

Estimating phosphorus loss from New Zealand grassland soils

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Abstract The potential for phosphorus (P) loss from New Zealand grassland soils was assessed using a combination of measured soil chemical properties and concentrations of dissolved reactive P (DRP) determined in drainage and overland flow from simulated rainfall experiments. Soil analyses included Olsen P, calcium chloride (0.01M CaCl₂) and water extractable DRP, P sorption index (PSI), and % P retention. Results confirmed that DRP concentrations in drainage and overland flow were closely related to CaCl₂- and water-extractable DRP in soil, respectively. The preliminary data indicated that the potential concentration of DRP in subsurface and overland flow from pasture soils that have not been recently grazed and at a small scale (e.g., overland flow from 1-m lengths) could be estimated from Olsen P and PSI (or P retention) data according to the following equations:

$$\begin{aligned}\text{DRP (subsurface flow)} &= 1.480 (\text{Olsen P/PSI}) \\ &= 0.069 (\text{Olsen P/P} \\ &\quad \text{retention}) + 0.007\end{aligned}$$

$$\begin{aligned}\text{DRP (overland flow)} &= 0.495 (\text{Olsen P/PSI}) \\ &= 0.024 (\text{Olsen P/P} \\ &\quad \text{retention}) + 0.024.\end{aligned}$$

Keywords phosphorus; pasture; nutrient loss

INTRODUCTION

Phosphorus (P) loss from soil to water is implicated in the accelerated eutrophication of surface waters. The potential for loss increases with soil P concentration, but can vary with the transport pathway (Heathwaite & Dils 2000). For example, P loss in overland flow commonly has a greater particulate P component due to erosion than does P loss in subsurface flow (Sharpley et al. 1993). However, the ionic strength of subsurface flow can often be greater as a result of more contact time with soil than occurs with overland flow (except perhaps in preferential or by-pass flow). Both the soil to solution ratio and the ionic strength are known to effect the concentration of P in solution (Evens & Sorensen 1984; Koopmans et al. 2002). Fortunately, laboratory tests have been derived to estimate potential P loss in subsurface flow from the plough layer and tentatively also for overland flow at small scales (McDowell & Sharpley 2001).

There is a need to estimate the potential for a soil to contribute P to overland and subsurface flow from easily measured parameters. Work in New Zealand and overseas has advocated the use of common agronomic (e.g., Olsen or Mehlich-3 extractable P) or environmental (e.g., acid ammonium oxalate extraction for P sorption of Al and Fe oxides) soil tests as methods to judge when an increase in P loss potential may occur (Breeuwisma & Silva 1992; Pote et al. 1996; McDowell & Condron 1999). However, while such methods have management potential for soils where this relationship is known, this potential cannot at present be extrapolated with certainty to all soils. Furthermore, such tests may not be suitable for all soils (e.g., acid ammonium oxalate extractions for P saturation; Hughes et al. 2000), or may not reliably estimate the magnitude of P loss. With this in mind the objectives of this study were to design simple laboratory tests to estimate P in subsurface and overland flow and then to show how readily available soil test P data such as Olsen P and P retention can be used to estimate P in subsurface and overland flow for a range of New Zealand grassland soils of different P status.

Table 1 Selected physiochemical parameters of the 44 grassland soils used in this study.

