Potential water quality impact and agronomic effectiveness of different phosphorus fertilisers under grazed dairying in Southland

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Abstract
Phosphorus (P) loss from land is a central factor in poor surface water quality in Southland. Much loss of P can occur if surface runoff occurs soon after the application of highly water soluble P fertilisers (e.g. superphosphate). Three P fertilisers (superphosphate, serpentine super, and a Ca-phosphate) of different water solubilities were applied (30 kg P/ha in spring) to a grazed dairy pasture, and the relative agronomic effectiveness and P losses determined. Across all 3 years, there were no differences in annual pasture production among the different types of P fertilisers. For 2 years out of 3, significantly more P was lost via surface runoff from the superphosphate-treated plots than from plots treated with either serpentine super or the Ca-phosphate. On average, the use of low water soluble Ca-P fertiliser decreased P losses by an average of 47% over the 3 years. It is currently recommended that to decrease P losses associated with fertiliser, applications should be timed when runoff events are unlikely for at least 3 weeks following application. If this runoff cannot be avoided, or to ensure P losses are as low as possible, the use of a low water soluble P product may be of benefit.
Key words: Surface runoff, phosphate fertilisers, phosphorus loss, superphosphate.

Introduction
The loss of phosphorus (P) from land to surface waters can result in eutrophication. Sources of P loss within a typical grazed paddock can be categorised as from: soil, denuded plant material, animal excreta and fertiliser (McDowell *et al*. 2007). Losses from fertiliser have been estimated to be <10% of total load (McDowell *et al*. 2007), but can greatly exceed this fraction if rainfall occurs soon after application. Previous work has indicated that the period of increased potential loss for superphosphate is about 21 days (Nash *et al*. 2004). The mechanism of loss is via surface runoff (hereafter termed runoff) and relies on P being water soluble. If a fertiliser is less water soluble, there is less opportunity for P to be lost via runoff. Instead, P will be gradually taken up by soil sorption sites. Hence, an ideal P fertiliser would minimise losses, but maximise uptake by soil and plant. Although previous work using rainfall simulation has identified some factors important in decreasing P losses from fertilisers (McDowell & Catto 2005), uncertainty surrounds their applicability in a grazed field situation. This paper outlines an assessment of pasture production and P losses in runoff from a grazed dairy pasture in Southland after the application of three P fertiliser products with different water solubility.

Materials and Methods
Runoff trial
The Tussock creek site is located 20 km northeast of Invercargill on a Pukemutu silt loam (Mottled Fragic Pallic soil; anion storage capacity (ASC) = 29%). The site has a slope of 2^{o} and has been used for dairying for about 15 years (farm average 3.0 cows/ha). During May, 2008, 24 plots were installed. Each plot was bounded by three, 3 m long, and 25 mm thick, wooden boards that were dug 125 mm into the ground, leaving 25 mm above the soil surface. The boards were arranged in a open square while the fourth, downslope side consisting of a v-shaped metal border, which housed a 2.5 cm wide hole at the soil surface that was attached to a PVC pipe and drained all surface runoff from each rainfall event into two, 70-L containers buried beneath the level of the plots up to 30 m away.

The trial had four treatments each with six replicates: control, superphosphate, serpentine super and a Ca-phosphate (Ca-P) supplied by Ballance Agri-Nutrients. The respective water soluble P concentrations of the fertilisers were 85, 34 and 12 g/kg, while total P concentrations were 100, 88, and 83 g/kg. Fertilisers were applied at 30 kg P/ha in October, 2008 (and 30 kg P/ha inadvertently by the farmer in February, 2009), and 30 kg P/ha was applied in September 2009 and 2010. The rate of application and timing reflected typical farmer practice to maintain optimal soil Olsen P for pasture production as determined via the nutrient budgeting programme, Overseer® (Wheeler *et al*. 2007). Soil sampling to 7.5 cm depth of each plot was conducted in August, 2009, 2010 and 2011 for analysis of Olsen P, water extractable P (WSP; McDowell & Condron 2004) and anion storage capacity.

