the physical, chemical, and biological properties of the soil-plant system to assimilate the waste components without adversely affecting soil or causing contaminants to be released into the wider environment, in either the short or the long term. Land application can have a variety of beneficial or detrimental effects, depending on the characteristics of the wastewater and the soil.

Forested sandy soils are often used for wastewater treatment because they have a number of desirable features. For example, applying wastewater to these soils as fertiliser can greatly increase their productivity potential and the additional water can extend their growing season. Wastewater can be applied almost all year round on forested lands without interruption by seeding, cropping, or harvesting schedules.

Irrigation with municipal wastewater could change soil properties that play an important role in the transformation, retention, and movement of nutrients present in the applied wastewater (Magesan *et al.* 1998). In particular, soil physical properties such as texture, structure, porosity, and hydraulic conductivity will influence soil water content and aeration, which in effect control the type and rates of soil microbial activity and chemical reactions. In spite of the importance of soil physical characteristics (Pagliai & Antisari 1993), only a small percentage of the numerous publications concerning land disposal of wastes is devoted to the effect of wastewater on soil physical properties. Moreover, in New Zealand, little research has been carried out in this area (Cameron *et al.* 1997).

The objective of the study reported here was to examine the impact of irrigation with municipal wastewater (different qualities) on soil physical properties of two forested soils, of different origin, in New Zealand.

MATERIALS AND METHODS

Site and Wastewater Descriptions

Waitarere

This site is near Levin (40°33 S, 175°12 E) in the North Island. The soil is "excessively drained dune sand" classified as a sandy Recent soil (Hewitt 1992) and Psamment (Soil Survey Staff 1992), and typically has 3–6% C and 0.13–0.21% total N at 0–5 cm depth, with pH 5.1–5.5 (Yeates 1995). Soil texture is sandy, bulk density is 1.17 Mg/m^3, total porosity is 55%, and percentage sand:silt:clay content is 88:5:7. The site has been irrigated with primary-treated wastewater from the seaside community at 60 mm/week since 1991 (Magesan *et al.* 1999).

Whakarewarewa

This site is located in Whakarewarewa Forest (38°11S, 176°17E) near Rotorua in the central North Island. The soil here is classified as Vitric Orthic Allophanic (Hewitt 1992) and Typic Udivitrand (Soil Survey Staff 1992), developed in free-draining volcanic tephra. It contains varying quantities of allophane, a clay mineral, throughout the profile (Cook *et al.* 1994) and typically has 7–8% C and 0.3–0.4% total N at 0–5 cm depth, with pH 6.1. Soil texture is sandy, bulk density is 0.72 Mg/m^3, total porosity is 69%, and percentage sand:silt:clay content is 56:32:12. The site has been irrigated with tertiary-treated municipal wastewater from Rotorua city at 56 mm/week since 1991 (Magesan *et al.* 1999).

Wastewater characteristics

Wastewater applied at the Waitarere site had higher concentrations of suspended solids and biological oxygen demand (BOD) than that applied at Whakarewarewa (Table 1).

TABLE 1–Characteristics of wastewater applied at the two field sites, averaged over 5 years.

Wastewater component (g/m^3)	Waitarere	Whakarewarewa
pH (no unit)	6.2	7.2
BOD	123	5.5
Suspended solids	185	5.5
Ammonium-nitrogen	5.7	3.3
Nitrate-nitrogen	49	6.5
Dissolved reactive phosphorus	17	3.5

Soil Sampling and Analysis

At the time of sampling, *Pinus radiata* tree canopy closure was complete and the forest floor was covered with needle litter. Four undisturbed soil cores (100 mm inside diameter and 70 mm high) in stainless steel liners were taken from 0–100 and 100–200 mm depths, to determine the impact of wastewater irrigation on some soil physical properties. Bulk and particle density, total porosity and macroporosity, total and readily available water capacities were measured following Claydon (1997), steady-state saturated hydraulic conductivity (K) following the method of Klute & Dirksen (1986), and unsaturated hydraulic conductivity (at –40 mm potential) ($K_{-40\ mm}$) following the method of Cook *et al.* (1993). Significance was tested using the two sample t-test for each property grouped by treatments.

