The sustainable management of sewage wastewater irrigation to pasture

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ABSTRACT

Land application is increasingly being used for the treatment of sewage wastewater, yet when large quantities of nutrients and water are applied to land on a continuous basis, effective management becomes critical. We investigated the ability of a soil-pasture system to effectively assimilate and utilize wastewater nutrients in a cut and carry system. The processed wastewater has a high P content due to contributions from local meat processing operations. Wastewater was irrigated at three rates (450, 700 and 950 mm) over a 24 week period, delivering 143, 220 and 298 kg ha^{-1} of nitrogen (N) and 83, 128 and 172 kg ha^{-1} of phosphorus (P), respectively. Pasture yield increased with increasing rate of wastewater application, as did plant uptake of N and P. Concentrations of N and P in drainage also increased with increasing rate of wastewater application. Total N loss in drainage from wastewater treated plots, measured over 10 weeks, ranged from 4.50- to 18.64 kg N ha^{-1}. Total P losses under wastewater irrigation ranged from 0.35- to 7.14 kg P ha^{-1}. Application of wastewater did not increase N_2O emissions above background levels.

INTRODUCTION

As the difficulties associated with the treatment of municipal wastewater and the benefits of land treatment become more widely appreciated, there has been a shift toward land application as a final fate for treated sewage wastewater. Regional authorities in New Zealand advocate the application of wastewater onto land rather than direct discharge into surface waters (Barton *et al.* 2005; Cameron *et al.* 1997; O'Connor *et al.* 1996). The benefits of applying municipal sewage to land are threefold. Firstly, in many cases, it is the cheapest and most socially acceptable form of final treatment. Secondly, land application facilitates the re-cycling of valuable nutrients and water back into agricultural production systems. Thirdly, by limiting the volume of wastewaters that are discharged directly to surface waters, pollution is reduced. However, when wastewater is applied to land, resource management legislation requires that this does not cause adverse effects on the receiving environments and therefore effective management of wastewater nutrients are required.

Cut and carry systems, where forage or pasture crops are grown with the use of wastewater and routinely harvested and removed in bulk from the treatment site, ensure the removal of wastewater nutrients from the growing area. Non-grazing of these sites avoids the nitrogen inputs from animal urine that are so problematic (Barton *et al.* 2005; O'Connor *et al.* 1996). However, one of the major challenges confronting sustainable management of land application of sewage wastewater is the very large volumes of effluent that have to be irrigated to land. The aim of this study was to investigate the effects of excessive hydraulic loading of secondary treated sewage wastewater to a free-draining fine sandy loam soil on nutrient transformations and losses following irrigation. Here, we describe the accumulation of N and P in pasture and soils and losses through leaching and nitrous oxide gas emissions.

MATERIALS AND METHODS

The Feilding Sewage Treatment Plant, in the Manawatu region processes approximately 7000 m^3 of solid and liquid waste per day. Treatment includes primary filtration, secondary aeration and UV disinfection prior to discharge to the Oroua River. Wastewater used in this field trial was diverted from the Treatment Facility’s discharge source as required.

Sixteen plots (3 m x 3 m) were established on a fine sandy loam soil, with low P retention. Plots were hydraulically isolated from each other by a 300 mm wooden barrier, inserted to a depth of 250 mm around the perimeter of each plot. The pasture species was a perennial ryegrass cultivar, ‘Quartet’. Wastewater was irrigated to the plots once a week between 18 December 2005 and 1 June 2006. The wastewater was applied at three rates to give total irrigation depths of 450, 700 and 950 mm, hereafter, referred to as low, medium and high, respectively. In order to isolate the effect of wastewater constituents on soil and pasture growth from that of water irrigation, a further treatment of bore water was applied at a rate of 450 mm over the same time period. Each of these treatments was replicated four times. These application rates correspond to the volume of sewage wastewater that must be diverted from the discharge to the Oroua River if new water quality standards are to be met. Wastewater was applied by hand using a 20 mm hose and tap fitting at an application rate of 16.6 mm/hr (0.278 mm/min).

Using 10 year historic climatic data gathered from weather data at the Feilding Sewage Treatment Plant, we predicted the average irrigation demand between 18 December and 1 June at this site to be 177 mm. The depth of wastewater irrigation exceeded this predicted demand by as much as five times for the highest rate of wastewater application.

Drainage samples were collected for 10 weeks, between 31 March 2006 and 1 June 2006, using suction cup samplers at depths of 250 and 450 mm. Drainage volumes were predicted using a soil water balance. The drainage samples were analysed for concentrations of mineral N, total N, dissolved reactive P (DRP) and total P.

Pasture was cut using hand shears to a height of 50 mm, five times during the experiment period (11 January, 20 February, 4 April, 10 May and 1 June of 2006). Dried pasture samples were ground and analysed for total N and P concentration.

