Journal of Environmental Quality SPECIAL SECTION

PHOSPHORUS FATE, MANAGEMENT, AND MODELING IN ARTIFICIALLY DRAINED SYSTEMS

Extreme Phosphorus Losses in Drainage from Grazed Dairy Pastures on Marginal Land

Richard W. McDowell* and Ross M. Monaghan

Abstract

With the installation of artificial drainage and large inputs of lime and fertilizer, dairy farming can be profitable on marginal land. We hypothesized that this will lead to large phosphorus (P) losses and potential surface water impairment if the soil has little capacity to sorb added P. Phosphorous was measured in drainage from three "marginal" soils used for dairying: an Organic soil that had been developed out of scrub for 2 yr and used for winter forage cropping, a Podzol that had been developed into pasture for 10 yr, and an intergrade soil that had been in pasture for 2 yr. Over 18 mo, drainage was similar among all sites (521–574 mm), but the load leached to 35-cm depth from the Organic soil was 87 kg P ha^{-1} ($\sim$89% of fertilizer-P added); loads were 1.7 and 9.0 kg ha^{-1} from the Podzol and intergrade soils, respectively. Soil sampling to 100 cm showed that added P leached throughout the Organic soil profile but was stratified and enriched in the top 15 cm of the Podzol. Poor P sorption capacity (<5%) in the Organic soil, measured as anion storage capacity, and tillage (causing mineralization and P release) in the Organic and intergrade soils were thought to be the main causes of high P loss. It is doubtful that strategies would successfully mitigate these losses to an environmentally acceptable level. However, anion storage capacity could be used to identify marginal soils with high potential for P loss for the purpose of managing risk.

Many nations desire to produce more food while maintaining or improving land and water quality and profitability (Anon., 2010; Ministry of Business, Innovation, and Employment, 2013). Increasing competition for productive land is encouraging the development of marginal land. Organic (including Peat) and Podzol soils (New Zealand Soil Classification closest to Fibrists and Aquods in US Soil Taxonomy) are often defined as "marginal" (Ibrahim et al., 2013). To profitably develop these soils often requires substantial inputs of lime and fertilizer to overcome poor soil fertility and the installation of artificial drainage networks to remove excess water (Kang et al., 2013). Many Organic and Podzols soils also have few aluminum (Al) and iron (Fe) oxides, resulting in low P-sorption capacity, and a low bulk density that facilitates subsurface flow (Holden et al., 2006). Together with development factors, these characteristics promote the loss of phosphorus (P) from land to surface water, thereby contributing to the potential risk of eutrophication (Smith et al., 1995).

Many Organic and Podzol soils have been developed for intensive agriculture (e.g., dairying). For example, in the Waikato region of New Zealand there are about 94,000 ha, of which 80% have been developed for agriculture and horticulture (O'Connor et al., 2001). Worldwide, about 15% of peatlands have been drained and used for cropping, grazing, and forestry (Joosten et al., 2012). However, due to the factors reported above, high P losses are often reported. For example, P losses of 4 to 10 kg ha^{-1} yr^{-1} have been measured from Organic soils used for grazed-dairying in the Florida Everglades and polders in The Netherlands (Dunne et al., 2007; van Beek et al., 2009). Both areas have been used for dairying for many decades. Therefore, the greatest rates of oxidation and mineralization of organic matter and slumping may have already occurred. Furthermore, O'Connor et al. (2001) noted that anion storage capacity (ASC), a measure of a soil's P-sorbing Al and Fe-oxides, in peat soils that had been recently developed for agriculture in the Waikato region of New Zealand increased as the peats became more "mineral like." During the mineralization of organic matter, some organic P compounds may be released or transformed

J. Environ. Qual.
doi:10.2134/jeq2014.04.0160
Received 10 Apr. 2014.

*Corresponding author (richard.mcdowell@agresearch.co.nz).

AgResearch, Invermay Agricultural Centre, Private Bag 50034 Mosgiel, New Zealand. Assigned to Associate Editor Douglas Smith.

Abbreviations: ASC, anion storage capacity; FRP, filterable reactive phosphorus; FURP, filterable unreactive phosphorus; TFP, total filterable phosphorus; TP, total phosphorus; WSP, water-soluble phosphorus.

into orthophosphate that is bioavailable to algae (Whitton et al., 1991). This raises the potential that P losses from freshly developed soils, especially those rich in organic matter, may be initially very high. The risk of P loss may be further enhanced by adapting grazed dairy systems to marginal land in cool areas. For instance, growing a forage crop (e.g., *Brassica*) that is grazed in winter instead of winter-inactive pasture has been shown to be a source of P loss via surface runoff from mineral soils (McDowell and Houlbrooke, 2009). Although the major loss pathway from Organic and Podzol soils is likely to occur via subsurface routes, we hypothesize that P losses, irrespective of transport pathways, may be large due to much lower P sorption capacities and greater hydraulic conductivities than found in most mineral soils.

