New Zealand Journal of Agricultural Research, 2002, Vol. 45: 245–253
0028–8233/02/4504–0245 $7.00/0 © The Royal Society of New Zealand 2002

The potential for phosphorus loss in relation to nitrogen fertiliser application and cultivation

R. W. McDOWELL
R. M. MONAGHAN
AgResearch Limited
Invermay Agricultural Centre
Private Bag 50 034
Mosgiel, New Zealand

Abstract The amounts and forms of dissolved phosphorus (P) leached from undisturbed and cultivated soil in lysimeters were measured from sites that had received N fertiliser at 0, 200 or 400 kg N ha^{-1} yr^{-1} for 4 years. Soil in mini-lysimeters, 18 cm i.d. by 25 cm depth, was leached at monthly intervals over autumn and winter (500 mm total drainage) to simulate a relatively wet autumn–winter for eastern Southland (typical drainage, c. 350 mm yr^{-1}). The major form of P leached was dissolved organic P (DOP), which represented 67 and 80% of total dissolved P (TDP) losses in the undisturbed and cultivated soil treatments, respectively. Historical N inputs had little effect on the amounts of dissolved reactive P (DRP), DOP or TDP leached from the undisturbed soils. However, DRP, and to a lesser extent TDP, losses decreased as historical N fertiliser inputs increased in the cultivated soil treatment. Significantly greater losses of DRP were observed from undisturbed compared with cultivated soils. The lower DRP losses in cultivated soil were attributed to greater sorption of P during matrix flow. These results suggest that, although DRP losses are of little concern following cultivation of pastoral soils, the greater mobility and loss of DOP in drainage, in both undisturbed and cultivated soils, represents a potential risk to water quality and loss of P from the plant rooting zone. Further study to examine the bioavailability of DOP is warranted to determine its potential risk to surface water.

Keywords phosphorus; subsurface flow; cultivation; dissolved organic P; dissolved reactive P; nitrogen application

INTRODUCTION

Southland has seen a steady increase in dairy cow numbers over the past 10–15 years, which has increased pressure to produce sufficient quality pasture while minimising any potential environmental impact. With the cost of urea fertiliser decreasing, and milk returns increasing in recent years, greater attention has been given to using nitrogen (N) fertiliser as a tool for increasing pasture production throughout the growing season. The impact of increasing fertiliser N inputs on pasture production and nitrate leaching in Southland has been documented (Monaghan et al. 2000). However, little is known about the consequences of intensive management (e.g., N application to, and cultivation of, dairy pastures) on phosphorus (P) losses from these soils. This is pertinent since recent attention has focused on P as the limiting nutrient in the accelerated eutrophication of Southland freshwaters (Environment Southland 2000).

Opinions on P losses in response to N additions within the literature are conflicting. For example, Williams & Young (1994) found that P losses increased by 10% following N additions to a reseeded blanket bog. Similarly, Roberts et al. (1989) found P concentrations in drainage from an upland site in Wales increased from 0.05 to c. 0.3 mg P l^{-1}. However, Hawkins & Scholefield (1996) found that applications of N in various forms at 200 or 400 kg ha^{-1} yr^{-1} had no effect on P losses in drainage waters from grazed permanent grassland in Devon. Thus, one of our objectives was to determine the relative concentrations and loads of P in drainage waters from soils that had received 200 and 400 kg N ha^{-1} yr^{-1} in addition to a

---

A02017; published 9 December 2002
Received 11 March 2002; accepted 16 August 2002

maintenance application of P, in contrast to soils that received P alone at the same rate. A second objective was to determine the relative concentrations and loads of soluble reactive P (mainly orthophosphate) in contrast to soluble organic P; this is based on the premise that organic P forms are more mobile than inorganic P which is highly sorbed (Turner & Haygarth 2000). Our third objective was to assess P loss from the same soils if cultivated, such as for the establishment of a forage crop in preparation for later reseeding.

MATERIALS AND METHODS

Field site

The site was located in eastern Southland, 4 km west of Edendale township. Average annual rainfall for this area is c. 1000 mm, with an average annual surplus rainfall (drainage) of c. 350 mm. Fields are flat to undulating, with slopes ranging from 0 to 4°. The soil is a Fleming silt loam (mottled fragic Pallic soil), which has poor natural drainage caused by a slowly permeable B horizon at 50–80 cm depth.