Soil samples were collected on the 8 June, the week after irrigation had finished, from the following depths; 0-75 mm, 75-150 mm, 150-300 mm, 300-450 mm and 450-600 mm. Dried soil samples were then analysed for NH_4^+, NO_3^- and TKN and TKP concentrations.

Nitrous oxide flux was measured using a closer chamber technique over an 8 day period following irrigation events on 6 March and 1 June. Each treatment consisted of three replicates, while only two replicates were taken for background N_2O levels. A measurement of N_2O flux was taken immediately prior to both irrigation events to determine background

N_2O flux (day 0). Measurements were then taken 24 hours after irrigation (day 1) and again two days (day 2) and seven days (day 7) after the irrigation event. Having sealed the chamber with the lids, samples were taken from each chamber using a 50 mL syringe, immediately following closure of the lid (t_0) and again after one hour (t_{60}). In order to minimise the variation in the flux pattern, sampling was always carried out between 10-11 am.

Significant differences and LSD values between treatments were tested using an analysis of variance procedure by SAS Institute Inc. (SAS 1989)

RESULTS

Wastewater characteristics

The Fielding Sewage Treatment Plant processes an equal volume of waste from both domestic and industrial sources. Industrial contributions come primarily from meat and skin processing plants operating in the local reticulation zone. The concentrations of mineral-N and DRP varied during the study period due to changes in the volume of water and retention periods of wastewater liquor in the pond system, and to the differences in industrial contributions between low and high production seasons (e.g. during lambing and beef culling season). In the case of N, the vast majority (>80%) is in mineral form, while for P, organic forms comprise approximately half the total amount (Table 1).

Table 1. Mean (and standard error) values for selected characteristics of secondary-treated domestic wastewater at the Feilding Sewage Treatment Plant between December 2005 and June 2006 and typical concentrations of nutrients from New Zealand Municipal Wastewater Treatment Plants.

Parameter	Feilding secondary treated municipal wastewater	Typical values for secondary treated municipal wastewater*#
	(mg L^{-1})	
Suspended solids	23.1 (3.17)	30 - 40
Biological oxygen demand	10.51 (0.95)	20 - 35
Total nitrogen	31.30 (4.18) [1]	20 - 35
Ammonium	8.88 (3.35)	12
Nitrate	16.38 (2.20)	-
Total phosphorus	18.10 (1.57) [1]	4 - 6.5
Dissolved reactive P	10.04 (0.87)	-

[1] Mean concentrations and SEM are reported for nine samples collected between April and June.
* Suspended-growth aerobic system
\# Source Potts *et al.* (2000).

Wastewater irrigation added 140, 220 and 300 kg N ha^{-1} and 80, 130 and 170 kg P ha^{-1} to the low, medium and high treatments, respectively (Table 2).

Table 2. Amount of nitrogen and phosphorus applied to soil in treated wastewater between the 18 December 2005 and 1 June 2006. All in kg/ha unless stated.

	Wastewater applied (mm)	N Applied			P applied	
		Inorg	Org	Total	Reactive	Total
Low	450	105	35	140	45	80
Med	700	165	55	220	70	130
High	950	225	75	300	95	170

Dry matter production and nutrient uptake

Pasture yield, measured between 11 January and 1 June 2006, increased with increasing rate of wastewater application. Wastewater application increased pasture production from 7.9 t DM/ha (water) to 8.90 - 9.75 t DM/ha: these increases in yield above the water-only treatment are mostly attributable to the supply of nutrients in wastewater. The nitrogen-use efficiency, expressed as kg DM kg^{-1} N, was greatest for the low level of wastewater application (10.24 kg DM kg^{-1} N) followed by the high (8.21 kg DM kg^{-1} N) and medium (7.99 kg DM kg^{-1} N) rates. The concentrations of N and P in pasture increased with increasing wastewater application rate.

Compared with the water treatment, the application of wastewater significantly ($P<0.05$) increased the total N and P uptake by pasture (Table 3). Overall N recovery for all wastewater treatments represents 31-34% of the amount applied. Pasture uptake of P accounted for only 10.4-11.1% of the amount applied in wastewater. When considering the ratio of N: P in wastewater, 1.0:0.6 (Table 2), with that in pasture biomass, 1.0:0.2, it becomes evident that this wastewater source is P-rich. Consequently, when wastewater is applied to meet plant N requirements, P is applied in excess of crop demand.

Table 3. Total uptake (herbage yield x concentration of nutrient in herbage) of N and P by ryegrass pasture grown under a range of different irrigation depths of wastewater and water at the Feilding Sewage Treatment Plant between 11 January and 1 June (2006).