The development of marginal land for intensively grazed dairying on Organic and Podzol soils (especially if cropped and used for forage grazing in winter) may exacerbate P losses. However, losses must be measured and the contributing factors understood for losses to be mitigated. The primary objective of this paper was to therefore quantify P losses in subsurface flow (i.e., shallow drainage) from three (Organic to Podzol) soils developed out of native vegetation no longer than 10 yr ago and used for intensive dairy grazing. The soils have varying concentrations of Al and Fe, with the lowest concentration present in an Organic soil cropped for winter forage. A secondary objective was to determine if ASC values could be used as a measure to identify soils with high potential for P loss.

Materials and Methods

Site Management

The trial was conducted on a flat (<1% slope) dairy farm southeast of Invercargill, Southland, New Zealand. This region of coastal Southland receives an average of ∼1100 mm of annual rainfall spread evenly over the year. The three sites selected included a forage crop, an established pasture, and a newly established pasture site all with artificial mole-pipe drainage installed at a depth of 40 to 60 cm that discharged into open drains that were 1 m deep. The 1-ha forage crop site was located on an Otanomomo peat sown with a mixture of swede and kale in December 2011 and repeated in January 2013. The crop was grazed for 5 wk by approximately 100 dairy cows beginning in late August 2012. The established pasture site was located on a Tisbury soil that had been under pasture for 10 yr. The newly established site exhibited similar Organic subsoil properties, but during development drain clearings (dredged from the bottom of the open drain) were incorporated into topsoil. It was therefore labeled as an intergrade soil. The site was sown in pasture in spring 2011. On the other side of open drains and abutting the forage crop and established pasture sites were areas of Otanomomo Organic and Tisbury Podzol soils in undeveloped scrub. The drainage from scrubland within 50 m of the open drains was thought to show a similar drainage pattern to that in the trial sites; hence, these scrubland sites were defined as reference sites.

During the lactation season (from early September through to mid-May), pasture sites were grazed every 24 to 28 d at a stocking intensity of ∼65 cows ha^{-1} d^{-1} (farm average, 2.3 cows ha^{-1}). However, due to the poor drainage at the newly established site (intergrade soil), pasture was grazed by about 50 dry stock cattle in mid- and late November (∼15 cows ha^{-1} d^{-1}), assuming the normal grazing rotation in December 2012. Additional soil and management details for each site are given in Table 1.

Measurements and Analyses

Eight runoff plots were installed in February 2012 on the Podzol and intergrade soils but not on the organic soil because surface runoff was deemed highly unlikely. Plots consisted of 4-m long by 1-m-wide wooden boards placed 25 cm deep into the soil, leaving 5 cm above the surface. At the downslope end, the wooden board was replaced by a metal frame (140° v-shaped) of the same width and depth with an outlet that directed surface runoff into a 65-L container.

Subsurface drainage in each soil was intercepted by 64 Teflon suction cups (MacroRhizon, Rhizosphere Research Products) installed at a 45° angle to a depth of 35 cm and arranged in eight rows of eight cups spaced 7 m apart. The cups were confirmed as not sorbing orthophosphate before installation and were located above the water table, except during and immediately after some rainfall events (Fig. 1). In the Organic soil, cups were removed in December 2012 to allow for cultivation and reinstalled in early February 2013. Eight cups were also installed at each of two undeveloped or grazed reference sites under scrub on an Otanomomo Organic soil and Tisbury Podzol soil. Due to operational issues, data for the first three drainage events from the reference sites were unavailable.

Twelve soil samples were taken of the 0- to 7.5-cm, 7.5- to 15-cm, 15- to 30-m, 30- to 45-cm, 45- to 60-cm, and 60- to 100-cm soil depth layers in May 2012 and 2013 at each site. Samples were air-dried, crushed, and sieved <2 mm. Soils

Table 1. Soil and management properties.

Property	Soil type		
Soil order	Organic soil	Podzol soil	Intergrade soil
Soil name	Ontanomomo peat	Tisbury silt loam	Ontanomomo/Tisbury
NZ classification	Sphagnic Fibric Organic	Typic perch-gley Podzol	
U.S. classification	Fibrist	Aquod	
Land use	Forage crop: *Brassica napus* sp. (swede), *Brassica oleracea* L. (kale)	Established Pasture	New Pasture
Fertilizer† 2011/12	64:30:40	0:32:45	60:27:40
2012/13	91:67:26	192:19:45	192:19:45
Lime, kg ha^{-1}	300 (2011); 500 (2012)	250 (each season)	300 (2011); 500 (2012)
Grazing schedule	5 wk, from late Aug.	every 24–28 d from Sept. to May	initial light grazing in Nov. 2012, thereafter as per established pasture site

† N:P:K, kg ha^{-1}; all P fertilizer applications made in November of each year.