Samples of runoff were filtered through a 0.45 µm

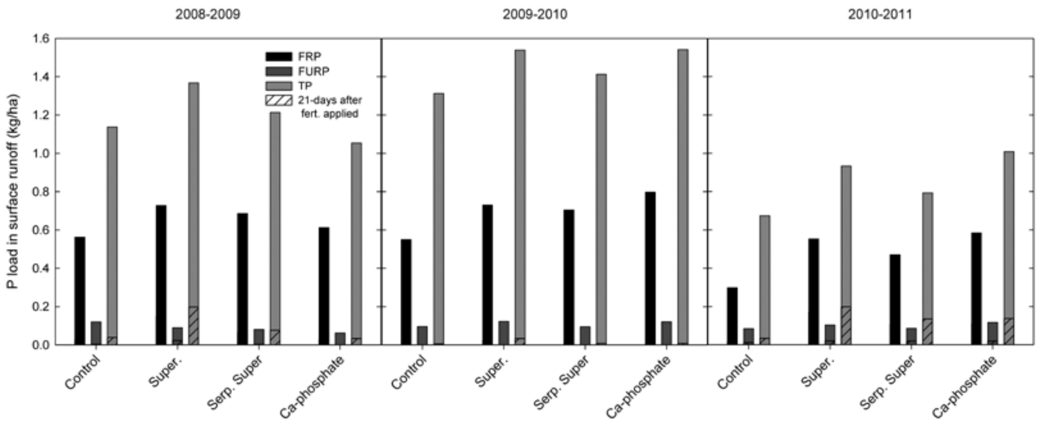

Fig. 1. Mean annual loads and the loads during the 21 days following fertiliser application (hatched bars) in surface runoff of filterable reactive phosphorus (FRP), filterable unreactive P (FURP), and total P (TP) for each year.

Table 1. Flow-weighted mean P concentrations (mg/L) for each year and within 21 days of fertiliser application of filterable reactive phosphorus (FRP), filterable unreactive P (FURP), particulate P (PP), and total P (TP). The least significant difference (LSD_{05}) at the *P*<0.05 level is given along with the *F*-statistic for comparison of treatment means (bold if significant).

Year / treatment	--------------- Annual means (mg/L) ---------------				--- Means within 21 days of fertiliser application (mg/L) ---			
	FRP	FURP	PP	TP	FRP	FURP	PP	TP
2008/2009								
Control	0.777	0.162	0.686	1.626	1.293	0.139	0.198	1.629
Super-10	1.177	0.137	0.882	2.196	6.883	0.738	1.627	9.249
Serpentine super	0.873	0.108	0.775	1.757	3.227	0.181	0.406	3.815
Ca-phosphate	0.973	0.108	0.717	1.798	1.879	0.167	0.259	2.305
All LSD_{05}	0.255	0.053	0.395	0.367	3.133	0.428	0.688	3.442
All F-statistic	**0.028**	0.129	0.620	**0.015**	**0.006**	**0.022**	**<0.001**	**<0.001**
Ex. Control LSD_{05}	0.295	0.049	0.345	0.332	3.664	0.495	0.788	4.023
Ex. Control F-statistic	0.155	0.341	0.348	**0.009**	**0.030**	**0.040**	**0.005**	**0.006**
2009/2010								
Control	0.429	0.074	0.491	1.023	0.200	0.025	0.096	0.320
Super-10	0.616	0.102	0.553	1.292	1.320	0.045	0.543	1.910
Serpentine super	0.575	0.074	0.510	1.159	0.390	0.023	0.073	0.490
Ca-phosphate	0.585	0.087	0.458	1.153	0.670	0.021	0.098	0.790
All LSD_{05}	0.134	0.044	0.103	0.183	1.076	0.038	0.285	1.178
All F-statistic	0.039	0.500	0.302	**0.049**	0.180	0.536	**0.006**	**0.045**
Ex. Control LSD_{05}	0.145	0.047	0.114	0.195	1.266	0.043	0.334	1.386
Ex. Control F-statistic	0.823	0.454	0.235	0.260	0.303	0.429	**0.014**	0.102
2010/2011								
Control	0.243	0.058	0.247	0.541	0.220	0.146	0.079	0.450
Super-10	0.476	0.087	0.256	0.797	3.180	0.367	0.116	3.660
Serpentine super	0.390	0.071	0.211	0.656	1.930	0.344	0.148	2.420
Ca-phosphate	0.492	0.100	0.291	0.849	2.090	0.353	0.118	2.560
All LSD_{05}	0.116	0.022	0.102	0.212	0.757	0.160	0.111	0.819
All F-statistic	**<0.001**	**0.023**	0.455	**0.027**	**<0.001**	**0.027**	0.644	**<0.001**
Ex. Control LSD_{05}	0.103	0.251	0.114	0.216	0.900	0.183	0.126	0.966
Ex. Control F-statistic	0.058	0.253	**0.024**	**0.052**	**0.023**	0.951	0.846	**0.035**