Soil	Classification	pH	Organic C (g kg ⁻¹)	Olsen P (mg kg ⁻¹)	Total P (mg kg ⁻¹)
Cargill silt loam	Acidic Mafic Brown	5.5	57.8	29	1169
Egmont black silt loam	Typic Orthic Allophanic	5.7	53.0	7	629
Eyre silt loam	Weathered Orthic Recent	5.8	34.3	73	1255
Fork silt loam	Typic Orthic Brown	6.0	25.2	20	690
Haldon stony silt loam	Typic Immature Pallic	5.5	48.5	15	707
Hamilton clay loam	Typic Orthic Granular	5.7	93.6	11	1559
Himatangi sand	Typic Sandy Brown	7.0	29.0	46	862
Hurunui stony loam	Typic Orthic Brown	5.6	78.7	32	904
Kiripaka silt loam	Typic Orthic Allophanic	6.4	102.8	57	2461
Lismore stony silt loam	Pallic Firm Brown	5.6	39.0	18	707
Mahoenui silt loam	Typic Orthic Recent	5.3	54.4	16	560
Mangamahu silt loam	Mottled Orthic Brown	5.3	39.3	10	401
Mangatea clay loam	Pallic Orthic Brown	5.4	85.9	8	682
Mapua sandy loam	Mottled Albic Ultic	5.2	19.5	10	116
Mataura silt loam	Typic Orthic Recent	6.1	30.5	11	585
Maunu silt loam	Typic Orthic Oxidic	5.7	102.3	10	1413
Mihiwaka silt loam	Acidic Mafic Brown	5.8	38.5	30	707
Ngakuru loam	Typic Orthic Allophanic	6.5	84.3	117	1862
Northope silt loam	Typic Orthic Gley	6.7	17.0	10	633
Oamaru clay loam	Weathered Rendzic Melanic	6.8	43.2	92	1291
Okarito peaty silt loam	Silt-mantled Perch-gley Podzol	5.4	130.4	37	597
Oruanui silty sand	Podzolic Orthic Pumice	5.3	88.9	50	1127
Patoka fine sandy loam	Buried-allophanic Orthic Pumice	5.7	93.4	14	1585
Portobello silt loam	Typic Mafic Brown	5.3	46.4	18	658
Poukawa peaty loam	Peaty Orthic Gley	6.0	31.9	24	1218
Pukaki silt loam	Humose Orthic Brown	5.2	49.1	11	663
Pukemutu silt loam	Argillic-mottled Fragic Pallic	6.1	17.5	16	390
Richmond silt loam	Typic Orthic Gley	5.7	36.5	15	813
Riponui clay	Yellow Albic Ultic	5.8	21.6	15	317
Rotoiti sandy loam	Typic Orthic Pumice	5.5	50.9	51	560
Stratford sandy loam	Typic Orthic Allophanic	5.4	67.8	42	2746
Taihape silt loam	Mottled Orthic Brown	6.0	50.5	10	341
Taupo silty sand	Immature Orthic Pumice	5.1	55.4	80	1311
Te Kauwhata clay loam	Typic Orthic Granular	5.7	50.0	19	938
Te Kuiti sandy loam	Typic Orthic Allophanic	5.8	34.7	14	573
Temuka silt loam	Typic Orthic Gley	6.5	39.6	54	1056
Waikiwi silt loam	Typic Firm Brown	5.8	64.2	8	414
Waikoikoi silt loam	Mottled Fragic Pallic	6.2	22.3	26	609
Waiotira clay loam	Typic Acid Brown	5.3	46.5	18	682
Waipawa silt loam	Typic Argillic Pallic	5.5	38.4	18	524
Waitahuna silt loam	Mottled Fragic Pallic	5.8	39.9	88	1236
Warepa silt loam	Mottled Fragic Pallic	5.6	43.0	39	633
Wharekoke silt loam	Perched-gleyed Densipan Ultic	5.4	33.6	18	439
Wingatui silt loam	Weathered Fluvial Recent	5.6	35.5	25	877
Woodlands silt loam	Typic Firm Brown	5.1	58.8	8	487

MATERIALS AND METHODS

Soil extractions

Samples (0–7.5 cm) of 44 soils currently under grassland were collected from different areas of New Zealand (Table 1), air-dried, crushed, and sieved (<2 mm). Each soil was analysed for pH in water (1:2.5 soil to solution ratio), and organic C by LECO® combustion. A range of P analyses were conducted.