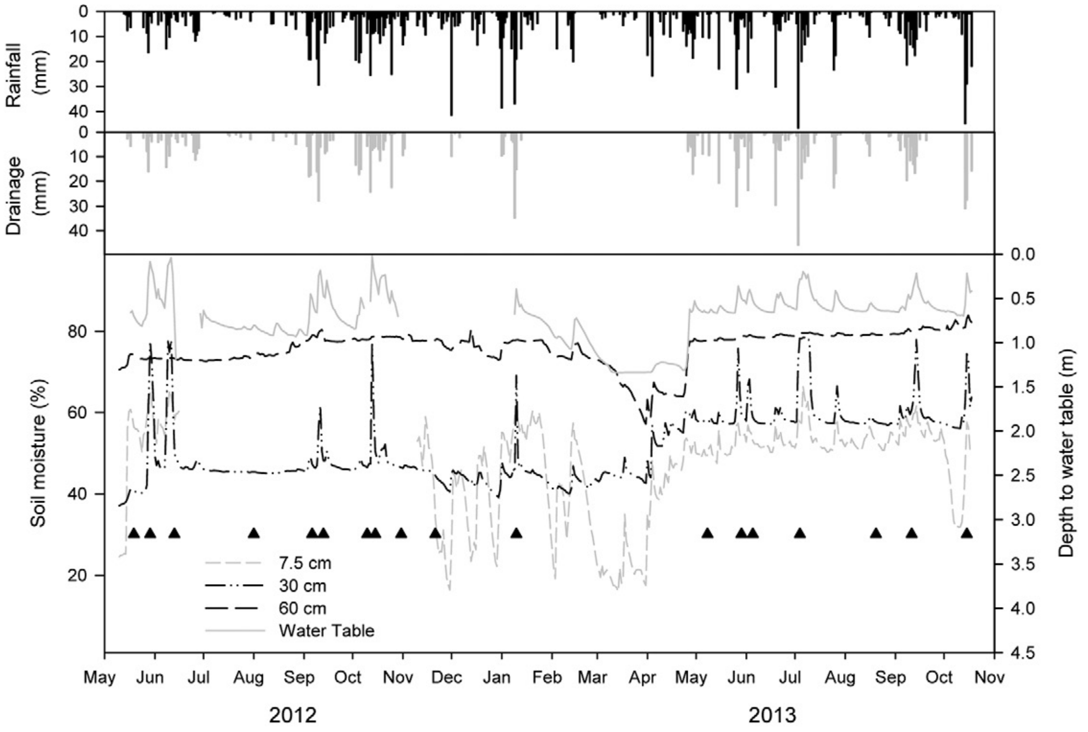

Fig. 1. Daily rainfall, drainage, volumetric water contents (at 7.5, 30, and 60 cm depths), and the depth to the water table for the period May 2012 to October 2013 for the Podzol site. Triangles indicate drainage sampling events.

were analyzed for Olsen P (Olsen et al., 1954), water-soluble P (McDowell and Condron, 2004), pH (1:2 soil/water ratio), and ASC (Saunders, 1965). Samples were also taken of the 0- to 5-cm and the 30- to 35-cm depths for bulk density, pore size distribution, and hydraulic conductivity.

Meteorological data were measured at the established pasture and forage crop sites using two Watchdog 2900ET automatic weather stations (Spectrum Technologies Inc.). Soil moisture contents were recorded via three Waterscout SM 100 soil moisture sensors installed at 5, 30, and 60 cm depth. Potential evapotranspiration was calculated using the PET function (Penman–Monteith equation) in Specware 9 pro (version 9.03). The ratio of actual to potential evapotranspiration was assumed to be 1 when soil moisture contents were between field capacity and when there was a limiting soil water deficit of 50% of plant-available water. Thereafter, this ratio decreased linearly to become 0 at the permanent wilting point (Monaghan and Smith, 2004). Drainage was calculated using a soil water balance model (Woodward et al., 2001), with input data including daily rainfall, potential evapotranspiration, and soil available water holding capacity. Drainage from the intergrade soil was calculated with data logged from the established pasture meteorological station located 300 m to the east of the site. A TruTrack WT-HR-2000 water level logger was installed to a depth of 2 m to measure the depth to ground water. Drainage at the two reference sites was assumed to be similar to that from the Organic and Podzol soils. However, some differences are likely due to land use.

Drainage and surface runoff sampling occurred on an event basis from May 2012 to October 2013, with samples collected within 2 d of each event. All samples were filtered (0.45 μm) and analyzed for filterable reactive P (FRP) within 24 h. Filtered and unfiltered samples were digested using acidified persulfate (Eisenreich et al., 1975) within a week to give total filterable P (TFP) and total P (TP), respectively. Filterable unreactive (i.e., organic) P (FURP) was defined as the difference between TFP and FRP. All P analyses were determined by the colorimetric method of Watanabe and Olsen (1965).

Summary statistics were generated with GENSTAT for Windows v13.2. For each collection date, the concentration of P fractions in drainage was calculated as the mean concentration from all suction cups. Subsurface drainage losses of P were calculated using the mean concentrations in drainage multiplied by the extended volume of total drainage since the previously sampled event. In July and December, drainage was minimal and hence was not sampled. Respective losses for these months were calculated by averaging concentrations for June and August and for November and January, respectively. All data were checked for normality and log-transformed if required. Data are presented as back-transformed means corrected for bias (Ferguson, 1987) and compared using LSD at $P < 0.05$.

