

## Movement of phosphorus in soil at the Rotorua land treatment system

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### ABSTRACT

Treated sewage effluent from Rotorua city, New Zealand, has been spray-irrigated into Whakarewarewa Forest since 1991 to minimize effluent-derived nitrogen (N) and phosphorus (P) entering Lake Rotorua. To assess the capacity of the ecosystem to assimilate the effluent-derived nutrients, a long term field trial was established within the Rotorua land treatment system. The objective of this study was to determine the accumulation, redistribution and movement of P in the volcanic soil after 11 years of effluent irrigation. Effluent has been applied to the plots on the trial site at 4 loading rates, including 0 (control), 37 (low), 71 (medium) and 112 (high) mm week<sup>-1</sup> since October 1991. Each treatment had 3 replicates. In July 2002, soil samples were taken within the trial plots at five depths: 0-10, 10-20, 20-40, 40-60, and 60-100 cm. The soil samples were analyzed for pH, total organic C, total P (TP), and soil test P, including Olsen-P and Mehlich-3 (M3) P.

Soil pH had increased significantly ( $P < 0.05$ ) across the whole profile in all effluent treated plots compared with the control plots. Concentrations of M3Ca and M3Mg in the top 40 cm were significantly higher in effluent irrigated plots. Concentrations of soil TP, Olsen-P and M3P in all effluent treatments had increased significantly. Most effluent-derived P had accumulated in the top 40 cm. Concentrations of soil Olsen-P and M3P in the medium and high effluent treatments increased at all depths and were over environmental threshold levels in the top 20 cm, suggesting a potential for soil P to move downward with drainage water. Soil P accumulation and movement in the soil profile increased with effluent irrigation rate. Phosphorus saturation ratio index (M3PSR) calculated as the molar ratio of M3P to M3(Al + Fe) appeared to be inadequate as an indicator for downward movement of soil P in the land treatment system, but Olsen-P proved to be a sensitive indicator of P movement in the soil. Regular soil sampling and Olsen P measurement using 60 mg P kg<sup>-1</sup> as a threshold can provide a satisfactory solution for monitoring the movement of P down the soil profile.

**Keywords:** land application, phosphorus saturation, sewage effluent, wastewater.

### INTRODUCTION

Treated wastewater has been irrigated to land in many parts of the world to reuse water and nutrients, or to provide further treatment. Soil nutrient levels may build up when effluent is irrigated to an area continuously. In particular, when the loading of a land application system is based on N loading to meet crop requirement, P may be oversupplied and accumulate in the

soil. Phosphorus retention capacity of a soil is often limited and varies with different soil characteristics. When excessive P is loaded, soil P sorption capacity may be saturated. Consequently, soil P may be desorbed and leached (Allen *et al.* 2006; Zvomuya *et al.* 2006). In practice, although effluent application rates are usually based on N or hydraulic loading, P loading is more likely to be a limiting factor over the life of a land treatment system (USEPA 1981). Researchers have developed a number of approaches, such as P sequential fractionation, degree of phosphorus saturation (DPS), bioavailable threshold P level as measured by various extractants, and Mehlich-3 (M3) P sorption ratio (M3PSR), to examine the redistribution of added P and to predict the potential risk of soil P entering ground/surface water (Hedley *et al.* 1982; Heckrath *et al.* 1995; Sharpley *et al.* 1995; Sims *et al.* 2002).

Secondary-treated municipal sewage effluent from Rotorua city in the central North Island, New Zealand, was historically discharged to Lake Rotorua, contributing to eutrophication and algae blooms in the lake that threatened the area's tourism industry. Since 1991 the Rotorua wastewater treatment plant has been upgraded to include an activated sludge process for improved nutrient removal, and the treated effluent has been spray-irrigated in the nearby Whakarewarewa Forest on volcanic soils. The purpose of the land application was to engage the physical, chemical and biological processes in the soil-water-plant system to provide further nutrient removal. Regular water quality monitoring of the outflow stream from the land treatment catchment, which was one of the water recharge contributors to Lake Rotorua, indicated that there was a considerable reduction in net N and P input to the lake caused by the effluent discharge (Tomer *et al.* 1997). However export of effluent-derived N from the land treatment system has increased in recent years (Tozer *et al.* 2005). Whereas leaching loss of P from the Rotorua land treatment system was considered low, there was little understanding of the behaviour of effluent-derived P in the soil. Therefore, the objective of this study was to investigate the forms, redistribution, and movement of soil P after 11 years irrigation on a long term trial site within the Rotorua land treatment system.