Experimental treatments began in the spring of 1996 and included three rates of fertiliser N input: 0, 200, and 400 kg N ha^{-1} yr^{-1} (as urea), hereafter referred to as 0N, 200N, and 400N treatments, respectively. Each treatment was replicated three times in a randomised block design, with plot sizes of 0.09 ha. Urea applications were split, each consisting of 50 kg N ha^{-1}, with the broad aim of enhancing spring and autumn pasture growth. Thus, for 200N and 400N treatments, 50 units of urea was applied in early August and then again in early March with additional urea applications in the following one or two grazing rounds, respectively. In December of each year 450 kg of 15% potassium superphosphate ha^{-1} was applied to each plot (equivalent to c. 35 kg P ha^{-1} yr^{-1}) to maintain optimum soil Olsen P concentrations for pasture growth (c. 20–25 mg P kg^{-1}; Roberts et al. 1994).

Due to the extra pasture grown in the N-fertilised treatments, stocking rate varied between treatments to ensure that all extra pasture grown was eaten. A mixture of heifers, 2–5-year-old steers and dry cows were used to graze the plots at c. 4-weekly intervals between early August and late May. Nil winter grazing is a common management practice in this part of Southland, a strategy that has evolved mainly to protect pastures from pugging damage during the wet winter period. Plots were grazed to a constant pasture residual of c. 1500–1600 kg DM ha^{-1}.

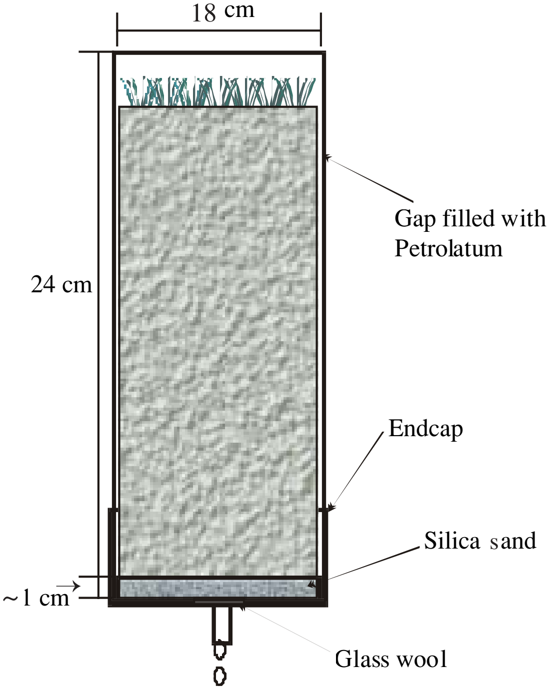


Fig. 1 Lysimeter construction.

Lysimeters

Three lysimeter cores (18 cm i.d., 24 cm deep) were taken from each replicate field plot in February 2001 to give a total of 54 lysimeters. These were then taken to an environmentally controlled (20°C during the day and 10°C at night) greenhouse at the Invermay Agricultural Centre in Mosgiel. Each lysimeter core was taken by carefully excavating around the soil and gently lowering a PVC pipe. A cutting ring was used at the lower end of the pipe to give a small gap between the intact soil core and the lysimeter casing (Fig. 1). When the pipe had been completely lowered, soil beneath it was cut with a knife to give a "clean break" at the base. Half of the lysimeter cores (nine of each treatment) were inverted and broken up by hand to simulate a cultivation event. Soil was then repacked into PVC tubes. The base of each lysimeter was packed with fine grain silica sand (nominal grain size < 70 µm) before a base cap was glued in place. In the remaining nine undisturbed lysimeters the gap between the soil core and the PVC pipe was filled with petrolatum to seal the intact cores and prevent edge-flow. In the base cap of each lysimeter an outlet hole was made to which suction could be applied when precipitation events occurred.

Drainage collection and analysis

Over 7 months, 630 mm of rainfall (reverse osmosis water, with P concentration of less than the detection limit of 0.005 mg l^{-1}) was sprinkled onto each lysimeter to simulate a wet autumn–winter period (90 mm spread over a 3-day period at the start of each month). This yielded 480 mm total drainage, which was obtained by applying 50 cm suction during each rainfall event (sufficient to drain large pores active in water flow). Suction was maintained by a vacuum pump and network linked to a monitoring water column. Between events, 7.5 mm of water was applied every 10 days to replace evaporative losses. Herbage was cut regularly and returned to each lysimeter. Cultivated soils were left fallow. Leachate samples were spiked with phenyl mercuric acetate (5 µg l^{-1}) to prevent any additional microbial growth. Following each drainage event, leachate from each of the three lysimeters within a replicate field plot were combined for P analysis so as to minimise analytical demands.

Before analysis, samples were filtered through glass fibre filter paper (samples thereafter referred to as dissolved) to remove any interference by silica sand (Whatman GF/C, nominal pore size ≤ 0.7 µm). Previous work by McDowell & Sharpley (2001a) has demonstrated that dissolved fractions filtered through 0.45 µm filter membranes are similar to those obtained from GF/C filtered samples. Samples were analysed for dissolved reactive P (DRP) and total dissolved P (TDP) after digestion by aqua regia (4:1 conc. $HCl:HNO_3$ mix, Crosland et al. 1995) using the method of Watanabe & Olsen (1965). Dissolved organic P (DOP) was calculated as the difference between TDP and DRP.