Results and Discussion

Soil Properties, Rainfall, and Drainage

The quotient of Olsen P and ASC has been shown to provide a good estimate of water-soluble P (WSP) concentration and P losses in surface runoff and subsurface drainage from pasture soils (McDowell and Condron, 2004). In the Podzol soil, Olsen P and WSP concentrations were most enriched at the soil surface and generally decreased with depth (Table 2). This reflected the longer period (10 yr) of P inputs to this site and the much greater ASC throughout the profile than the Organic soil. In contrast, Olsen P concentrations were enriched throughout the Organic soil profile. Olsen P enrichment in combination with low ASC values means that the Organic soil would have little capacity to sorb additional P and P would be leached should drainage occur (Table 2). Enrichment and poor sorption also explains why Olsen P concentrations showed little increase throughout the profile in 2013 compared with 2012, but leaching increased WSP concentrations considerably. The enriched ASC in the top 45 cm of the intergrade soil is likely due to incorporation of open drain cleanings during cultivation in 2011. Soil pH was greatest in the 0 to 7.5 cm depth due to liming but was least at the recently developed Organic soil.

During 2012, all sites received less than the long-term average rainfall in winter but received much more in spring (Table 3). Rainfall during summer and spring of 2013 was near average, whereas winter 2013 was relatively wet. Maximum daily rainfall was 37 mm (Fig. 1), but intensities never exceeded 5 mm h^{-1}. Coupled with a soil bulk density that ranged from 0.2 to 0.5 g cm^{-3}, hydraulic conductivity >500 mm h^{-1}, and flat topography, very little surface runoff was measured in three events, and surface runoff was absent from the Podzol soil (Table 3).

P Concentrations and Loads in Drainage and Runoff

Filterable reactive P concentrations in drainage were greatest from the Organic soil, followed by the intergrade and Podzol soils. As a proportion of total filterable P, FRP was commonly 80

Table 2. Mean Olsen P and water soluble P concentrations, anion storage capacity, and pH values for each soil.

Site/sample depth	Soil test†							
	Olsen P		WSP		ASC		pH	
	2012	2013	2012	2013	2012	2013	2012	2013
cm	mg L^{-1}				%			
Organic soil (forage crop)								
0–7.5	11 (2)‡	17 (5)	0.12 (0.03)	0.30 (0.04)	7 (2)	2 (3)	5.3 (0.2)	5.3 (0.2)
7.5–15	7 (3)	11 (2)	0.07 (0.02)	0.15 (0.03)	5 (3)	<1 (2)	4.6 (0.1)	4.7 (0.2)
15–30	8 (4)	15 (3)	0.09 (0.02)	0.17 (0.03)	5 (2)	<1 (2)	4.6 (0.2)	4.3 (0.2)
30–45	11 (3)	12 (2)	0.11 (0.03)	0.16 (0.02)	10 (2)	<1 (2)	4.4 (0.2)	3.9 (0.1)
45–60	16 (5)	15 (2)	0.13 (0.02)	0.24 (0.03)	6 (3)	<1 (2)	4.2 (0.1)	3.8 (0.2)
60–100	15 (4)	15 (2)	0.12 (0.02)	0.13 (0.02)	<1 (2)	5 (3)	3.9 (0.2)	3.9 (0.2)
Podzol soil (established pasture)								
0–7.5	50 (7)	51 (4)	0.19 (0.03)	0.18 (0.03)	54 (5)	47 (4)	5.7 (0.3)	5.7 (0.2)
7.5–15	41 (6)	46 (3)	0.13 (0.02)	0.15 (0.02)	55 (7)	61 (6)	5.2 (0.2)	5.0 (0.1)
15–30	29 (4)	31 (3)	0.11 (0.02)	0.10 (0.02)	52 (6)	60 (5)	4.9 (0.2)	4.9 (0.2)
30–45	20 (4)	21 (4)	0.08 (0.02)	0.09 (0.02)	56 (4)	60 (4)	4.8 (0.2)	4.7 (0.1)
45–60	8 (3)	11 (2)	0.04 (0.01)	0.05 (0.02)	75 (7)	82 (8)	4.7 (0.2)	4.5 (0.2)
60–100	3 (3)	4 (1)	0.01 (0.02)	0.02 (0.02)	84 (9)	91 (9)	4.5 (0.2)	4.3 (0.2)
Intergrade soil (new pasture)								
0–7.5	17 (4)	21 (4)	0.07 (0.02)	0.10 (0.03)	43 (4)	50 (4)	6.2 (0.2)	6.6 (0.2)
7.5–15	9 (3)	16 (4)	0.04 (0.02)	0.10 (0.03)	59 (5)	62 (5)	4.6 (0.1)	4.8 (0.1)
15–30	7 (2)	8 (2)	0.04 (0.02)	0.06 (0.02)	39 (6)	39 (6)	4.2 (0.2)	4.2 (0.2)
30–45	7 (2)	11 (2)	0.04 (0.02)	0.09 (0.03)	33 (5)	25 (4)	3.8 (0.2)	4.0 (0.1)
45–60	6 (3)	8 (2)	0.04 (0.02)	0.05 (0.01)	17 (6)	28 (4)	3.6 (0.2)	3.9 (0.2)
60–100	4 (1)	7 (1)	0.03 (0.01)	0.05 (0.02)	13 (9)	21 (5)	3.7 (0.2)	3.9 (0.2)

† ASC, anion storage capacity; WSP, water-soluble P.