- 1) Olsen P was determined using a soil:solution ratio of 1:20 and quoted on a weight (mg kg^{-1}), not volume (mg litre^{-1}) basis, negating the influence of bulk density (Olsen et al. 1954).
- 2) $\text{CaCl}_2\text{-P}$ (an estimate of P in subsurface flow; McDowell & Sharpley 2001), was measured using a soil to 0.01M CaCl_2 solution ratio of 1:5 and a shaking time of 30 min before measuring dissolved reactive P (DRP) in the filtrate (<0.45 μm).
- 3) $\text{H}_2\text{O-P}$ (an estimate of P in overland flow), was determined using a soil to deionised water ratio of 1:300 and a shaking time of 45 min before measuring DRP.
- 4) PSI (P sorption index), was determined from the amount of P sorbed, x (mg P kg^{-1}), from an addition of 1.5 g P kg soil^{-1} (as KH_2PO_4 in 0.01M CaCl_2) after shaking for 24 h at a soil to solution ratio of 1:20. The PSI was then calculated as the quotient $x \log C^{-1}$, where C is the solution concentration (mg litre^{-1}) in the filtrate (Whatman #42). This quotient is highly correlated to the P sorption maximum in a wide range of soils (Bache & Williams 1971).
- 5) Percent P retention (%P remaining after equilibration with a soil P saturating solution, buffered at pH 4.6) was assessed according to the methods outlined by Saunders (1964).
- 6) Total P was determined by the digestion of 0.15 g of soil (ground < 500 μm) with 5 ml concentrated $\text{HNO}_3\text{:HCl}$ in a 1:4 mix (Crosland et al. 1995).

All P determinations (except P retention; Saunders 1964) were made using the method of Watanabe & Olsen (1965). All soil extractions were made in duplicate except for the $\text{CaCl}_2\text{-P}$ and $\text{H}_2\text{O-P}$ extractions which were conducted in triplicate.

Additional analyses

For the calibration of laboratory tests to estimate overland and subsurface flow, data from the literature was supplemented by rainfall simulation studies generating overland flow from 11 intact grassland soils selected to represent a wide range of New

Zealand soil types under pasture. The soils were Woodlands (Typic Firm Brown), Waikiwi (Typic Firm Brown), Mataura (Typic Orthic Recent), Northhope (Typic Orthic Gley), Pukemutu (Argillic-mottled Fragic Pallic), Waikoikoi (Mottled Fragic Pallic), Waitahuna (Mottled Fragic Pallic), Lismore (Pallic Firm Brown), Rotoiti silt loam (Typic Orthic Pumice), Taupo sandy silt (Immature Orthic Pumice) and Ngakuru loam (Typic Orthic Allophanic) soils (Table 1). All soils were taken in triplicate from field sites around the country to a 5 cm depth using either a turf cutter or spade during winter of 2001. The exception to this general rule was the Waitahuna and Lismore soils which were taken to 7.5 cm depth and the Rotoiti, Taupo, and Ngakuru soils which were taken in summer 2002. Pasture was trimmed to a uniform 5 cm height before soils were placed into boxes 1 m long by 20 cm wide and 7.5 cm deep with six small (2 mm diameter) holes drilled for some drainage. Soil samples for analysis were taken to the full depth of each soil box from the upslope end.

Overland flow was generated by applying artificial rainfall (tap water, P less than detection limit of 0.005 mg P litre^{-1}) at 1.5 cm h^{-1} to boxes, inclined at 5% slope and within 1 week, and generally within 3 days, of collection. The rainfall simulator uses one TeeJet 1/4HH-SS30WSQ nozzle (Spraying Systems Co., Wheaton, IL) positioned approximately 250 cm above the soil surface in order for raindrops to gain terminal velocity (Sharpley et al. 1999). The nozzle, plumbing, in-line filter, and pressure gauge were fitted onto a 305 × 305 × 305 cm aluminium frame. The simulated rainfall had drop-size, velocity, and impact energies approximating natural rainfall (Shelton et al. 1985). Samples of overland flow were collected for 1 h after flow had started; a subsample was taken and filtered (<0.45 μm), and P determined in duplicate.

Additional data for DRP loss in subsurface flow from Woodlands silt loam soils were taken from McDowell & Monaghan (2002; Fig. 1A). The rainfall simulation and soil boxes used in this study accurately mimic mechanisms controlling the release of soil P to saturation-excess overland flow in the field (Sharpley 1985, 1995). Recent work has shown the use of small scale plots and rainfall simulation can be used to estimate P losses from dairy pastures (Cornish et al. 2002). However, they are not designed to quantify P losses on the field scale *per se* (Sharpley et al. 1982).

All summary statistics (mean, standard error, minimum, and maximum) and regression analyses were made using SPSS v. 10.0 (SPSS Inc. 1999).