Soil analyses

Three soil samples for each lysimeter were taken to 25 cm depth at the same time as lysimeter core extraction. These samples, and samples (to the same depth) from lysimeters dissected after the last rainfall event, were air dried, ground, and sieved to < 1 mm aggregate size. Soils were then analysed for 0.5*M* bicarbonate extractable P (Olsen P) and 0.01*M* $CaCl_2$ extractable P ($CaCl_2$-P) for 30 min using soil to solution ratios of 1:20 and 1:5, respectively. The latter extraction procedure is designed to estimate P loss by subsurface flow (McDowell & Sharpley 2001b). Inorganic P was determined by extracting 1 g of soil in 25 ml of 0.5M H_2SO_4 for 16 h and total P determined after digestion of 0.5 g soil with 5 ml aqua regia (Crosland et al. 1995). Organic P was calculated as the difference between total P and inorganic P. Prior work indicated that for this soil there was no significant difference between the difference of total P and inorganic P by a single HCl extraction for inorganic P and the more time-consuming method of Saunders & Williams (1955). The concentration of P in plant unavailable forms (occluded P) was operationally defined as inorganic P minus Olsen P (plant available P), and represents occluded P associated with sesquioxide and mineral surfaces (Sharpley & Smith 1989). Soil pH was determined in water using a 1:2.5 soil to solution ratio. The total C and N concentrations of dried and ground pastures and the total C concentration of soils were determined with a LECO C/N analyser, while total P was determined following digestion of 0.25 g plant material with 5 ml aqua regia.

Statistical analyses

A design having three drainage and land uses (pasture soils before drainage [field cores], pasture soils after drainage [lysimeter cores] and cultivated soils after drainage [lysimeter cores]) by three N application rates (0N, 200N, and 400N) as a factorial, randomised block with three replicates was used as a statistical model for soil analyses. All statistical analyses were performed with SPSS version 10.0 (SPSS Inc. 1999). Each month P losses from each treatment were subjected to analysis of variance.

RESULTS

Soils

Mean soil P fractions along with total C and soil pH are given in Table 1. There was a significant effect of drainage and cultivation on all P fractions except occluded P. Similarly, the rate of N application affected all fractions except organic P. However, there appeared to be no interaction between the rate of N application and the effect of drainage or cultivation on any soil P fraction. Both drainage or cultivation and N application rate affected soil pH, presumably due to the acidification of soil by the application of N as urea and the leaching of cations in drainage (Roberts et al. 1989).

The mean concentrations of Olsen P in pasture soils after drainage was up to 30% less than before drainage. Conversely, in cultivated soils little decrease was evident, moreover a slight increase in Olsen P occurred in the 200N and 400N treatments. Inorganic P and potentially mobile P ($CaCl_2$-P; McDowell & Sharpley 2001b) mirrored this.

Up to 20% of total P was lost following leaching of the pasture soils. The maximum decrease for the cultivated soils was 14% (in the 400N treatment.) Fractionation of total P forms into total inorganic and organic P and occluded P (total inorganic P minus Olsen P), indicated that the majority of P lost was organic P. Clearly, organic P in these systems accounts for a large proportion of either P lost in drainage, readily mineralised, and/or taken up by pasture.

Drainage waters

Concentrations and loads of DRP, DOP, and TDP in drainage waters for the pasture and cultivated soils are given in Fig. 2 and 3 and Table 2. Analysis of variance indicated a significant effect of drainage and cultivation of soil previously in pasture and significant differences between the concentrations of P fractions after each drainage event (Fig. 2 and 3). For the total loads of DRP and TDP fractions after all events (Table 2) a significant difference was measured between pasture and cultivated soils after drainage. In general, more DRP and TDP was lost from the pasture soil than the cultivated soils. In the cultivated soils, a significant difference was measured between the loads of DRP from lysimeters receiving no N and those receiving 200 and 400 kg N ha^{-1} yr^{-1}. However, loads of DOP were similar, and no significant differences were noted either between pasture or cultivated lysimeters or between those receiving different rates of N.