‡ Numbers in parentheses represent SEM.

Table 3. Three-monthly rainfall and drainage totals for each soil and surface runoff from the intergrade soil.

Months (2012–2013)	Organic soil (forage crop)†		Podzol (established pasture)†		Intergrade soil (new pasture)‡	35-yr mean rainfall§
	Rainfall	Drainage	Rainfall	Drainage	Surface runoff	
	mm					
May–July	164	133	176	140	0.6	248
Aug.–Oct.	386	258	400	278	0.9	268
Nov.–Jan.	343	80	371	110	–	233
Feb.–Apr.	223	50	248	46	0.5	292
May–July	369	321	402	359	–	248
Aug.–Oct.	268	150	300	198	–	268

† No surface runoff occurred at the forage crop and established pasture sites.

‡ Rainfall at the new pasture site obtained from established pasture meteorological station.

§ Obtained from Environment Southland's monitoring site at Garvie Road, Woodlands, Southland, New Zealand.

to 95% and was usually greatest in the Organic soil and least in the Podzol. Over time, concentrations were relatively consistent in the Podzol but decreased in the intergrade soil, perhaps due to the declining influence of P loss associated with tillage and sowing into pasture (Williams and Young, 1994). In contrast, FRP concentrations in the Organic soil were much greater in winter and spring of 2013 than in 2012. Concentrations in drainage from the Organic soil did not appear to change in 2012 after the crop was grazed but instead increased in winter events as a result of a build-up of leachable P during a dry summer and autumn (Fig. 1 and 2). Apart from one event in January, TP concentrations in surface runoff (data not shown) from the intergrade soil (flow-weighted mean, 0.06 mg L^{-1}) were lower ($P < 0.05$) than TFP in drainage (flow-weighted mean, 0.8 mg L^{-1}). Although concentrations of FRP, FURP, and particulate P were all enriched in the January event, net P losses via surface runoff were small due to the low volumes recorded (Table 4).

Losses of P from grazed pastures come from fertilizer, soil, dung, and unused forage (McDowell et al., 2007). Direct losses from fertilizer application are likely to be minimal in the Podzol and intergrade soils because few events occurred immediately after November applications, allowing fertilizer-P time to sorb

