



Short communication

Treatment of pasture topsoil with alum to decrease phosphorus losses in subsurface drainage

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ABSTRACT

Phosphorus loss from land can impair surface water quality. Losses *via* subsurface flow can be substantial, but most strategies to mitigate P losses focus on surface runoff. Aluminium sulphate (alum) was applied at 25 and 50 kg Al ha⁻¹ to a flat, podzol soil under pasture regularly grazed by dairy cattle. Over a year, losses of filtered (<0.45 μm) reactive P (FRP) and total filtered P (TFP) intercepted at 35-cm depth by Teflon suction cups were c. 0.6 and 1.0 kg P ha⁻¹, respectively for the control treatment. The 50 kg Al ha⁻¹ treatment decreased FRP and TFP by 26 and 27%, respectively: no significant difference to the control was noted for alum applied at 25 kg Al ha⁻¹. The cost-effectiveness was estimated at 190–952 USD kg⁻¹ P mitigated. While more cost-effective strategies should be practised first, surface applying alum may provide an option where sub-surface P losses must be lowered further especially if applied to a small area of high P loss.

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1. Introduction

The loss of P from land can impair surface water quality *via* eutrophication (Carpenter et al., 1998). In a review of New Zealand land uses, McDowell and Wilcock (2008) found that P losses were enriched from dairy-farmed land. Under certain soil physical (e.g. low slope) or chemical (e.g. poor P sorption capacity) conditions, subsurface flow can be a more important mechanism of P loss than surface runoff. In the New Zealand soil classification (Hewitt, 1998), many podzol soils are prone to subsurface P losses (*viz.* leaching) due to a combination of high hydraulic conductivity, poor anion storage capacity (ASC: an indicator of P sorption capacity; McDowell and Condon, 2004), and macropore flow especially if intercepted by artificial drainage (Monaghan and Smith, 2004).

Strategies to mitigate P loss from dairy systems have focused on minimising losses by surface runoff. However, there are far fewer strategies to mitigate P losses *via* subsurface flow. In a review of potential technologies to remove P in drainage water, Buda et al. (2012) highlighted several structures that filter-out P from drainage water such as flue gas desulfurization gypsum ditch filters (Bryant et al., 2012), the use of iron oxides in and around tile drains (McDowell et al., 2008; Chardon et al., 2012), and steel slag filter beds to remove P from drainage water at catchment outlets

(Penn et al., 2012). However, McDowell and Nash (2012) also noted that as scale and complexity of flow-paths increased the cost-effectiveness of strategies to mitigate P loss decreased. Strategies that aim to decrease P loss most cost-effectively focus on decreasing the availability of P at source; for example, by decreasing soil Olsen P concentration (McDowell and Nash, 2012).

In many soils, especially those used for intensive pastoral grazing, maintaining soil Olsen P as low as agronomically possible may still lead to substantial P loss *via* subsurface flow due to poor P sorption capacity and continual inputs from excretal returns (McDowell and Nash, 2012). One amendment, aluminium sulphate (alum) has been used to decrease the potential for P loss in surface runoff (e.g. McDowell and Norris, 2014). Alum was therefore tested to determine if it could also be used to cost-effectively decrease P loss in subsurface flow from a grazed pasture.

2. Methods and materials

2.1. Preliminary leaching trial

A preliminary leaching trial was conducted using a Tisbury silt loam soil (Typic Perch-gley podzol in the New Zealand soil classification – equivalent to an Aquod in US Taxonomy; Hewitt, 1998) from pasture-based grazed dairy farm >10 years old. Soil was sampled of the 0–7.5-cm depth, broken up by hand to remove plant roots and passed through a 2-mm sieve. A sub-sample was dried and analysed for ASC (Saunders, 1965) as a measure of the soil's

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Table 1

Soil test values with depth at the field site. The least significant difference at the $P < 0.05$ level of significance (LSD_{05}) is given for the comparison of means for each depth.