Irrigation Treatment	Total N uptake	Total P uptake
	kg N ha^{-1}	kg P ha^{-1}
Water	189.68	28.45
Low	230.77	35.98
Medium	248.75	39.58
High	272.16	44.57
LSD	29.84	5.08

Soil analysis

The effect of irrigation on selected soil properties is given in Table 4. As many workers have noted, irrigation with agricultural and domestic wastewater frequently causes increases of pH in receiving surface soils (Barton *et al.* 2005; Cameron *et al.* 1997; Quin and Woods 1978; Schipper *et al.* 1996; Sparling *et al.* 2006). Here, soil pH of wastewater irrigated plots was significantly higher ($p<0.05$) than water irrigated plots, by as much as 0.40 units, and is likely to be influenced by the salt content (Ca^{2+}, Mg^{2+}, Na^+ and K^+) of the wastewater. When wastewater contains N predominantly as nitrate, plant uptake of nitrate is favoured (Schipper *et al.* 1996) causing the release of hydroxyl ions to maintain the ionic equilibrium between the root and soil solution. These hydroxyl ions give rise to an increase in soil pH. The reduction of nitrate to ammonium within the plant, also results in the release of hydroxyl ions into the root zone with similar effects (Bolan *et al.*1991; Bolan *et al.* 2004).

As expected, application of wastewater at all rates had no significant impact on total N and P content of soil to a depth of 75 mm (Table 4). This was also true for soil samples taken at 75-150, 150-300, 300-450 and 450-600 mm depths (data not shown). Many similar studies report no significant change in total N and P after one year (Sakadevan *et al.* 2000), two years (Barton *et al.* 2005) and four years (Sparling *et al.* 2006) of weekly applications of wastewater. Only wastewater at the high rate of application had significantly higher nitrate-N levels in the top 75 mm above the water treatment (Table 4), however, no differences were observed between treatments at sampling depths of 150-300, 300-450 and 450-600 mm depths (data not shown). For ammonical-N, no differences were observed between treatments at all sampling depths.

Often, recent soils, similar to the one used in this experiment, are favoured for land treatment systems due to their ability to receive large volumes of wastewater without surface ponding (Sparling *et al.* 2006). However, in many instances these soils have a low P sorption capacity and require only small P additions to raise the Olsen P values. In addition to this, there is also an increase in pH with increasing application rate and this consequently encourages the availability of orthophosphates in solution by further limiting the P retention capacity.

Table 4. Selected soil properties for the top 75 mm soil, sampled on the 8 June 2006.

	pH	Olsen P	P Retention	Total N	NO_3-N	NH_4-N	Total P
		mg/kg	%	g / kg of soil			
Water	5.9	32.78	19.11	2.00	1.27	2.60	0.76
Low	6.2	37.41	19.39	2.00	2.28	3.78	0.75
Med	6.3	35.53	16.94	2.00	3.00	2.63	0.75
High	6.2	43.65	16.52	2.00	2.30	2.85	0.77
LSD	0.1	7.67	2.58	0.02	1.12	2.69	0.05

Nitrogen and phosphorus leaching

Application of municipal wastewater significantly ($P<0.05$) increased the nitrate-N concentration in drainage samples at a depth of 450 mm (Table 5). The concentration of nitrate-N in drainage between wastewater treatments was similar. Although the concentration of NO_3^--N in drainage samples was, in all cases, lower than the concentration of the applied wastewater, it is ecologically significant, as, generally it is one order of magnitude greater than the level of 0.1 mg N litre^{-1} which is likely to promote aquatic weed growth (Ministry for the Environment 1992). However, on no occasion did this concentration exceed the recommended drinking water level of 11.3 mg NO_3-N litre^{-1} (Ministry of Health 1995).

Table 5. Mean N concentrations in suction cup samples and cumulative N losses (suction cup N concentration x drainage volume during the 24 hours proceeding irrigation). Samples were collected between 31 March and 1 June 2006.

	Water	Wastewater			LSD
		Low	Medium	High	
NO_3-N (mg/l)	1.46	4.55	5.27	4.49	1.12
NH_4-N (mg/l)	0.05	0.10	0.28	0.24	0.13
Organic-N (mg/l)	2.40	2.40	1.99	2.43	0.69
Total Drainage (mm)	60	60	160	260	-
Loss of NO_3-N (kg/ha)	0.90	3.19	8.88	12.17	-
Loss of NH_4-N (kg/ha)	0.03	0.04	0.37	0.61	-
Total N loss (kg/ha)	2.35	4.50	12.36	18.64	-

The amount of drainage from the plots was strongly influenced by irrigation depth. Total-N lost through leaching from wastewater plots increased with the application rate. As the concentrations of N in the drainage water from wastewater treatments were similar (Table 5), differences in cumulative N loss between wastewater treatments can be attributed primarily to differences in drainage volume.