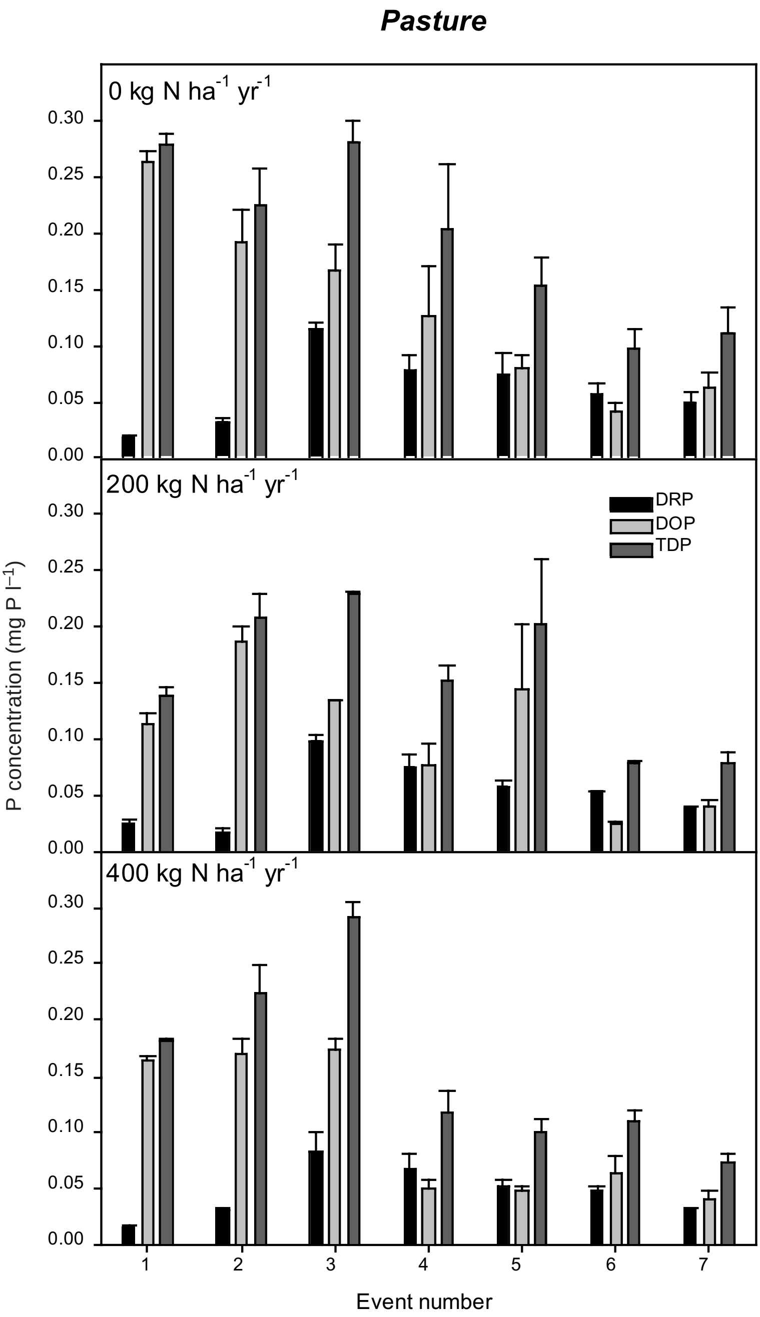
From the first drainage event to the final drainage event (Event 7), concentrations of TDP from lysimeters in pasture receiving no N were regularly in excess of the 0.1 mg l^{-1} threshold for algal growth and eutrophication (OECD 1982). In lysimeters with soils that had received 200 and 400 kg N ha^{-1} yr^{-1}, similarly high TDP concentrations were observed until Event 5. Conversely, in the cultivated soils, TDP exceeded 0.1 mg P l^{-1} only during the first three drainage events of the 0N and 200N treatments, and only for the first two drainage events of the 400N treatment.

In all cases, DOP made up the majority of TDP. This was especially the case in the cultivated soils (Table 2), where very high (>0.1 mg DOP l^{-1}) concentrations were found for the first three drainage events. This is in agreement with the loss of organic P from the soil (Tables 1 and 2). However, the greatest total load of DOP was from the pasture soil lysimeters that received no N fertiliser, while the least load of DOP generally occurred from those

Table 1 Mean, and ± 95% confidence intervals in parentheses, of soil P fractions and pH values before and after drainage events. Probability of >*F*-statistic from analysis of variance for effects of phosphorus (P) fractions and pH.