membrane and analysed for filterable reactive P (FRP; also called dissolved reactive P) and, after persulphate digestion, total filterable reactive P (TFP; also called total dissolved P). An unfiltered sample was also digested yielding total P (TP). Fractions defined as filterable unreactive (largely organic) P (FURP) and particulate P (PP) were determined as the difference between TFP and FRP and TP less TFP, respectively. Annual P loads (kg P/ha) were calculated as the product of P concentration and the volume of runoff. Due to differing volumes of surface runoff between plots, treatments were compared using an ANOVA of flow-weighted mean concentrations derived from the quotient of load and flow during the year for each plot. An additional ANOVA was performed on flow-weighted mean concentrations for events during the 21-day period(s) after application of treatments.

Agronomic trial

A pasture production trial of the same fertilisers was conducted at AgResearch-Woodlands (15 km east of Invercargill) on a Waikiwi Typic Firm Brown Soil (ASC = 60%) with an Olsen P concentration <10 mg/L. New pasture species were established in the autumn of 2008 by direct drilling ('Bealey', 'Alto' ryegrass and 'Sustain', 'Apec' white clover). Plots (3 × 1 m in size) were established with 15 replicates of each fertiliser applied annually in September at a rate of 50 kg P/ha. Base fertilisers (including N) were applied as required. Pasture production was measured by rising plate meter, with herbage trimmed off immediately afterward. Following trimming, trials were re-plated to give residual herbage values. In addition, trial plots were plated before the treatments were applied to give a measure of uniformity.

Results and Discussion

Runoff trial

The mean concentrations of Olsen P at the beginning of the trial was 44 mg/L, but had increased by the end of the trial to between 50 mg/L in the serpentine super treatment and 58 and 59 mg/L in the Ca-P and superphosphate treatments, respectively. A similar difference was noted between treatments for WSP at the end of the trial.

Rainfall during the trial averaged 1100 mm annually, producing between 26 and 42 runoff events (totalling 66 to 119 mm runoff). Compared to the annual runoff, little runoff occurred during the 21 days after fertiliser application (2, 1 and 6 mm in each respective year). Variation in flow volumes among plots (reflected by a coefficient of variation commonly >50% year-on-year) required the analysis of flow-weighted mean concentrations rather than loads. Concentrations of both PP and FURP did not vary among treatments in any year. There was no difference between the control and either serpentine super or Ca-P treated plots. However, more TP was lost from superphosphate treated plots than the control or serpentine super treated plots in 2008/2009, and from superphosphate compared to the control, serpentine super or Ca-P treatments in 2010/2011 (Table 1). In 2009/2010, all fertiliser products lost more FRP than the control, but there was no difference in losses between fertilisers.

During 2008/2009, an additional 30 kg P/ha of superphosphate was mistakenly applied to all the plots

Table 2. Seasonal and annual production results from (kg DM/ha) Woodlands. The least significant difference (LSD_{05}) at the *P*<0.05 is given along with the *F*-statistic for fertiliser comparison (bold if significant)

	2008/2009				2009/2010			
Treatment	Spring	Summer	Autumn	Total	Spring	Summer	Autumn	Total
Control	4795	5677	2071	12543	5200	5552	1988	12739
Super 10	5006	5937	2122	13064	5519	5721	2191	13431
Serp Super	4993	5937	2118	13047	5463	6079	2170	13713
Ca-P	5118	6071	2200	13389	5444	6147	2255	13846
LSD_{05}	304	393	162	669	311	364	183	610
F-statistic	0.433	0.765	0.217	0.469	0.154	**0.042**	0.737	0.121
	2010/2011				3 year total			
Treatment	Spring	Summer	Autumn	Total	Spring	Summer	Autumn	Total
Control	4365	4652	2924	11942	14360	15881	6983	37224
Super 10	5703	6579	3490	15772	16228	18237	7803	42268
Serp Super	5541	6709	3743	15993	15996	18725	8032	42753
Ca-P	5454	6468	3546	15469	16016	18687	8001	42704
LSD_{05}	283	379	169	644	578	843	346	1518
F-statistic	0.414	0.572	**0.018**	0.467	0.429	0.691	0.238	0.571

by the farmer. Although neither requested nor desired, the application demonstrated two points: 1) that the application of 60 kg P/ha to fertiliser-treated plots resulted in loads that were only 20% greater than lost from the control (30 kg P/ha for 2008/2009) treatment, which was probably related to 2) the application during late summer (early March) when runoff was unlikely.