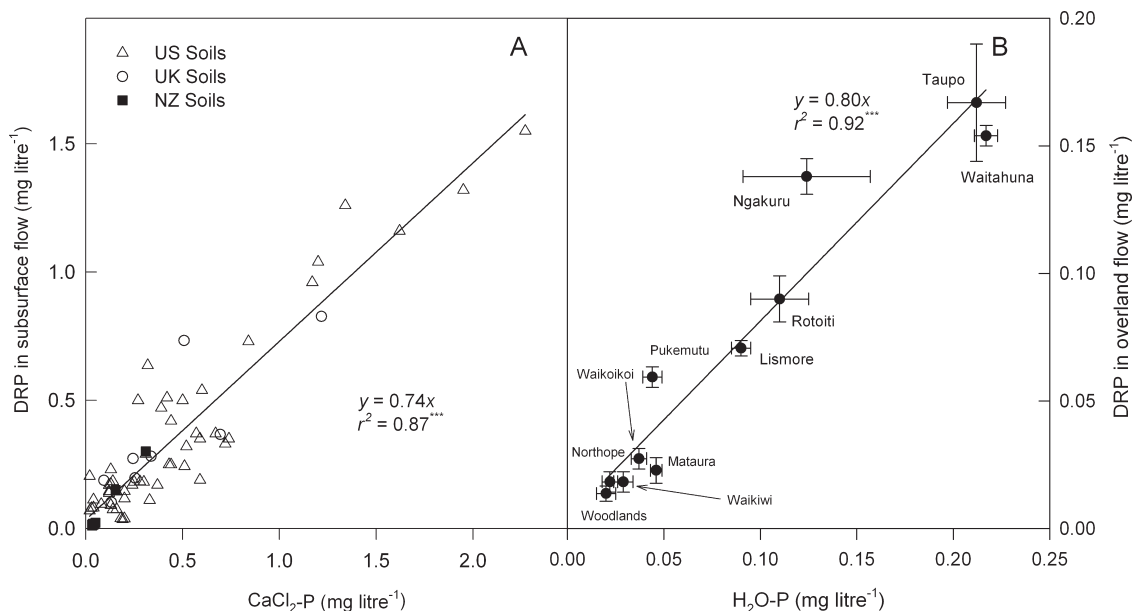


Fig. 1 Relationship between dissolved reactive P (DRP) in subsurface flow and $\text{CaCl}_2\text{-P}$ for the United States (McDowell & Sharpley 2001), United Kingdom (McDowell & Sharpley 2001), and New Zealand (McDowell & Monaghan 2002; McDowell unpubl.) soils (A), and between DRP in overland flow and $\text{H}_2\text{O-P}$ for selected New Zealand grassland soils (B). Error bars are the standard errors for three replicates.

RESULTS AND DISCUSSION

Laboratory extractions for P loss estimations

Soil chemical data are given in Tables 1 and 2. The soils cover the majority of the soil groups found in New Zealand. Since all of the soils were under grassland when sampled, it is not surprising to see the least variation is evident in pH, while other chemical parameters such as Olsen P, organic C, and % P retention reflect their pedological origin and probably recent fertiliser management (Table 2). The soils selected to evaluate a quick laboratory test to predict P in overland flow represent a wide ranging subset of soils from this group, while data from the literature is used to show the validity of an established quick laboratory test for P in subsurface flow (McDowell & Sharpley 2001; McDowell & Monaghan 2002).

To truly predict P desorption into solution, and thus into subsurface and overland flow, the medium must reflect the cation status as well as the ionic strength of the aqueous phase of the system (Ryden & Syers 1975; Beauchemin et al. 1996). Thus, for subsurface flow, a short-term (30 min) extraction of

soil with 0.01M CaCl_2 at a soil to solution ratio of 1:5 was designed by Schofield (1955) to simulate the correct ionic strength for soil solution in near-neutral pH and calcareous soils. This test has been used recently for the prediction of P behaviour and concentration in subsurface flow in the United Kingdom, United States, and New Zealand (McDowell & Condron 1999; McDowell & Sharpley 2001; Blake et al. 2002; McDowell & Monaghan 2002; McDowell unpubl.). The data for these studies is plotted in Fig. 1A and shows a good relationship between P in subsurface flow and $\text{CaCl}_2\text{-P}$. However, this data only pertains to P lost from the top 20–30 cm of surface soil. This does not imply that, in general, this estimate corresponds to the quantities of P leaving the soil profile in subsurface flow, unless intercepted by preferential flow pathways and/or tile drains (Heckrath 1997).