Land use and N application rate kg N ha^{-1}	Olsen P mg kg^{-1}	$CaCl_2$-P mg l^{-1}	Inorganic P mg kg^{-1}	Organic P mg kg^{-1}	Occluded P mg kg^{-1}	Total P mg kg^{-1}	pH
Pasture soil before drainage							
0	16.2 (3.1)	0.027 (0.004)	260 (3)	494 (42)	243 (4)	754 (40)	5.9 (0.1)
200	13.1 (3.3)	0.024 (0.002)	262 (88)	379 (71)	249 (88)	641 (56)	5.9 (0.1)
400	12.0 (2.7)	0.019 (0.004)	209 (9)	462 (91)	197 (7)	671 (94)	5.7 (0.1)
Pasture soil after drainage							
0	11.4 (0.5)	0.019 (0.004)	245 (30)	359 (25)	234 (30)	604 (53)	6.1 (0.1)
200	11.8 (0.9)	0.015 (0.002)	234 (24)	368 (15)	222 (24)	602 (13)	6.1 (0.1)
400	11.9 (0.6)	0.014 (0.004)	189 (3)	359 (16)	177 (2)	548 (14)	5.9 (0.1)
Cultivated soil after drainage							
0	16.0 (3.0)	0.034 (0.003)	301 (72)	354 (110)	284 (73)	655 (78)	5.7 (0.1)
200	15.4 (4.0)	0.027 (0.008)	304 (97)	317 (83)	289 (94)	621 (38)	5.6 (0.1)
400	13.5 (1.8)	0.022 (0.003)	241 (38)	333 (32)	227 (38)	574 (68)	5.5 (0.1)
F-statistic							
Drainage–cultivation	0.004	<0.001	0.049	0.003	0.062	0.002	<0.001
N application rate	0.050	<0.001	0.038	0.249	0.042	0.026	<0.001
Land use × N application rate	0.241	0.405	0.997	0.469	0.996	0.419	0.471

Fig. 2 Mean concentrations of phosphorus (P) fractions in drainage water in each drainage event from lysimeters with soil in pasture. Bars represent SEM for three replicates. DRP, DOP, and TDP are dissolved reactive P, dissolved organic P, and total dissolved P, respectively.



soils that had received the most N fertiliser. As the number of drainage events increased, the concentration of DOP decreased, presumably as organic P supply became exhausted. Conversely, DRP concentrations decreased much less over the same time period.

In most lysimeters a maximum concentration of DRP was reached after the third drainage event, presumably as the majority of mineralisation took place. In cultivated soils much less DRP was lost compared with soil with a pasture cover. This is probably caused by the greater sorption of P during