## MATERIALS AND METHODS

### Site description

Since 1991, treated sewage effluent in Rotorua had been sprinkler-irrigated to Whakarewarewa Forest, a commercial *Pinus radiata* forest situated in the Waipa Catchment of Rotorua, in the Central North Island of New Zealand to provide a nutrient source thereby achieving further nutrient removal. Soils are volcanic in origin, with sandy-loam textures, large porosities, and very high infiltration rates (e.g., saturated hydraulic conductivities  $> 45 \text{ mm hr}^{-1}$ ) with negligible runoff (Tomer *et al.* 1997). Precipitation at Rotorua averages  $1491 \text{ mm year}^{-1}$ , and pan evaporation averages  $1186 \text{ mm year}^{-1}$ .

A long-term field trial was established within the Rotorua land treatment system. The trial plots had four effluent rate treatments of 0 (control), 37 (low), 71 (medium) and  $112 \text{ mm week}^{-1}$ . There were three replicate plots of each irrigation treatment. Each plot had an outer area of  $60 \text{ m} \times 60 \text{ m}$ , and an inner area of  $40 \text{ m} \times 40 \text{ m}$  for sampling and measurement.

Concentration of total P in irrigated effluent averaged  $3.1 \text{ mg P L}^{-1}$  with a range between  $0.4$  and  $9.0 \text{ mg P L}^{-1}$ . Immediately prior to soil sampling, the total P loading during the 11 year period was  $656$ ,  $1145$  and  $1986 \text{ kg P ha}^{-1}$  at the low, medium and high effluent treatments, respectively.

## Soil sampling and analysis

Soil was collected from all the treatment plots in July 2002. A number of soil cores were taken from each plot using a Höffer tube with an internal diameter of 30-mm at depths of 0-10, 10-20, 20-40, 40-60, and 60-100 cm. Samples from the same plot were bulked, air-dried, and ground to pass a 2-mm sieve before analysis. Total organic C in soil was determined by dry combustion using a Leco CNS 2000. Soil pH was measured in a 1:2.5 soil to water solution.

Total P in soil was digested following a micro-Kjeldahl digestion (Blakemore *et al.* 1987). Concentrations of total P and Olsen P were determined using molybdate blue method with a colorimeter (Murphy and Riley 1962). Soil samples were extracted with Mehlich 3 (M3) solution (Mehlich, 1984). Concentrations of P, Ca, Mg, Al and Fe in M3 extracts (M3P, M3Ca, M3Mg, M3Al, and M3Fe) were analyzed using ICP-OES (Perkin Elmer Optima 3000DV). Phosphorus saturation ratio (M3PSR) was calculated as the molar ratio of M3P to M3(Al + Fe) in  $\text{mmol kg}^{-1}$  (Sims *et al.* 2002).

## Statistical analysis

Analysis of variance (ANOVA) and Tukey's honest significant differences (HSD) method were used to test the statistical significance of the sewage effluent treatment effects using the SAS/STAT Version [9] GLM procedure. Regression analysis was conducted using the SAS REG procedure.