Depth (cm)	Soil test			
	Olsen P (mg L^{-1} soil)	WSP (mg L^{-1} extract)	ASC (%)	pH
0–7.5	51	0.18	47	5.7
7.5–15	46	0.15	61	5.0
15–30	31	0.10	60	4.9
30–45	21	0.09	60	4.7
45–60	11	0.05	82	4.5
60–100	4	0.02	91	4.3
LSD_{05}	5	0.03	12	0.3

P-sorbing Al and Fe oxide concentration, Olsen P concentration (Olsen et al., 1954) and water extractable P (WEP; McDowell and Condon, 2004). Eighty grams of field moist soil was placed inside 100-cm³ syringes (3-cm diameter) with some glass wool at the end to prevent soil loss. Alum was applied at rates of 0, 32, 64, 160, 320,

640, 1600 kg ha⁻¹, equivalent to 0, 5, 10, 25, 50, 100, 250 kg Al ha⁻¹ to the surface of 6 replicates each – yielding 42 syringes in total. Soils were leached with 40-mm of deionised over 8 h, 2, 15, 22, 29, 37 and 44 days after alum was applied. Leachate samples passed through a 0.45 μm filter and analysed for filtered reactive P (FRP) and pH (1:2 soil to water ratio).

2.2. Field trial

Alum was applied in October 2012 at 0, 25 and 50 kg Al ha⁻¹ to the same paddock used to collect the Tisbury silt loam (Table 1). The site had a slope of <1% and artificial drains installed at 70–80-cm depth to facilitate drainage to adjacent 1-m deep open channel drains. The paddock received regular annual fertiliser of a single application of 32 kg P ha⁻¹, 45 kg K ha⁻¹ and 100 kg Ca ha⁻¹ (as lime) as part of the wider dairy farm’s milking platform in December. Split applications of 30 kg N ha⁻¹ as urea were applied in September, November, January and March. Paddocks on the milking platform were rotationally grazed every 24–28 days