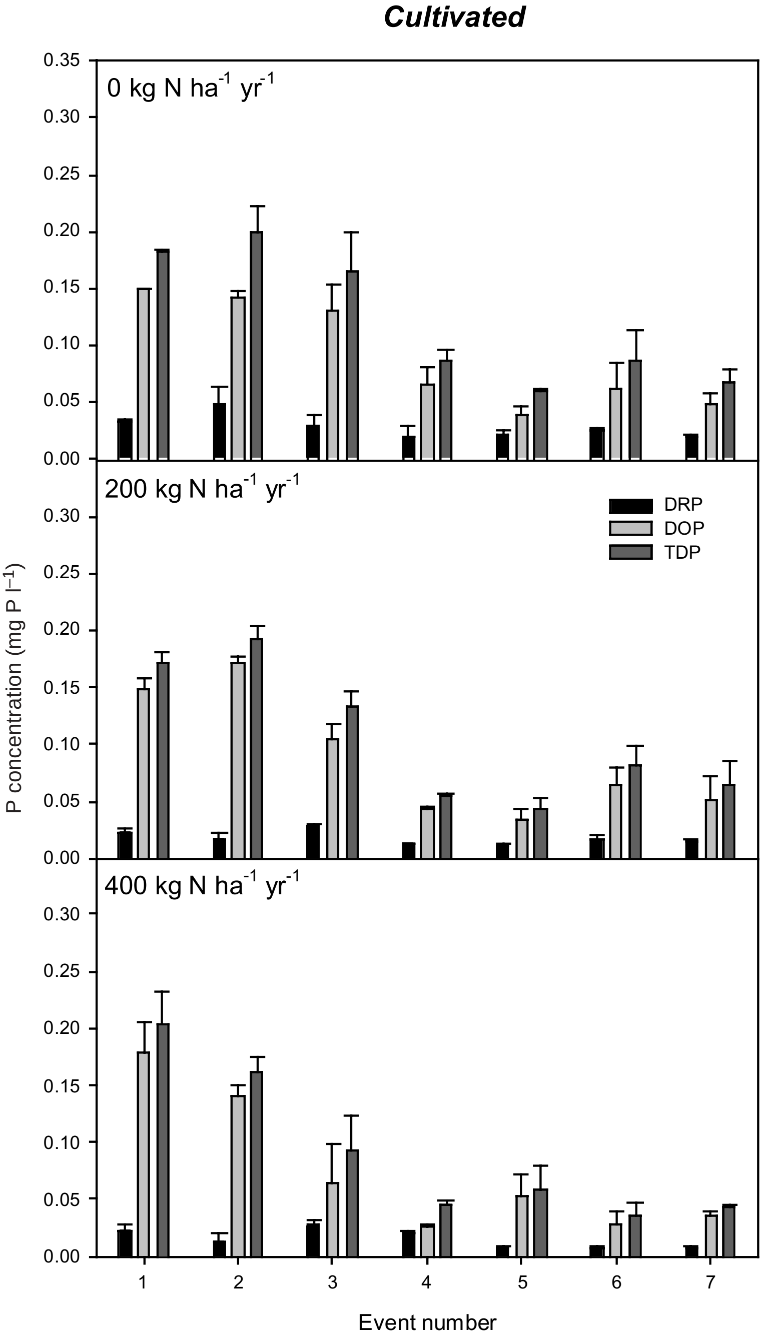


Fig. 3 Mean concentrations of phosphorus (P) fractions in drainage water in each drainage event from lysimeters with cultivated soil. Bars represent SEM for three replicates. DRP, DOP, and TDP are dissolved reactive P, dissolved organic P, and total dissolved P, respectively.

matrix flow in cultivated soil, whereas a proportion of DRP movement in pasture occurs in established pores with a history of mediating P movement and is less sorptive than the soil matrix (Jensen et al. 1998). The movement of water in preferential flow in large pores rather than as matrix flow may also help explain the discrepancy between concentrations of soil $CaCl_2$-P and DRP. For example, in Fig. 4 a regression between $CaCl_2$-P (measured for soils after the final drainage event) and DRP after the final event for cultivated soils shows a good relationship and a slope near to 1. This is well

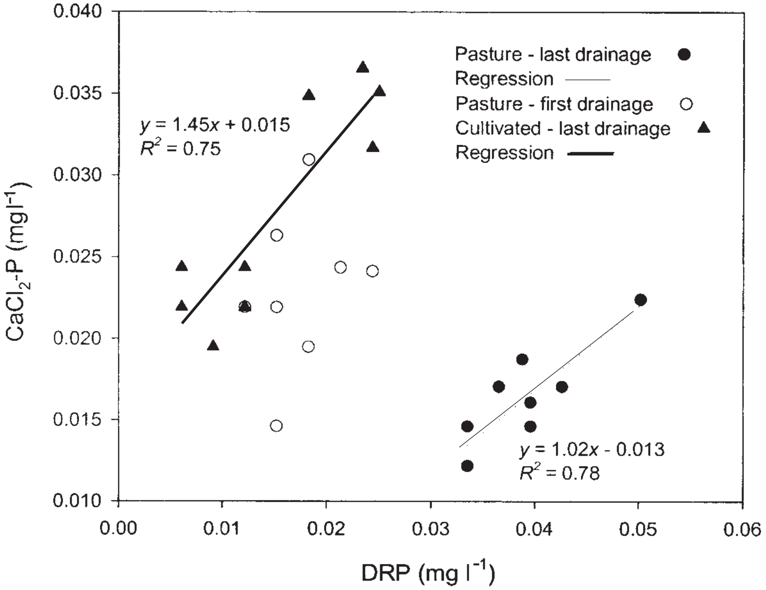


Fig. 4 Relationships between concentrations of $\mathrm{CaCl_2}$-P and dissolved reactive P (DRP) in drainage waters for pasture soils at the beginning and end of drainage and for cultivated soils at the end of drainage.

demonstrated in other work (e.g., McDowell & Sharpley 2001b). However, a good relationship with $\mathrm{CaCl_2}$-P was obtained only between $\mathrm{CaCl_2}$-P and DRP for pasture soils after the final drainage event. No such relationship occurred between $\mathrm{CaCl_2}$-P in soils before drainage and DRP in the first drainage event. This indicates the possible influence of preferential or by-pass flow is poorly estimated by $\mathrm{CaCl_2}$-P (McDowell & Sharpley 2001b).

Table 2 Mean loads (mg) of dissolved phosphorus (P) fractions in drainage waters for each treatment; dissolved reactive phosphorus (DRP); dissolved organic phosphorus (DOP); and total dissolved phosphorus (TDP). * and *** indicate significance at the $P < 0.05$ and 0.001 levels, respectively. NS, indicates not significant.

Land use and N application rate kg N ha^{-1}	DRP	DOP	TDP
Pasture			
0	0.699	1.108	1.745
200	0.599	0.897	1.399
400	0.549	0.649	1.031
Cultivated			
0	0.329	0.871	1.159
200	0.201	0.896	1.083
400	0.169	0.694	0.853
SED			
Land use	0.041***	0.155*	0.110NS
N application rate	0.051*	0.190NS	0.134NS

DISCUSSION

In a recent review of the effects of tillage on the mineralisation and leaching of phosphate, Addiscott & Thomas (2000) concluded that while tillage may increase the mineralisation of organic P, the process is probably too slow to cause large losses as occurs with nitrate. While our data lend some support to this conclusion by showing much lower concentrations and loads of DRP in drainage from cultivated soils, compared with pasture soils, the concentrations and loads of DOP were similar. Unlike DRP, which can be readily fixed and immobilised in the soil, DOP is more mobile and can readily move through the soil (Frossard et al. 1989; Chardon et al. 1997). Furthermore, while DRP is immediately bioavailable there is increasing awareness that a significant part of DOP may also be bioavailable following the release of inorganic P by phosphatase enzymes (Jannson et al. 1988).