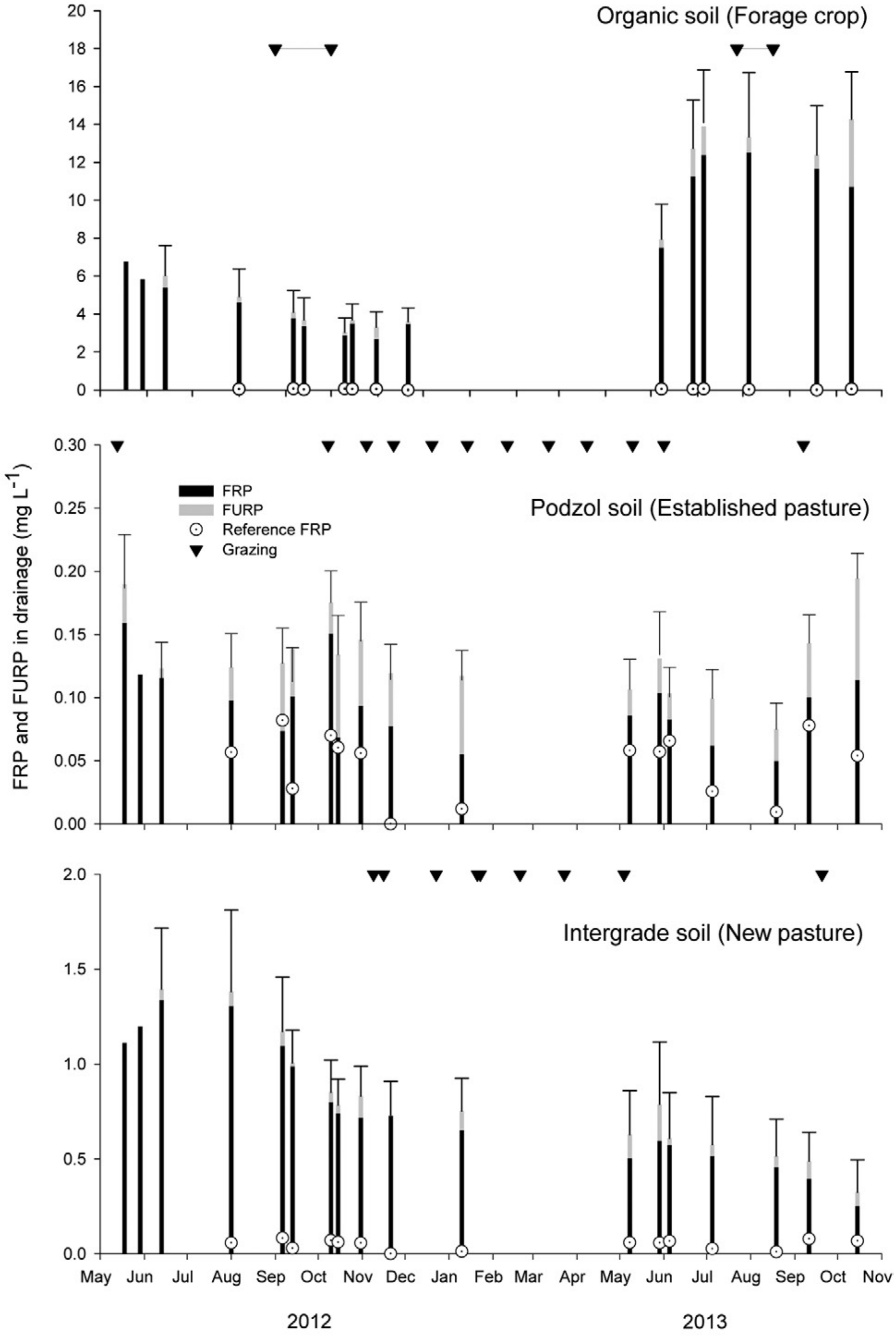

Fig. 2. Mean concentrations of filterable reactive P (FRP) and filterable unreactive P (FURP) in drainage from each soil. Error bars represent the 95% confidence interval for the sum of P fractions presented. Mean FRP concentrations in drainage at nearby reference sites are also included for comparison. Note the different scales on the *y* axis.

to the soil (Nash et al., 2004). Soil ASC for the Organic soil was much lower than for the other soils (Table 2). The resulting poor sorption provided a large pool of leachable P available for the next drainage event. However, both the Podzol and intergrade soils exhibited an ASC near 50%, but drainage P concentrations were greater in the intergrade soil. The disparity may be due to tillage-induced mineralization of organic matter that released a flush of organic P and orthophosphate. Organic anions would have also been released that would compete with P for soil sorption sites (Guppy et al., 2005). The influence of dung deposits appeared minimal because neither FRP nor FURP increased after grazing despite an estimated 58 kg of P ha^{-1} being returned to the paddock in dung (assuming an annual output of 6.1 kg P per cattle beast and a 5-wk grazing period) (Haynes and Williams, 1993).

Differences in concentrations were reflected in loads estimated as lost in drainage to 35 cm depth in each soil. Calculated total filterable loads for the May 2012 to October 2013 monitoring period were 1.7, 9.0, and 86.7 kg P ha^{-1} from the Podzol, intergrade, and Organic soils, respectively. Loads were always greater from the Organic soil than the other soils but were also greater for the intergrade soil compared with the Podzol in winter and spring when most drainage occurred (Table 4). For the 12-mo period from August 2012 to October 2013, loads of FRP from the Organic and Podzol soils were greater than those from the corresponding reference sites. The loads of FURP from the Organic soil were much greater than the reference site but were not different from the reference site for the established pasture (Podzol soil).

The loads measured from the forage crop and grazed pastures represent some of the largest loads ever recorded. Loads of up to 4 kg P ha^{-1} yr^{-1} were noted for surface runoff losses from Podzols supporting grazed dairy pastures in the West Coast region of New Zealand (McDowell, 2010). High loads from Organic soils have also been noted elsewhere. For example, Miller (1979) reported losses of up to 37 kg P ha^{-1} yr^{-1} from Organic soils in Ontario, Canada, and rates of up to 168 kg P ha^{-1} yr^{-1} were reported from Organic wetland soils in Central Florida by Reddy (1983). However, these soils were supporting heavily fertilized horticultural crops or sugarcane.

Detection of P in drainage collected at 35-cm depth may not result in losses to surface water because transport via deeper tile drains depend on the height of the water table and dilution of P-rich drainage with groundwater. For instance, Martin et al. (1997) and Sapek et al. (2007) found that although P concentrations were enriched in flooded Peat soils, losses in tile drainage only occurred when the water table dropped sufficiently to allow drainage to escape. In our soils, mole-pipe drains were placed shallow enough (40–60 cm depth) to facilitate drainage to abutting 1-m-deep open ditches, thereby avoiding the water table impairment of pasture or crop production. These drains also provided a good conduit for P to be lost to nearby surface waters.

Potential Management

With losses of >8 and 80 kg P ha^{-1} from the Podzol and Organic soils, respectively, it is clear that losses should be mitigated to avoid impairing receiving freshwater bodies. It is also clear that losses from the Organic soil represent an agronomic cost (losses equivalent to 89% of P input as superphosphate fertilizer, which currently retails at about 300–400 New Zealand dollars a tonne). Several strategies are available for mitigating P losses from grazed pasture (e.g., use of low-water-soluble P fertilizers or surface application of alum; McDowell and Nash [2012]), but the majority focus on mitigating losses via surface runoff. Although some strategies, such as maintaining a low Olsen P and sowing P-efficient crops or pasture grasses or applying less P, may decrease P losses considerably, it is unlikely that losses can be decreased to those reflecting the mean for dairy farms in New Zealand (1.9 kg P ha^{-1} yr^{-1}) (McDowell and Wilcock, 2008). This is especially the case in the Organic soil. There is some evidence to suggest that losses may decrease with time as the Organic soil becomes more "mineral like," but in the interim annual average losses of recently developed pastures are estimated to be >10 kg P ha^{-1} for at least 25 yr (Simmonds et al., 2013). In conclusion, although development of a low-ASC Organic soil such as the one studied here may be profitable, the

Table 4. Three-monthly (and total) mean loads of filterable reactive P and filterable unreactive P at each site and the LSD at the $P < 0.05$ level for the comparison of mean loads between soils.