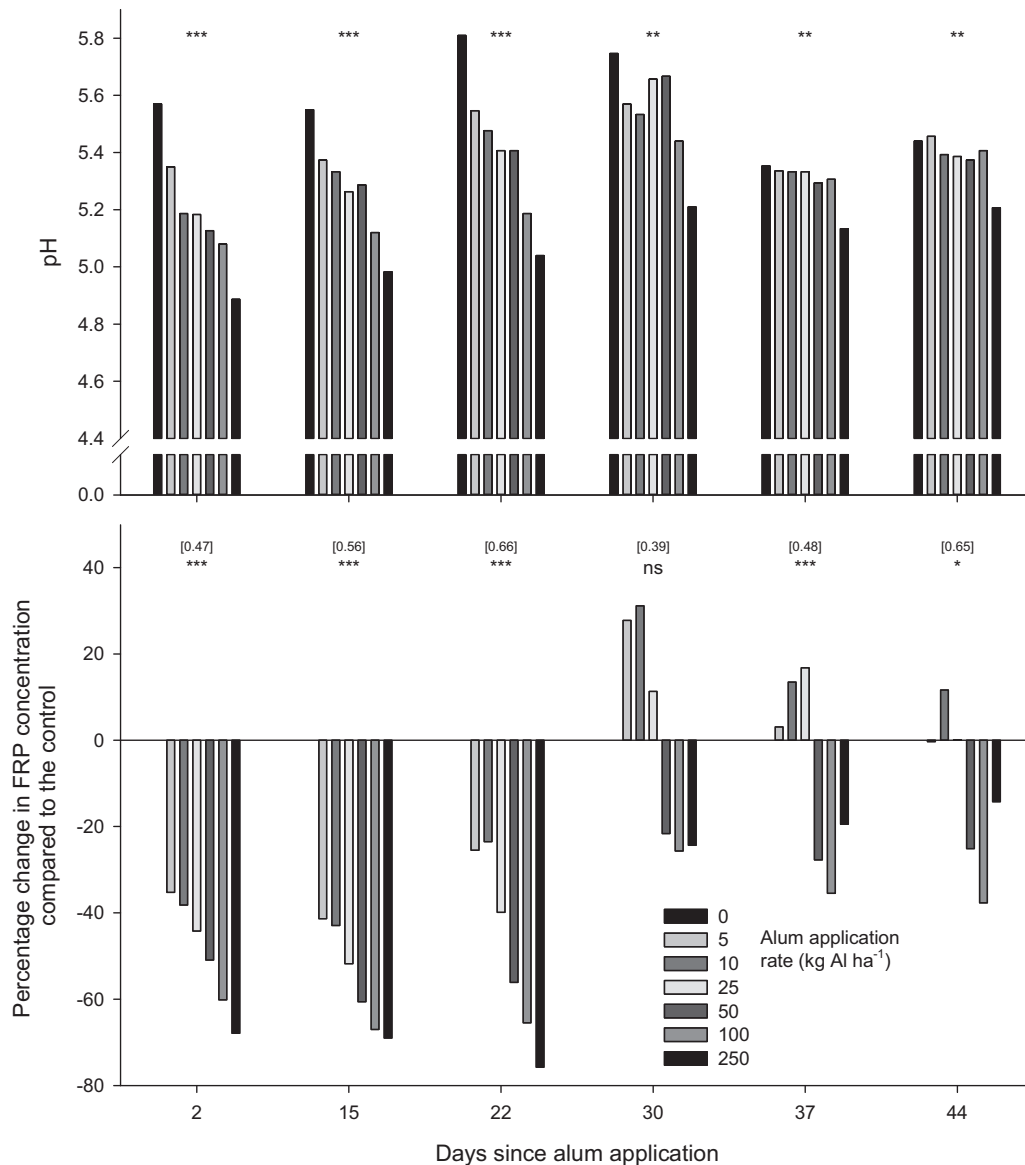


Fig. 1. Mean leachate pH and percentage change compared to the control for filtered reactive P (FRP) concentration with time after different rates of aluminium sulphate was applied. Values in parentheses are the mean concentration of FRP in leachate for the control. An asterisk indicates a significant difference in mean FRP concentrations between rates for each event (** and *** indicate significance at the $P < 0.01$ and < 0.001 level, respectively).