RESULTS AND DISCUSSION

Bulk and Particle Densities

Irrigation with primary-treated wastewater at the Waitarere site significantly ($p<0.05$) decreased the bulk density at both depths (Table 2); irrigation with tertiary-treated wastewater at the Whakarewarewa site did not change the bulk density of the surface soil but increased bulk density at the lower depth (Table 3). It appears that wastewater quality influences soil

TABLE 2–Mean values of some soil physical properties at control and wastewater-irrigated sites at Waitarere. For each depth, within rows, determinations followed by the same letter do not differ significantly at $p = 0.05$

Soil property	0–10 cm		10–20 cm	
	Control	Wastewater	Control	Wastewater
Bulk density (Mg/m^3)	1.21 a	0.75 b	1.49 a	1.23 b
Particle density (Mg/m^3)	2.61 a	2.47 b	2.72 a	2.63 a
Total porosity (%)	54 a	70 b	46 a	54 b
Macroporosity (%)	9 a	21 b	21 a	16 a
TAWC * (%)	33 a	33 a	14 a	17 a
RAWC † (%)	30 a	16 b	10 a	14 a
Saturated K‡ (mm/h)	159 a	185 a	239 a	280 a
Unsaturated $K_{-40\ mm}$ (mm/h)	91 a	18 b	98 a	106 a

* TAWC = total available water capacity
† RAWC = readily available water capacity
‡ K = hydraulic conductivity

TABLE 3–Mean values of some soil physical properties at control and wastewater-irrigated sites at Whakarewarewa. For each depth, within rows, determinations followed by the same letter do not differ significantly at $p = 0.05$

Soil property	0–10 cm		10–20 cm	
	Control	Wastewater	Control	Wastewater
Bulk density (Mg/m^3)	0.63 a	0.65 a	0.71 a	0.79 b
Particle density (Mg/m^3)	2.20 a	2.32 a	2.34 a	2.38 a
Total porosity (%)	72 a	72 a	70 a	67 a
Macroporosity (%)	11 a	22 b	22 a	9 b
TAWC * (%)	33 a	25 a	22 a	32 b
RAWC † (%)	26 a	12 b	16 a	19 a
Saturated K‡ (mm/h)	39 a	114 a	46 a	7.2 b
Unsaturated $K_{-40\,mm}$ (mm/h)	12 a	21 a	17 a	8.0 a

* TAWC = Total available water capacity
† RAWC = Readily available water capacity
‡ K = hydraulic conductivity

bulk density because at the Waitarere site the wastewaters contained higher BOD and suspended solids (Table 1) than at the Whakarewarewa site. Similar results have been reported previously. Mathan (1994) reported that irrigation of municipal wastewater with high BOD to a sandy loam soil decreased bulk density, and Sopper & Richenderfer (1979) reported that the spray irrigation of tertiary-treated wastewater had little effect on the bulk density of forested soils.

In most mineral soils, the mean particle density is generally in the range 2.6–2.7 Mg/m^3, close to the density of quartz which is often prevalent in sandy soils (Hillel 1980). Although the particle density of the Waitarere site was in the typical range, that of the Whakarewarewa site was low (2.2–2.4 Mg/m^3) (Tables 2 and 3). The difference may be due to the origins of their soil. As for bulk density, it appears that wastewater quality affected the particle density at these sites. For example, wastewater irrigation at the Waitarere site significantly decreased the particle density of the surface soil (Table 2), most probably because of the presence of organic matter (Hillel 1980), whereas it did not change the particle density of the surface soil at the Whakarewarewa site (Table 3).