Although mineralisation of organic P probably occurs in our soils, it is not clear from where the organic P originates; either plant residues or soil organic P, or both could be involved. In both pasture and cultivated lysimeter soils, organic P concentrations were less than in the pasture soils before drainage. This was especially the case for the pasture soils. This would suggest that it was the loss of organic P from the soil and not from plant residues (as in the cultivated soils) that was the predominant pool involved, and furthermore that this pool of organic P is highly labile (water soluble). This is consistent with the wide C:P ratio of the plant residues, as it is suggested that for ratios > 300:1 (C:P) immobilisation occurs and for ratios < 200:1 (C:P) mineralisation occurs (Fuller et al. 1956; Dalal 1977). Phosphorus from plant residues in our study would likely be immobilised (C:P ratio > 300, Table 3) before any mineralisation or release to drainage occurred. A delay in mineralisation may also help explain why DRP losses reached a maximum after the third drainage event (and then slowly decreased with additional drainage). Similar delayed reactions were also noted by Sharpley & Smith (1989) for lucerne (*Medicago sativa*), peanut (*Arachis hypopaea*), soybean (*Glycine max*) and wheat (*Triticum aestivum*) residues and by Fuller & Nielson (1957) for oat residues (*Avena sativa*).

The loss of organic P from soils can be largely mediated by soil physical disturbance, microbial action, and phosphatase enzyme activity. Both would have been highly active under the warm and moist conditions used here. Several studies have noted that such activity is further enhanced by the initial cultivation of soil (reviewed by Addiscott & Thomas 2000). However, similar amounts of organic P were lost from the pasture soils following drainage. This would suggest that the organic P lost as DOP was in a readily leachable form or that plant growth was enhancing mineralisation. While there is a suggestion of this, the data indicate that a proportion of plant-mediated mineralisation and uptake was coming from the occluded P soil pool.

Table 3 Total phosphorus (P) and carbon (C) and C:P ratio for pasture soils after drainage finished. ** and NS, indicates significance at the $P < 0.01$ level, and not significant, respectively.

Land use and N application rate kg N ha^{-1}	Total P mg kg^{-1}	Total C g kg^{-1}	C:P ratio
0	1654	415	251
200	1953	417	213
400	2126	430	202
SED			
N application rate	413NS	4.6**	64NS

The analysis of variance indicates that there was a significant effect of N application rate on occluded P, which was absent for organic P. As N application rate increases, plant growth is stimulated but becomes more limited by the amount of P available, thus P is sequestered from pools of P not ordinarily available (Magid et al. 1996). Similarly, Thien & Myers (1992) found that by adding N to a soil and incubating it for 7 days, the bicarbonate-extractable P concentration was 280% greater, showing the liberation of P from pools not previously bicarbonate extractable.

Our study only shows the potential for P loss. It does not take into account the connectivity between drainage from the soil depth studied and depths commonly used for tile drains in Southland (40–75 cm). From this point of view our data would suggest that DRP losses are of little concern from freshly cultivated soils. However, the large quantity of DOP loss (up to 85% of TDP in some cases) is of concern, due to its greater mobility in both pasture and cultivated situations. Clearly, the bioavailability of DOP loss from our soils needs to be quantified to fully understand the risk to surface waters.

CONCLUSIONS

Our results have demonstrated that increasing the rate of fertiliser N application to pasture soils causes a significant decrease in the soil Olsen P and occluded P concentrations. Although a similar decrease was found for P loads in drainage with increasing N application rate this was not statistically significant in the pasture soils, but was significant for DRP loss from cultivated soils. In all soils, and particularly the cultivated soils, DOP made up the majority of P lost due to its greater mobility compared with DRP. However, in cultivated soils DRP losses were much less than from pasture soils, presumably because of sorption during matrix flow. The potential risk of P loss from pasture soils was greater than from cultivated soils, although both lost similar amounts of DOP. The bioavailability of DOP clearly needs to be assessed to determine its potential risk to surface waterbodies.

ACKNOWLEDGMENTS

Funding for this work was provided by the New Zealand Foundation for Research, Science and Technology under contract AGRX002.

REFERENCES

Addiscott, T. M.; Thomas, D. 2000: Tillage, mineralisation and leaching: phosphate. *Soil and Tillage Research 53*: 255–273.