Months	Organic soil (forage crop)		Podzol soil (established pasture)		Intergrade soil (new pasture)		LSD	
	FRP†	FURP‡	FRP	FURP	FRP	FURP	FRP	FURP
	———	———	———	kg P ha^{-1}	———	———		
May–July	7.11	2.22	0.17	0.25	1.76	0.44	1.25	0.13
Aug.–Oct.	8.17	0.74	0.26	0.11	2.42	0.14	1.73	0.25
Nov.–Jan.	2.68	0.11	0.07	0.07	0.68	0.08	1.25	0.08
Feb.–Apr.	4.60	0.47	0.04	0.01	0.26	0.08	1.12	0.12
May–July	36.42	3.95	0.28	0.11	1.96	0.30	1.45	0.60
Aug.–Oct.	16.25	4.01	0.20	0.11	0.69	0.16	2.06	0.68
Total	75.22	11.50	1.02	0.66	7.77	1.20	1.85	0.35
Total for ref. sites§	0.39¶	0.39¶	0.43#	0.31††	–	–	0.15	0.18

† Filterable reactive P.

‡ Filterable unreactive P.

§ Total for the reference sites excludes drainage during the first May–July period and assumes the same drainage as for the Organic and Podzol soils.

¶ A *t* test indicated a significance difference in drainage loads between Forage crop and reference sites for the Aug. 2012–Oct. 2013 period ($P < 0.001$).

A *t* test indicated a significance difference in drainage loads between Forage crop and reference sites for the Aug. 2012–Oct. 2013 period ($P < 0.01$).

†† A *t* test indicated no significance difference in drainage loads between Forage crop and reference sites for the Aug.–Oct. period.

rate of P loss is exceptionally high. Therefore, by identifying areas with high P loss potential with the measurement of soil ASC, development of marginal land may be better managed to avoid impairing receiving waters.

Acknowledgments

This work was partly funded by DairyNZ Ltd. and the Ministry of Business, Innovation and Employment funded Clean Water, Productive Land programme (contract C10X1006).

References

Anon. 2010. Food harvest 2020: A vision for Irish agri-food and fisheries. Department of Agriculture, Fisheries and Food, Dublin, Ireland. http://www.agriculture.gov.ie/media/migration/agri-foodindustry/foodharvest2020/2020FoodHarvestEng240810.pdf (accessed Jan. 2014).

Dunne, E.J., K.A. McKee, M.W. Clark, S. Grunwald, and K.R. Reddy. 2007. Phosphorus in agricultural ditch soil and potential implications for water quality. J. Soil Water Conserv. 62:244–252.

Eisenreich, S.J., R.T. Bannerman, and D.E. Armstrong. 1975. A simplified phosphorus analytical technique. Environ. Lett. 9:43–53. doi:10.1080/00139307509437455

Ferguson, R.I. 1987. Accuracy and precision of methods for estimating river loads. Earth Surf. Process. Landf. 12:95–104. doi:10.1002/esp.3290120111

Guppy, C.N., N.W. Menzies, P.W. Moody, and F.P.C. Blamey. 2005. Competitive sorption reactions between phosphorus and organic matter in soil: A review. Soil Res. 43:189–202. doi:10.1071/SR04049

Haynes, R.J., and P.H. Williams. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49:119–199. doi:10.1016/S0065-2113(08)60794-4

Holden, J., M.G. Evans, T.P. Burt, and M. Horton. 2006. Impact of land drainage on peatland hydrology. J. Environ. Qual. 35:1764–1778. doi:10.2134/jeq2005.0477

Ibrahim, T.G., O. Fenton, K.G. Richards, R.M. Fealy, and M.G. Healy. 2013. Spatial and temporal variations of nutrients loads in overland flow and subsurface drainage from a marginal land site in South East Ireland. Biol. Environ. Proc. R. Irish Acad. 113:1–18. doi:10.3318/BIOE.2013.13

Joosten, H., M.-J. Tapio-Biström, and S. Tol. 2012. Peatlands: Guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Food and Agriculture Organization of the United Nations and Wetlands International. http://www.fao.org/docrep/015/an762e/an762e.pdf (accessed May 2014).