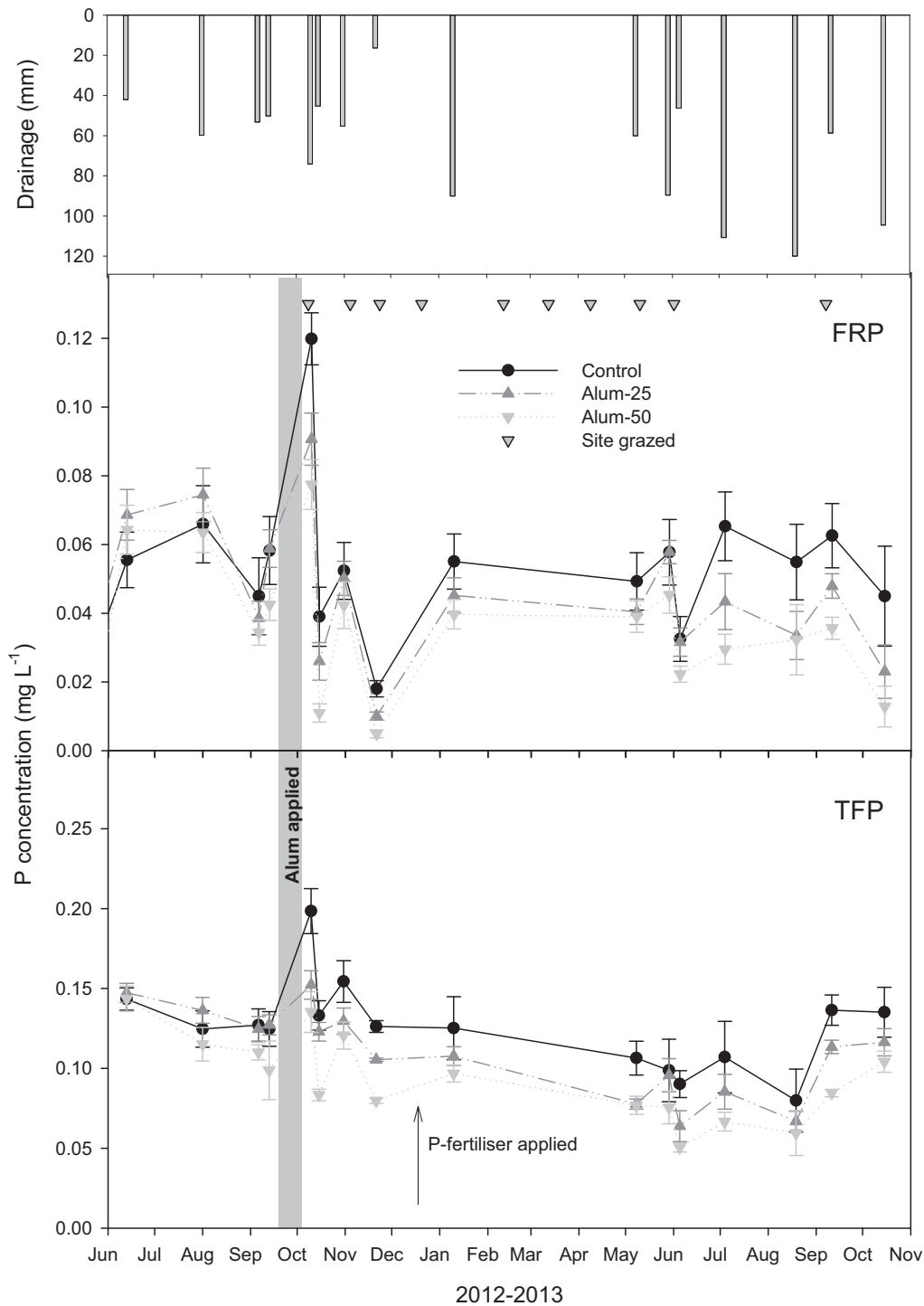


Fig. 2. Total drainage and mean filtered reactive P (FRP) and total filtered reactive P (TFP) in drainage events sampled *via* suction cups from treatments receiving 0 (control), 25 and 50 kg of Al as aluminium sulphate (alum). Error bars represent the 95% confidence interval for each treatment and event.

during lactation (from early September through to mid-May) at a common stocking intensity of c. 65 cows ha⁻¹ day⁻¹ (farm average 2.3 cows ha⁻¹). The site received, on average, 1100-mm of annual rainfall.

Previous research at the site indicated that the occurrence of surface runoff was rare (McDowell and Monaghan, 2014). Indeed, none has been measured in the 2 years prior to the present work. Subsurface drainage was intercepted at 35-cm by 60 Teflon suction cups (MacroRhizon, Rhizosphere Research Products, Wageningen, The Netherlands) installed in May 2012 at a 45° angle to a depth of

35-cm and arranged in 5 replicate (5 m²) plots of each treatment. Each replicate contained 4 cups each spaced 1-m apart. The cups were confirmed as not sorbing orthophosphate prior to installation and were located above the water table.

Twelve soil samples were taken of the 0–7.5, 7.5–15, 15–30, 30–45, 45–60 and 60–100-cm depths in May 2013 of the site, air-dried, crushed and sieved <2-mm. Soils were analysed for Olsen P, WEP, pH (1:2 soil to water ratio), and ASC (Saunders, 1965). Samples were also taken of the 0–5 cm depth for bulk density, pore size distribution and saturated hydraulic conductivity.

Table 2

Mean load (kg P ha⁻¹) of filtered reactive P, filtered unreactive P and total filtered P in drainage (October, 2012 to September, 2013) sampled *via* suction cups from plots receiving 0 (control), 25 and 50 kg Al ha⁻¹ as aluminium sulphate. The least significant difference at the $P < 0.05$ level of significance (LSD₀₅) is given for the comparison of treatment means.