## RESULTS AND DISCUSSION

### Changes in soil pH, carbon and cations and their implications for P retention

Soil pH in all effluent irrigated plots at all depths were significantly ( $P < 0.05$ ) higher than that in the control with slightly larger increases in pH at higher irrigation rates. Soil pH ranged from 5.3 to 5.7 in the control plots, but ranged from 6.1 to 6.5 in the effluent irrigated plots (Table 1). Higher concentrations of organic C in the effluent treated plots than in the control plots were observed at the 0-10 cm depth interval, although these differences were not significant statistically (Table 1) because of a high variation. Concentrations of both soil M3Ca and M3Mg were significantly ( $P < 0.05$ ) higher in all effluent treated plots down to 40 cm depth (Table 1), indicating accumulation of effluent-derived Ca and Mg in the soil. The largest difference was observed at 20-40 cm depth interval, where concentrations of soil M3Ca and M3Mg were respectively more than 8 and 5 times greater in the high effluent treatment than the control plots. There were little differences in M3Ca and M3Mg concentrations amongst the low, medium and high irrigation rates, except at the 20-40 cm depth interval, where M3Ca concentration was significantly ( $P < 0.05$ ) greater in the high effluent treatment than the low and medium treatments (Table 1). Concentration of M3Ca was significantly greater in the high effluent treatment than the control throughout the 1 m soil profile (Table 1). Whereas concentration of soil M3Fe were not affected by effluent irrigation, concentrations of soil M3Al were significantly ( $P < 0.05$ ) greater in the effluent treatments at the top layer (0-10 cm) than in the control treatment (Table 1).

**Table 1.** Effect of effluent irrigation on selected soil chemical properties ( $\text{mg kg}^{-1}$ , except for pH, C and M3PSR).

Treatment	pH	C%	TP	Olsen P	M3P	M3Al	M3Fe	M3Ca	M3Mg	M3PSR
0 - 10 cm										
Control	5.32b	4.50a	292b	3.3b	12b	2861a	164a	1063b	158b	0.003c
Low	6.06a	5.32a	862a	66.6a	166a	2283b	154a	2470a	357a	0.06b
Medium	6.28a	5.90a	1106a	93.6a	289a	2155b	143a	3224a	376a	0.11ba
High	6.24a	5.53a	1067a	92.7a	298a	2041b	173a	3843a	424a	0.12a
10 - 20 cm										
Control	5.64b	2.80a	244b	2.2b	6.4b	2921a	72a	405b	64b	0.002b
Low	6.32a	3.03a	494ba	26.4a	46ba	2615a	93a	1027a	154a	0.02ba
Medium	6.46a	3.29a	830ba	60.3a	160a	2471a	88a	1603a	169a	0.06a
High	6.46a	3.12a	984a	72.2a	187a	2585a	113a	2170a	193a	0.06a
20 - 40 cm										
Control	5.66b	1.70a	182b	1.3b	2.6a	2890a	55a	132c	20b	0.001b
Low	6.35a	2.20a	248ba	2.7b	2.3a	2565ba	50a	390b	68a	0.001b
Medium	6.52a	2.28a	372ba	13.3ba	19a	2515b	52a	626b	101a	0.006ba
High	6.49a	2.33a	703a	38.7a	74a	2497b	64a	1121a	106a	0.03a
40 - 60 cm										
Control	5.70c	1.42a	162b	1.5b	1.3a	2774a	48a	83b	20b	0.0004a
Low	6.22b	1.75a	213ba	1.3b	0.9a	2590a	44a	180ba	48ba	0.0003a
Medium	6.52a	1.54a	223ba	1.9b	1.2a	2447a	39a	208ba	50ba	0.0004a
High	6.47ab	1.88a	316a	7.1a	6.7a	2588a	50a	572a	67a	0.002a
60 - 100 cm										
Control	5.71b	1.30a	165a	0.9a	0.6a	2737a	48a	65b	21b	0.0002a
Low	6.18a	1.20a	184a	1.3a	0.6a	2608a	46a	99ba	31ba	0.0002a
Medium	6.37a	1.17a	177a	1.3a	0.3a	2556a	41a	102ba	38ba	0.0001a
High	6.45a	1.37a	258a	3.3a	2.8a	2609a	43a	284a	52a	0.001a

\*Values with the same letter in a column at the same depth are not significantly different ( $\alpha = 0.05$ ).

In a previous study on the same site, McLay *et al.* (2000) investigated selected soil chemical properties. They found soil pH increased at least by 0.5 units after 4 years effluent irrigation. They also found that soil cation exchange capacity (CEC) increased in the effluent treatments, particularly in the high effluent treatment. In addition, exchangeable Ca and Mg increased in the effluent treated plots, and most of effluent-derived Ca and Mg was retained in the soil in exchangeable form (McLay *et al.* 2000). In these variable charged allophonic soils, the increases in CEC and extractable cations (e.g., Ca, Mg and Na) can be attributed to the increase in pH with effluent irrigation. On the other hand, the significant reduction in M3Al may also be attributed to increased pH in soil receiving effluent irrigation, because concentration of labile Al (e.g., M3Al) in soil generally decreases with increasing pH (Wang *et al.* 1999).