Previous work using rainfall simulation on soil turves indicated that the risk of P losses from fertiliser is much greater than unfertilised turves for at least 21 days after application (McDowell & Catto 2005). In Figure 1, hatched bars indicate the relative proportion of annual P load lost in the 21 days following P application. Twenty, 3, and 31% of annual FRP losses occurred during this time in the superphosphate treatment for the 2008/2009, 2009/2010 and 2010/2011 years, respectively. Proportions were similar for TP in the superphosphate treatment, whereas for FRP and TP the proportion was much less in other treatments. As a contrast, the depth of runoff in the 21-day period was 2–5% of total runoff, which means that in order to contribute between 3–31% of the load, concentrations were much greater than during the rest of the year. Given that the potential for P loss declines exponentially with time since P fertiliser application (McDowell & Catto 2005), it is not surprising that a surface runoff event shortly after treatment application in 2008/2009 and 2010/2011 yielded a much greater difference between treatments for all P fractions than for the whole year (Table 1). Furthermore, differences were more pronounced for superphosphate than for other P-fertilisers when the control treatment was excluded from the analysis. There was a gap of 13, 3 and 7 days between application and runoff in the 2008/2009, 2009/2010 and 2010/2011 years, respectively, but little runoff occurred in the 2009/2010 year resulting in much lower losses.

In addition to the time since fertiliser was last applied, it is also known that P losses are exacerbated by the presence of grazed animals via excretal returns, soil treading damage or the poor utilisation of pasture (McDowell *et al*. 2007). A multiple regression of runoff volumes (R; in L), the number of days since fertiliser was applied (F) or grazing events (G), fertiliser treatment (T; coded 1 through 4 for Control, Ca-P, Serpentine Super and Superphosphate, respectively), and time of year (D, January 1 = 1), accounted for a total of 52% of the variation in TP loads. The majority (*c*. 40%) of TP was accounted for by R, followed by F (9%), G (2%), D (1%) and T (1%). The predictive equation was:

$$\text{TP load (event mg)} = 1.095R - 0.0305F - 0.07G - 0.035D + 3.4T + 1424$$

Agronomic trial

The application of P fertilisers resulted in no increase in pasture production in 2008/2009, but did increase pasture production in 2009/2010 and 2010/2011. There were no differences in annual pasture production as a result of the different P fertiliser formulations (Table 2). There were some seasonal differences between the P formulations with Ca-P producing more pasture production in the summer of 2009/2010 than superphosphate, while in the autumn of 2010/2011 the superphosphate application resulted in less pasture production than all other P fertilisers except Ca-P (Table 2).

Conclusions and recommendations

The application of P fertilisers at maintenance rates of 30 kg P/ha/yr was shown to increase the annual loss of TP in a grazed dairy pasture in Southland, especially during the 21-day period after application. The TP losses associated with superphosphate application accounted for an average of 26% more P loss than the control. However, compared to superphosphate, losses from serpentine super and Ca-P (a new low water-soluble P fertiliser) decreased mean FRP and TP concentrations in surface runoff for 21 days after application by up to 91% (average over 3 years = 49% for FRP and 46% for TP). The annual decrease compared to superphosphate was up to 70%, but averaged over the 3 years of the trial at 33% for FRP and 47% for TP. A multiple regression of the Tussock Creek data indicated that flow volume accounted for a significant proportion of variance in P loads, followed by the time between application and runoff. From an agronomic viewpoint, pasture production was maintained similarly by all of the P fertilisers tested. Hence, it is recommended that to decrease P losses associated with highly water soluble P fertiliser (e.g. superphosphate), applications should be timed when runoff events are unlikely for at least 21 days after application, or at least of low volume. However, if this cannot be avoided, or to ensure P losses are as low as possible, the use of a low water-soluble P product may be of benefit. While reactive phosphate rock (RPR) has been recommended to be used in high rainfall (>800 mm/year) and low pH (<5.8) areas (Sinclair *et al*. 1993; McDowell *et al*. 2010), there is a requirement for low water-soluble P products for areas not suitable for RPR use.

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