Treatment	FRP	FURP	TFP
Control	0.614	0.420	1.036
Alum (25 kg Al ha ⁻¹)	0.484	0.373	0.846
Alum (50 kg Al ha ⁻¹)	0.392	0.362	0.753
LSD ₀₅	0.182	0.060	0.243

Meteorological data was measured using two Watchdog 2900ET automatic weather stations (Spectrum Technologies Inc., Aurora, IL). Soil moisture was recorded *via* three Waterscout SM 100 soil moisture sensors installed to 5 cm, 30 cm and 60 cm. Potential evapotranspiration (PET) 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 a limiting soil water deficit of 50% of plant available water. Thereafter, this ratio decreased linearly to become zero 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.

Sampling of drainage water from suction cups occurred on an event basis. All samples were filtered (0.45 µm) and analysed for FRP within 24 h. Filtered samples were digested using acidified persulphate (Eisenreich et al., 1975) within a week to give total filtered P (TFP) and filtered unreactive (*viz.* organic) P (DOP) determined as the difference of 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. Sub-surface flow losses of P were calculated using the mean concentrations in drainage multiplied by the total drainage since the previous sampled event. Drainage prior to the first event was set as that which occurred in the 18 previous days of the month. From February to April 2013, drainage was minimal and hence was not sampled. Respective losses due to small amounts of drainage in these months were calculated by averaging concentrations for January and April. Annual loads (October 2012 to September, 2013) were checked for normality and log-transformed if necessary before being compared *via* an analysis of variance.

3. Results and discussion

Data from the preliminary trial indicated that compared to the control, the mitigation of P leaching losses increased with alum application rate, but decreased with time since application, presumably as the reactive agent (Al) was either leached from the soil or transformed into more crystalline Al-hydroxides. Soil pH decreased with increasing alum application rates, largely driven by a decrease of up to 0.8 pH units at the 250 kg Al ha⁻¹ application rate (Fig. 1). However, rates <250 kg Al ha⁻¹ affected soil pH less and showed little difference to the control soil by the fourth leaching event – 37 days after application (Fig. 1).

During the field trial, rainfall totalled 1321-mm causing 713-mm of drainage biased towards winter (359-mm) and spring (198-mm). Mean annual concentrations of FRP and TFP in the

control plot were 0.055 and 0.14 mg L⁻¹, respectively. Prior to the application of alum there was no significant difference in the mean concentrations (or load) of P fractions between treatments (Fig. 2). After applying alum at 25 kg Al ha⁻¹, the flow-weighted FRP and TFP concentrations were less than the control, but only for some events (*e.g.* 21 November), whereas concentrations in the 50 kg Al ha⁻¹ treatment were less than the control for all events but the event in June. When translated into loads there was no significant difference between the control and the 25 kg Al ha⁻¹ treatment. However, FRP and TFP losses from the 50 kg Al ha⁻¹ were 26 and 27% less than the control, respectively (Table 2).

Despite applying fertiliser, and the soil receiving P from excreta during several grazing events, P concentrations did not appear to suddenly increase (Fig. 2). This suggests that samplers were not intercepting macropore flow enriched with P from topsoil (Table 1), fertiliser or dung. In contrast, the low bulk density (0.79 g cm⁻³) and high macroporosity (>15% v/v) of the soil suggests that samples more likely intercepted matrix flow (Houlbrooke et al., 2008). However, this does leave the possibility that some P loss *via* macropore flow may have been missed.

3.1. Potential use of alum

McDowell and Norris (2014) found that surface applying 25 kg Al (as alum) ha⁻¹ to topsoil can decrease P losses in areas where the main mechanism for P loss is surface runoff. However, the present study is the first to target subsurface flow P losses from grazed pasture. When applied to the soil surface, McDowell and Norris (2014) assessed cost-effectiveness at 172–944 USD kg⁻¹ total P mitigated for alum costing 30–150 USD Mg⁻¹ (at 18% w/w alum; Anon, 2013). Assuming the same price for alum, cost-effectiveness at the 50 kg Al ha⁻¹ rate for TFP in subsurface flow was estimated to be 190–952 USD kg⁻¹ P mitigated. No estimate was made for the 25 kg Al ha⁻¹ rate as the load was not significantly different to the control. According to McDowell and Nash (2012) this places the strategy in the medium to low range for cost-effectiveness of 20 strategies available to mitigate P loss from grazed grassland. Clearly, more cost-effective strategies to mitigate subsurface P losses such as decreasing soil Olsen P concentration should be practised first. However, applying alum may provide an option where losses must be lowered further. To further enhance the cost-effectiveness of alum, applications should be targeted to critical source areas that lose the most P, especially of bioavailable FRP, but come from a small part of the farm (Buda et al., 2012).