At the initial design stage, on the basis of P saturation it was predicted that the Rotorua land treatment system would have a life expectancy of 70 – 130 years, according to soil allophane content and P sorption measurements (Tomer *et al.* 1997). Perrot *et al.* (2002) suggested that this land treatment system's lifetime for P may be approximately 50 years, according to the P retention of the soil, movement of P down the soil profile and a possible shallower soil depth available for P retention due to lateral subsurface flow. These studies were all primarily based on amounts of allophane in soil. However, effluent-induced changes in soil chemical properties, such as increased pH and effluent-derived exchangeable Ca and Mg, and decreased labile Al (Table 1), can make the estimation of the life expectancy for P related effluent application more complicated. Significant increase of M3Ca and M3Mg in soil

indicates that Ca and Mg would be likely to play an important role in retaining effluent-derived P in the soil. Hu (2005) reported that after ~30 years irrigation by municipal and industrial wastewater, the pH in 0-15cm depths soil rose from ~5-6 to ~7.4-7.8, and the Ca-bound P became dominant P form, although Al-bound P was dominant soil P at early stage.

### **Soil P test and leaching potential**

Total P (TP) concentrations decreased with depth (Table 1). All effluent treatments significantly ( $P < 0.05$ ) increased the concentration of total soil P in the top 10 cm. Whereas most P added with effluent irrigation had accumulated in the top 40 cm soil, some P had moved to below this (Table 1). The high effluent treatment significantly ( $P < 0.05$ ) increased soil TP in depths to 60 cm over the control treatment, but there were no differences in TP concentrations between the low and medium treatments and the control treatment below 10 cm depth.

There was a larger difference between treatments in concentrations of soil Olsen P than in TP. All effluent treatments significantly ( $P < 0.05$ ) increased the concentration of soil Olsen P in the top 20 cm. At 40-60 cm depth, Olsen P concentration in the high effluent treatment was significantly ( $P < 0.05$ ) greater than in the low and medium as well as in the control treatments. Heckrath *et al.* (1995) used 60 mg kg<sup>-1</sup> of Olsen P as an environmental threshold to predict P leaching potential in a soil profile. When soil Olsen P is higher than this threshold, a rapid release of P to drainage can happen. In our current study, the top 10 cm soil Olsen-P concentrations were 1.1-, 1.5- and 1.6-time this threshold value in the low, medium, and high effluent treatments, respectively. Olsen P concentration in the 10 – 20 cm depth of the high treatment was also greater than this threshold, indicating a potential for P leaching. The significantly higher level of Olsen P for the high treatment in the 20 – 40 cm depth compared with the control (Table 1) is therefore not unexpected.

Like Olsen P, M3P is becoming an indicator for both agronomic and environmental soil test especially in soils dominated by Fe and Al oxyhydroxides (Sims *et al.* 2002). Increase of M3P concentrations in the topsoil of all effluent treated plots was similar to Olsen-P. Sims *et al.* (2002) reported that for a moderately acidic sandy soil, if the concentration of M3P is above 150 mg kg<sup>-1</sup>, it may lead to the loss of soluble P from soil to surface and shallow ground water as non-point P pollution. In the current study, concentrations of M3P of all effluent treatments in the top 10 cm soil, and those of the medium and high effluent treatments in the 10-20 cm layer, were higher than this environmental threshold, implying potential leaching loss of P in the soil profile.

### **Phosphorus saturation ratio (PSR)**

Phosphorus saturation ratio (M3PSR) calculated as the molar ratio of M3P to M3(Al+Fe) has been used as an index to predict the environmental risk soil P movement (Sims *et al.* 2002). Soils in effluent irrigated plots had significantly ( $P < 0.05$ ) higher M3PSR values than in the control. The M3PSR values in the low, medium and high effluent treatments were 17, 33, and 35 fold, respectively, higher than in the control treatment in the top 10 cm soil. Soil M3PSR value in the top 40-cm for the high effluent treatment was significantly ( $P < 0.05$ ) higher (30 fold) than in the control (Table 1).