Kang, S., W. Post, D. Wang, J. Nichols, V. Bandaru, and T. West. 2013. Hierarchical marginal land assessment for land use planning. Land Use Policy 30:106–113. doi:10.1016/j.landusepol.2012.03.002

Martin, H.W., D.B. Ivanoff, D.A. Graetz, and K.R. Reddy. 1997. Water table effects on Histosol drainage water carbon, nitrogen, and phosphorus. J. Environ. Qual. 26:1062–1071. doi:10.2134/jeq1997.00472425002600040018x

McDowell, R.W. 2010. Evaluation of two management options to improve the water quality of Lake Brunner, New Zealand. N. Z. J. Agric. Res. 53:59–69. doi:10.1080/00288231003606351

McDowell, R.W., and L.M. Condron. 2004. Estimating phosphorus loss from New Zealand grassland soils. N. Z. J. Agric. Res. 47:137–145. doi:10.1080/00288233.2004.9513581

McDowell, R.W., and D.J. Houlbrooke. 2009. Management options to decrease phosphorus and sediment losses from irrigated cropland grazed by cattle and sheep. Soil Use Manage. 25:224–233. doi:10.1111/j.1475-2743.2009.00231.x

McDowell, R.W., and D. Nash. 2012. A review of the cost-effectiveness and suitability of mitigation strategies to prevent phosphorus loss from dairy farms in New Zealand and Australia. J. Environ. Qual. 41:680–693. doi:10.2134/jeq2011.0041

McDowell, R.W., D. Nash, and F. Robertson. 2007. Sources of phosphorus lost from a grazed pasture receiving simulated rainfall. J. Environ. Qual. 36:1281–1288. doi:10.2134/jeq2006.0347

McDowell, R.W., and R.J. Wilcock. 2008. Water quality and the effect of different pastoral animals. N Zeal. Vet. J. 56:289–296.

Miller, M.H. 1979. Contribution of nitrogen and phosphorus to subsurface drainage water from intensively cropped mineral and organic soils in Ontario. J. Environ. Qual. 8:42–48. doi:10.2134/jeq1979.00472425000800010011x

Ministry of Business, Innovation, and Employment. 2013. Business growth agenda: Progress report 2013. Ministry of Business, Growth and Employment, Wellington, New Zealand. http://www.mbie.govt.nz/pdf-library/what-we-do/business-growth-agenda/bga-reports/bga-progress-report.pdf (accessed Jan. 2014).

Monaghan, R.M., and L.C. Smith. 2004. Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils: II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. N. Z. J. Agric. Res. 47:417–428. doi:10.1080/00288233.2004.9513610

Nash, D., M. Hannah, L. Clemow, D. Halliwell, B. Webb, and D. Chapman. 2004. A field study of phosphorus mobilisation from commercial fertilisers. Aust. J. Soil Res. 42:313–320. doi:10.1071/SR03062

O'Connor, M.B., R.D. Longhurst, T.J.M. Johnston, and F.N. Portegys. 2001. Fertiliser requirements for peat soils in the Waikato region. Proc. N. Z. Grassl. Assoc. 63:47–51.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. United States Department of Agriculture Circular No. 939. United States Government Print Office, Washington, DC.

Reddy, K.R. 1983. Soluble phosphorus release from organic soils. Agric. Ecosyst. Environ. 9:373–382. doi:10.1016/0167-8809(83)90022-1

Sapek, A., B. Sapek, S. Chrzanowski, and J. Jaszczyński. 2007. Mobilization of substances in peat soils and their transfer within the groundwater and into surface water. Agron. Res. 5:155–163.

Saunders, W.M.H. 1965. Phosphate retention by New Zealand soils and its relationship to free sequioxides, organic matter and other properties. N. Z. J. Agric. Res. 8:30–57. doi:10.1080/00288233.1965.10420021

Simmonds, B., R.W. McDowell, and L.M. Condron. 2013. Factors that influence phosphorus loss with the development of organic soils. In: L.D. Currie and C. Christensen, editors, Occasional report no. 26. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. http://www.massey.ac.nz/~flrc/workshops/13/Manuscripts/Paper_Simmonds_2013.pdf (accessed Jan. 2014).

Smith, R.V., S.D. Lennox, C. Jordan, R.H. Foy, and E. McHale. 1995. Increase in soluble phosphorus transported in drainflow from a grassland catchment in response to soil phosphorus accumulation. Soil Use Manage. 11:204–209. doi:10.1111/j.1475-2743.1995.tb00957.x

van Beek, C.L., C. van der Salm, A.C.C. Plette, and H. van de Weerd. 2009. Nutrient loss pathways from grazed grasslands and the effects of decreasing inputs: Experimental results for three soil types. Nutr. Cycling Agroecosyst. 83:99–110. doi:10.1007/s10705-008-9205-z

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and NaHCO3 extracts from soil. Soil Sci. Soc. Am. Proc. 29:677–678. doi:10.2136/sssaj1965.03615995002900060025x

Whitton, B.A., S.L.J. Grainger, G.R.W. Hawley, and J.W. Simon. 1991. Cellbound and extracellular phosphatase activities of cyanobacterial isolates. Microb. Ecol. 21:85–98. doi:10.1007/BF02539146

Williams, B.L., and M. Young. 1994. Nutrient fluxes in runoff on reseeded blanket bog, limed and fertilised with urea, phosphorus and potassium. Soil Use Manage. 10:173–180. doi:10.1111/j.1475-2743.1994.tb00482.x

Woodward, S.J.R., D.J. Barker, and R.F. Zyskowski. 2001. A practical model for predicting soil water deficit in New Zealand pastures. N. Z. J. Agric. Res. 44:91–109. doi:10.1080/00288233.2001.9513464