Chardon, W. J.; Oenema, O.; del Castilho, P.; Vriesema, R.; Japenga, J.; Blaauw, D. 1997: Organic phosphorus in solutions and leachates from soils treated with animal slurries. *Journal of Environmental Quality 26*: 372–378.

Crosland, A. R.; Zhao, F. J.; McGrath, S. P.; Lane, P. W. 1995: Comparison of aqua regia digestion with sodium carbonate fusion for the determination of total phosphorus in soils by inductively coupled plasma atomic emission spectroscopy (ICP). *Communications in Soil Science and Plant Analysis 26*: 1357–1368.

Dalal, R. C. 1977: Soil organic phosphorus. *Advances in Agronomy 29*: 83–112.

Environment Southland 2000: State of the environment report, October 2000. Invercargill, Environment Southland.

Frossard, E.; Stewart, J. W. B.; St Arnaud, R. J. 1989: Distribution and mobility of phosphorus in grassland and forest soils of Saskatchewan. *Canadian Journal of Soil Science 69*: 401–416.

Fuller, W. H.; Nielsen, D. R. 1957: The influence of straw and straw-fertilizer composts on the uptake of fertilizer phosphorus by plant. *Proceedings of Soil Science Society of America 21*: 278–282.

Fuller, W. H.; Nielsen, D. R.; Miller, R. W. 1956: Some factors influencing the utilization of phosphorus from crop residues. *Proceedings of the Soil Science Society of America 20*: 218–224.

Hawkins, J. M. B.; Scholefield, D. 1996: Molybdate-reactive phosphorus losses in surface and drainage waters from permanent grassland. *Journal of Environmental Quality 25*: 727–732.

Jansson, M.; Olsson, H.; Pettersson, K. 1988: Phosphatase: origin, characteristics and function in lakes. *Hydrobiologia 170*: 157–175.

Jensen, M. B.; Jorgensen, P. R.; Hansen, H. C. B.; Nielsen, N. E. 1998: Biopore mediated subsurface transport of dissolved orthophosphate. *Journal of Environmental Quality 27*: 1130–1137.

McDowell, R. W.; Sharpley, A. N. 2001a: Soil phosphorus fractions in solution: influence of fertiliser and manure filtration and method of determination. *Chemosphere 45*: 737–748.

McDowell, R. W.; Sharpley, A. N. 2001b: Phosphorus losses in subsurface flow before and after manure application to intensively farmed land. *The Science of the Total Environment 278*: 113–125.

Magid, J.; Tiessen, H.; Condron, L. M. 1996: Dynamics of organic phosphorus in soil under natural and agricultural ecosystems. *In*: Piccolo, A. *ed*. Humic substances in terrestrial ecosystems. Amsterdam, The Netherlands, Elsevier Science. Pp. 429–466.

Monaghan, R. M.; Paton, R. J.; Smith, L. C.; Binet, C. 2000: Nutrient losses in drainage and surface runoff from cattle-grazed pasture in Southland. *Proceedings of the New Zealand Grassland Association 62*: 99–104.

OECD 1982: Eutrophication of waters: monitoring, assessment and control. Organisation for Economic Co-operation and Development. Paris, France.

Roberts, A. M.; Hudson, J. A.; Roberts, G. 1989: A comparison of nutrient losses following grassland improvement using two different techniques in an upland area of mid-Wales. *Soil Use and Management 5*: 174–179.

Roberts, A. H. C.; Morton, J.; Edmeades, D. C. 1994: Fertiliser use on dairy farms. Hamilton, New Zealand, Dairy Research Corporation Ltd. 36 p.

Saunders, W. M.; Williams, E. G. 1955: Observations on the determination of organic phosphorus in soils. *Journal of Soil Science 6*: 254–267.

Sharpley, A. N.; Smith, S. J. 1989: Mineralization and leaching of phosphorus from soil incubated with surface-applied and incorporated crop residue. *Journal of Environmental Quality 18*: 101–105.

SPSS Inc. 1999: SPSS Version 10 user's manual. Chicago, SPSS Inc. 426 p.

Thien, S. J.; Myers, R. 1992: Determination of bioavailable phosphorus in soil. *Soil Science Society of America Journal 56*: 814–818.

Turner, B. L.; Haygarth, P. M. 2000: Phosphorus forms and concentrations in leachate under four grassland soil types. *Soil Science Society of America Journal 64*: 1090–1099.

Watanabe, F. S.; Olsen, S. R. 1965: Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. *Proceedings of the Soil Science Society of America 29*: 677–678.

Williams, B. L.; Young, M. 1994: Nutrient fluxes in runoff on reseeded blanket bog, limed and fertilized with urea, phosphorus and potassium. *Soil Use and Management 10*: 173–180.