Soil PSR describes the degree to which the potential P sorption sites were saturated with P. Sims *et al.* (2002) suggested 0.15 of M3PSR as an environmental threshold for soils with

moderate acidity and low organic matter. In our study none of the treatments had a soil M3PSR value greater than the threshold, implying a relatively low risk for P to move to deeper layers in this soil, which does not reflect the real situation as indicated by the depthwise distribution of P. In addition, M3PSR is based on concentrations of extractable soil Al and Fe without considering the concentration of Ca and Mg, which showed a significant increase with effluent irrigation. Therefore, M3PSR may not be an adequate indicator to predict the potential risk of soil P leaching in an effluent land treatment system, which provides significant levels of Ca and Mg inputs.

### **P movement monitoring**

Monitoring P in outflow streams from the land treatment system is an ultimate measurement of the system performance for P retention in soil (Tomer *et al.* 1997). Phosphorus movement through soil is generally slow because of its retention by soil components through adsorption and precipitation processes. Working life expectancy of the system for P can be monitored by degree of saturation of P in the soil profile. However, our current study demonstrates that downward movement of P in the soil profile can occur even before saturation of the upper layers occurs. Our results indicate that concentrations of soil TP, Olsen-P and M3P can all be used as indicators to monitor downward movement of P in the soil profile. Depending on the initial P status, the TP test can also provide quantitative information on P retention in a soil profile.

There were highly significant ( $P < 0.001$ ) linear relationships between Olsen P and TP ( $R^2=0.89$ ,  $n=60$ ), between M3P and TP ( $R^2=0.80$ ,  $n=60$ ), and between Olsen P and M3P ( $R^2=0.84$ ,  $n=60$ ). Olsen P and M3P levels in our current study were well over the environmental threshold values (Olsen P  $> 60 \text{ mg kg}^{-1}$ , Heckrath *et al.* 1995; M3P  $> 150 \text{ mg kg}^{-1}$ , Sims *et al.* 2002), in the upper soil layers. Both soil Olsen-P and M3P concentrations in the deeper layers reflected the level of P in the upper layers (Table 1). Between Olsen P and M3P tests, Olsen P appears to be a more sensitive indicator of effluent-derived P leaching in the soil profile (Table 1).

In recent years, measurement of bioavailability of multiple elements in M3 extraction using inductively coupled plasma (ICP) spectrometry has become increasingly acceptable in soil analysis. Using the M3 test, we may obtain information on P as well as soil exchangeable metal elements (e.g., Al, Fe, Ca, and Mg) related to P availability. The additional information may help our understanding of the ongoing change of soil chemistry that may alter the longevity of a land treatment system. On the other hand, the Olsen P test is widely used in New Zealand and most soil-testing laboratories offer it as a routine soil test. Compared with the TP and M3P tests, the Olsen P test is also relatively inexpensive and can be conducted more rapidly. Regular soil sampling and Olsen P measurement using  $60 \text{ mg P kg}^{-1}$  as a threshold can provide a satisfactory solution for monitoring the movement of P down the profile.

## **CONCLUSIONS**

After 11 years sewage effluent irrigation at the Rotorua land treatment system, soil pH has increased in the entire 100 cm profile sampled. Concentrations of M3Ca and M3Mg have increased in the soil profile in effluent irrigated plots, whereas M3Al concentration has decreased. These changes in soil pH and exchangeable cations may alter soil capacity to retain P in the long term. Soil TP, Olsen P, M3P, and M3PSR have significantly increased in the topsoil of all effluent treated plots. Although soil P accumulation and movement in the soil profile has increased with effluent irrigation rate, most effluent-derived P has accumulated in the top 40 cm. Concentrations of soil Olsen P and M3P in the medium and high effluent treatments are over environmental threshold levels in the top 20 cm, indicating that some soil P had moved downward with drainage water. Compared with M3P and M3PSR, Olsen-P appears to be a more sensitive indicator for monitoring the movement of effluent-derived P.