Total Porosity and Macroporosity

The total porosity of the control plot at the Waitarere site (range 46–54%; Table 2), was much lower than that at the Whakarewarewa site (range 70–72%; Table 3). Bulk and particle densities, two factors used to derive the porosity, were higher at the Waitarere site (Table 2) than at the Whakarewarewa site (Table 3) and could have affected soil porosity values. Irrigation with primary-treated wastewater significantly increased ($p<0.05$) total porosity at both depths at the Waitarere site (Table 2). The results were similar to those of Mathan (1994), who reported increases of up to 67% in total porosity in sewage-irrigated soils compared with the control. Irrigation with tertiary-treated wastewater at the Whakarewarewa site did not change the total porosity at either of the depths (Table 3) and this was similar to the studies reported by Sopper & Richenderfer (1979).

Macroporosity, a useful indicator of saturated hydraulic conductivity and potential aeration, increased significantly in the surface soils of the wastewater-irrigated plots at both sites (Tables 2 and 3), whereas it decreased in the lower layers of both soils (although the decrease was not significant at the Waitarere site). The significant increase in macroporosity may possibly have been due to increased biological activity after wastewater application (e.g., Yeates 1995).

Soil Water Characteristics

Soil water characteristics are among the most important measurements for assessing soil physical conditions, since they can indicate both the ability of the soil to store water and the aeration status of a drained soil, and can also be interpreted as a measure of pore-size distribution in non-swelling soils (Reeve & Carter 1991).

The soil water characteristics of the control and irrigated plots at the Waitarere site at both depths are given in Fig. 1 (a) and (b). Most of the water appears to have been released at <20 kPa; sandy soils generally contain large pores, and most water is released at low suction (Reeve & Carter 1991). In the surface soils, there were no significant differences between control and wastewater-irrigated plots at suction levels of 1, 2.5, and 5 kPa. At the higher suctions, however, more water was retained in the wastewater-irrigated plots, probably because of the addition of organic matter (Mbagwu 1992). At the lower depth, there were no significant differences between control and wastewater-irrigated plots, although there was some difference at the lower suctions (Fig. 1(b)).

The curves of the water release characteristics at the Whakarewarewa site are much smoother than those for Waitarere. The water content of the non-irrigated surface soil at the Whakarewarewa site decreased from 0.68 m^3/m^3 at 1.0 kPa to 0.22 m^3/m^3 at 1500 kPa suction. At 100–200 mm depth, the water contents of the wastewater-irrigated plots were consistently higher than those of the control plots (Fig. 1(d)).

Total and Readily Available Water Capacities

The total available water capacity (TAWC) at the Waitarere site did not change at either depth after wastewater irrigation, but the readily available water capacity (RAWC) significantly decreased in the surface soil (Table 2). In the control plots, the topsoils had greater amounts of available water than the subsoils, probably because of higher organic matter contents and the lower density of topsoils. Available water is generally expected to decrease with depth in a soil profile. Wastewater irrigation at the Whakarewarewa site did not significantly change the TAWC of the surface soil but decreased the RAWC of the irrigated plots (Table 3).

Saturated and Unsaturated Hydraulic Conductivities

At the Waitarere site, irrigation with primary-treated wastewater increased saturated hydraulic conductivity at both depths, although the increase was not statistically significant (Table 2). An increase in saturated hydraulic conductivity is usually associated with an increase in macroporosity (Mathan 1994). This is probably due to an improvement in soil structure, coupled with high faunal activity. Application of primary-treated wastewater at the