If the concentrations of N measured during the monitoring period are assumed to be typical then, by extrapolation and the use of the soil water balance, total losses for total-N of the order of 5.8-(control), 9.1-(low), 22.7-(medium) and 34.2-(high) kg N ha^{-1} are calculated for the wastewater irrigation season (24 weeks).

Table 6. Mean P concentrations in suction cup samples and cumulative P losses (suction cup P concentration x drainage volume over 24 hours of irrigation event). Samples were collected between 31 March and 1 June.

	Water	Wastewater			LSD
		Low	Medium	High	
DRP (mg/l)	0.11	0.52	1.51	2.23	0.66
Organic-P (mg/l)	0.10	0.21	0.60	0.83	0.46
Total Drainage (mm)	60	60	160	260	-
Loss of DRP (kg/ha)	0.06	0.25	2.29	6.81	-
Total P loss (kg/ha)	0.14	0.35	3.18	7.14	-

P concentration in drainage samples increased with increasing application rate (Table 6). This trend was most pronounced for DRP concentrations (Table 6). While most New Zealand soils tend to have relatively high P retaining capacities that limit P leaching from land treatment systems (Cameron *et al.* 1997), the soil in this field experiment site has a low P retention capacity. Rapid drainage through the coarse textured soil and high P loading rates resulted in an increase in the P concentration of the leachate. The DRP concentrations exceed the ecological standard (0.015mg DRP $litre^{-1}$) of the Australian and New Zealand Water Quality Guidelines for Fresh and Marine Water Quality (2000) by nearly 150 times.

If the concentrations of P measured during the monitoring period are assumed to be typical then, by extrapolation and the use of the soil water balance, it is predicted that a total of 0.4-(control), 1.2 (low), 8.5 (medium) and 17.3 (high) kg P ha^{-1} might have been lost during the 24 weeks of wastewater application, of which 50, 67, 79 and 97% would have been in dissolved reactive form.

Nitrous oxide emissions

Peak emissions of N_2O gas from wastewater treatment (Table 7) occurred within 24 hours of application and ranged from 6.9 to 12.5 g N_2O $ha^{-1}day^{-1}$. Cumulative N losses, measured as N_2O, over the seven day period in March and June were low and there was no significant difference between the wastewater treatments including water and an adjacent non-irrigated area. Low N_2O-N losses (2.4 kg N_2O $ha^{-1-}yr^{-1}$) were also reported by Barton et al. (1999b) following the application of wastewater at a N loading of 300 kg N $ha^{-1}yr^{-1}$ to forested pines grown on sandy loam soils. In related laboratory studies, these workers showed that denitrification enzyme activity in these soils is closely related to soil aeration status and when supplied with carbon and nitrate, the denitrification enzyme population showed a 40 fold increase between irrigated and non-irrigated soils. However, when limited by oxygen under similar amendment, populations increased by more than 1000 fold. Barton et al. (1999a) suggest that denitrification in sandy loam soils, and consequent N_2O emissions, will be limited when the water filled pore space (WFPS) is below 80%. In the current study, WFPS during the trial period rarely increased above 65% (data not shown) and therefore it is likely that the coarsely textured, free-draining soil did not remain anaerobic for a sufficient period to allow the denitrifying enzyme population to increase, despite the addition of C and N.

Table 7. Nitrous oxide fluxes following application of municipal wastewater to ryegrass pasture. Each value represents the mean of three samples unless stated otherwise.

	N added in wastewater (kg N ha^{-1})		N emitted as N_2O* (kg N ha^{-1})	
	March	June	March	June
Background	-	-	0.068 [1]	0.010 [1]
Water	-	-	0.030	0.014
Low	6.792	1.033	0.041	0.019
Medium	9.922	4.163	0.045	0.025
High	13.052 [2]	7.293 [2]	0.076 [2]	0.035 [2]

[1] represents the mean of two samples
[2] represents the mean of four samples
[*] No significant differences between treatments were found

CONCLUSIONS

Land application of treated municipal wastewater over six months resulted in an increase in pasture production and nutrient removal. Irrigation of the wastewater resulted in substantial leaching of both N and P. Losses of nutrients in drainage under wastewater irrigation are attributable to the large volumes of drainage generated and the high concentration of nutrients in drainage water. As the concentration of P in the treated wastewater is high, irrigation to land results in the application of quantities of P in excess of the requirements of pasture. This surplus P is likely to accumulate in soils over time until the soil P sorption capacity is saturated, further compromising the effectiveness of land treatment. In order to maintain the performance of the land treatment system over the long term and utilise wastewater to its full potential, loading rates must address both the attributes of the soil and the optimal requirement of the crop. The land treatment system at the Feilding Sewage Treatment Plant will require greater land area if it is to be sustainable.

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