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## **REFERENCES**

- Allen, B.L., and A.P., Mallarino. 2006. Relationships between extractable soil phosphorus and phosphorus saturation after long-term fertilizer or manure application. *Soil Sci. Soc. Am. J.* 70: 454-463.
- APHA. 1995. *Standard Methods for the Examination of Water and Wastewater*, 19<sup>th</sup> Edition. American Public Health Association, Washington, DC, USA.
- Blakemore, L.C., P.L., Searle, and B.K., Daly. 1987. *Methods for chemical analysis of soils*. New Zealand Soil Bureau Scientific Report 80. Lower Hutt, New Zealand.
- Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk Experiment. *J. Environ. Qual.* 24: 904-910.
- Hedley, M.J., J.W.B. Stewart, and B.S. Charhan. 1982. Changes in inorganic and organic soil phosphorus fractions by cultivation practice and by laboratory incubations. *Soil. Sci. Soc. Am. J.* 46: 970-976.
- Hu, C., Zhang, T.C., Huang, Y.H., Dahab, M.F., and Surampalli, R. 2005. Effects of long-term wastewater application on chemical properties and phosphorus adsorption capacity in soils of a wastewater land treatment system. *Environ. Sci. Technol.* 39: 7240-7245.
- McLay, C.D.A., M.D. Tomer., K.M. Hopkins., C.T. Smith and A.J. Thorn. 2000. Chemical changes in a volcanic forest soil after four years of effluent irrigation. Pp. 68-78. In: *Proceedings of the 2002 Annual Conference, New Zealand Land Treatment Collective, Auckland, New Zealand.*
- Mehlich, A. 1984. Mehlich No. 3 soil test extractant: a modification of Mehlich No. 2 extractant. *Commun. Soil. Sci. Plant. Anal.* 15: 1409-1416.
- Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta.* 27: 31-36.

- Perrott, K., M. Hawke, M. Kear, and E. Burke. 2002. Phosphorus movement down the soil profile at the Whakarewarewa effluent irrigation scheme and the expected P removal lifetime of the scheme. Pp. 120-125. In: Proceedings of the 2002 Annual Conference, New Zealand Land Treatment Collective, Whangamata, New Zealand.
- Sharpley, A.N., Dependence of runoff phosphorus on extractable soil phosphorus. 1995. *J. Environ. Qual.* 24: 920-926.
- Sims, J.T., R.O. Maguire, A.B. Leyten, K.L. Gartley, and M.C. Pautler. 2002. Evaluation of Mehlich 3 as an agri-environmental soil phosphorus test for the mid Atlantic United States of America. *Soil. Sci. Soc. Am. J.* 66: 2016-2032.
- Tomer, M.D., L.A., Schipper, S.K., Knowles, W.C., Rijkse, S.D., McMahon, C.T., Smith, A., Thorn, T. Charleson, 1997. A land-based system for treatment of municipal wastewater at Whakarewarewa Forest, New Zealand FRI Bulletin 199, New Zealand Forest Research Institute, Rotorua. 28pp.
- Tozer, W., K.J., Wilkins, H., Wang, M., van den Heuvel, T., Charleson, W.B., Silvester, 2005. Using <sup>15</sup>N to determine a budget for effluent-derived nitrogen applied to forest. *Isotopes Environ. Health Stud.* 41: 13-30.
- USEPA. 1981. Process design manual – Land treatment of municipal wastewater. EPA 625/-81-013 (COEEM 1110-1-501). Center for Environmental Research Information. USEPA, Cincinnati, OH, USA.
- Wang, H., Hedley, M.J., Bolan, N.S., Horne, D.J. 1999. The influence of surface incorporated lime and gypsiferous by-products on surface and subsurface soil acidity. I. Soil solution chemistry. *Aust. J. Soil Res.* 37: 165-180.
- Zvomuya, F., C.J. Rosen., and S.C. Gupta. 2006. Phosphorus sequestration by chemical amendments to reduce leaching from wastewater application. *J. Environ. Qual.* 35:207-215.