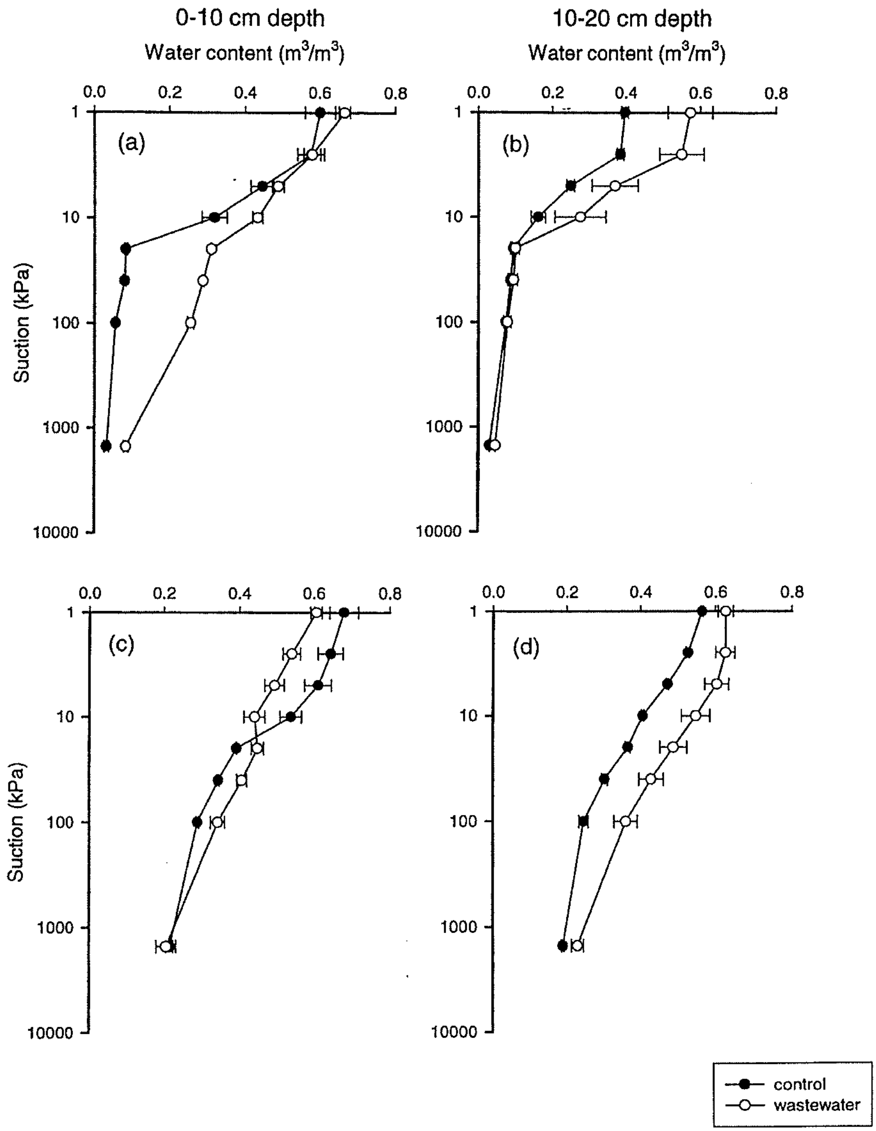

FIG. 1—Soil water characteristics of wastewater-irrigated plots at two depths at Waitarere (a,b) and Whakarewarewa (c,d) sites (standard errors are shown as error bars).

Waitarere site significantly increased the macroporosity (Table 2) and faunal activity (Yeates 1995). In the surface soils the unsaturated hydraulic conductivity of the irrigated plots decreased significantly compared with the control plots; there was no significant difference between treatments at lower depths.

At the Whakarewarewa site, irrigation with tertiary-treated wastewater did not significantly change the saturated hydraulic conductivity of the surface layer, though it decreased significantly at the lower depth (Table 3). Cook *et al.* (1994) reported a decrease in hydraulic conductivity in this soil after wastewater irrigation. Sopper & Richenderfer (1979) reported similar results after spray irrigation of wastewater on silt loam soil in pine forested areas.

CONCLUSIONS

This study suggests that wastewater quality can influence changes in soil physical properties, as application of primary-treated wastewater reduced bulk density and increased total porosity and macroporosity of a sand-dune soil. The vegetation may benefit because of improved aeration, and organic matter build-up in the soil. However, application of tertiary-treated wastewater to a volcanic soil did not affect bulk density or total porosity, but increased macroporosity. It appears soil origin also has a role in observed physical properties under wastewater irrigation.

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