4. Conclusions

Preliminary testing showed that the addition of alum to a soil with poor P-sorption capacity (measured as anion storage capacity) can decrease the potential for subsurface P losses in soils with only short-lived acidification of soil pH at rates <250 kg Al ha⁻¹. Field testing of alum at an application rate of 50 kg Al ha⁻¹ showed it was able to decrease the load of TFP lost in subsurface drainage intercepted at 35 cm by 27%. However, with estimates of 190–952 USD kg⁻¹ P mitigated by alum, more cost-effective strategies such as decreasing soil Olsen P should be used first.

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References

- Anon, 2013. Aluminum sulfate prices. Available at: <http://www.alibaba.com/showroom/aluminum-sulphate.html> (accessed 07.13).
- Bryant, R.B., Buda, A.R., Kleinman, P.J.A., Church, C.D., Saporito, L.S., Folmar, G.J., Bose, S., Allen, A.L., 2012. Using flue gas desulfurization gypsum to remove dissolved phosphorus from agricultural drainage waters. *J. Environ. Qual.* 41, 664–671.
- Buda, A.R., Koopmans, G.F., Bryant, R.B., Chardon, W.J., 2012. Emerging technologies for removing nonpoint phosphorus from surface and groundwater: introduction. *J. Environ. Qual.* 41, 621–627.
- Carpenter, S.R., Caraco, N.F., Corell, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* 8, 559–568.
- Chardon, W.J., Groenenberg, J.E., Temminghoff, E.J.M., Koopmans, G.F., 2012. Use of reactive materials to bind phosphorus. *J. Environ. Qual.* 41, 636–646.
- Eisenreich, S.J., Bannerman, R.T., Armstrong, D.E., 1975. A simplified phosphorus analysis technique. *Environ. Lett.* 9, 43–53.
- Hewitt, A.E., 1998. New Zealand soil classification. *Landcare Res. Sci. Ser.* 1, 1–133.
- Houlbrooke, D.J., Horne, D.J., Hedley, M.J., et al., 2008. Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Aust. J. Soil Res.* 46, 45–52.
- McDowell, R.W., Condron, L.M., 2004. Estimating phosphorus loss from New Zealand grassland soils. *N. Z. J. Agric. Res.* 47, 137–145.
- McDowell, R.W., Nash, D., 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.
- McDowell, R.W., Monoagha, R.M., 2014. Extreme phosphorus losses in drainage from grazed dairy pastures on marginal land. *J. Environ. Qual.* 44, 545–551.
- McDowell, R.W., Norris, M., 2014. The use of alum to decrease phosphorus losses in runoff from grassland soils. *J. Environ. Qual.* 43, 1635–1643.
- McDowell, R.W., Sharpley, A.N., Bourke, B., 2008. Treatment of drainage water with industrial by-products to prevent phosphorus loss from tile-drained land. *J. Environ. Qual.* 37, 1575–1582.
- McDowell, R.W., Wilcock, R.J., 2008. Water quality and the effects of different pastoral animals. *N. Z. J. Vet. Res.* 50, 289–296.
- Monaghan, R.M., Smith, L.C., 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.
- Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 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, D.C., USA.
- Penn, C.J., McGrath, J.M., Rounds, E., Fox, G., Haaren, D., 2012. Trapping phosphorus in runoff with a phosphorus removal structure. *J. Environ. Qual.* 41, 672–679.
- Saunders, W.M.H., 1965. Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter and other soil properties. *N. Z. J. Agric. Res.* 8, 30–57.
- Watanabe, F.S., Olsen, S.R., 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.
- Woodward, S.J.R., Barker, D.J., Zyskowski, R.F., 2001. A practical model for predicting soil water deficit in New Zealand pastures. *N. Z. J. Agric. Res.* 44, 91–109.