For overland flow, preliminary tests designed to estimate P have traditionally used much wider soil to solution ratios and lower ionic strengths to simulate, in general, less soil contact time, compared with subsurface flow. For example, Ryden et al. (1971a,b) used a water extraction at a soil to solution ratio of

1:400 to estimate the contribution of P into stream flow from an eroding urban stream bank. A water extraction has also been used by other workers (e.g., Sissingh 1971; Sharpley et al. 1982; Koopmans et al. 2001). Sharpley et al. (1982) also recognised that in order to estimate P in overland flow, allowance must be made for the selective erosion of P-rich fines in flow, effectively concentrating P in flow, compared with the suspension of whole source soil in flow, i.e., an enrichment ratio.

With these mechanisms in mind, we took rainfall simulation data from Sharpley & Smith (1989), Pote et al. (1999), McDowell & Sharpley (2001), and McDowell et al. (2003) and calculated the mean likely enrichment ratio (degree of P enrichment of sediment in overland flow compared with source soil) for more than 200 soils under pasture. This was calculated as approximately three for a 45-min overland flow event. By combining the enrichment ratio with data for the mean suspended sediment concentration in overland flow from 90 grassland soils from Southland (0.1 g litre^{-1}) under a low rainfall intensity of 1.5 cm h^{-1} (compared with USA studies that commonly use $> 5 \text{ cm h}^{-1}$) a soil to water ratio of 1:300 was derived (McDowell et al. 2003). Once filtered, the P measured in this extract was termed $\text{H}_2\text{O-P}$.

Using this laboratory extraction procedure, $\text{H}_2\text{O-P}$ in surface soil was estimated and compared with that generated from a 45-min rainfall simulation of 11 intact grassland soils (each with three replicates) from across New Zealand with a range of P concentrations in topsoil. As with the relationship between $\text{CaCl}_2\text{-P}$ and DRP in subsurface flow, a good relationship was gained between DRP in overland flow and $\text{H}_2\text{O-P}$ (Table 1; Fig. 1B).

Predicting $\text{CaCl}_2\text{-P}$ and $\text{H}_2\text{O-P}$

Several workers have attempted to relate soil P concentration and P saturation to P loss in overland and subsurface flow. For example, in the Netherlands, P in subsurface flow is related to the degree of P saturation of Al and Fe oxides estimated from an acid ammonium oxalate extraction (Breeuswma & Silva 1992). Work in the United States, United Kingdom, and Australasia has related P loss to soil test P concentrations with varying degrees of success (e.g., Mehlich-3 (Pote et al. 1996, 1999); Olsen P (Gillingham et al. 1997; McDowell & Condon 1999)).

Following an analysis of the data for correlations between $\text{CaCl}_2\text{-P}$ or $\text{H}_2\text{O-P}$ and the various soil chemical parameters tested, Olsen P, PSI, and P retention were found to be significantly correlated ($P \leq 0.05$; $r = 0.635, 0.489, 0.512$, respectively for $\text{CaCl}_2\text{-P}$; $0.760, 0.387, 0.418$, respectively for $\text{H}_2\text{O-P}$). Several studies have related the equilibrium P concentration at zero net sorption or desorption (EPC_0 ; deemed likely to represent the behaviour of P in flow) to measures of soil test P and concluded that a measure of P sorption was also necessary to fully predict EPC_0 . For example, Sallade & Sims (1997) and Hughes et al. (2000) both incorporated the PSI along with a soil P test (Mehlich-I extractable and Olsen extractable P, respectively) to predict EPC_0 . The PSI is known to be closely correlated with P sorption capacity and is a quick and reliable indicator for the potential of a soil to change its ability to retain P following P additions (Indiati & Sharpley 1997). By combining terms in various combinations within a stepwise multiple regression, a plot of the quotient of Olsen P and PSI against $\text{CaCl}_2\text{-P}$ or $\text{H}_2\text{O-P}$ was found to be highly significant

Table 2 Summary statistics for the 44 grassland soils used in the study.

Parameter	Mean	Standard Error	Minimum	Maximum
pH	5.7	0.07	5.1	7.0
Organic C (g kg^{-1})	53.7	3.88	19.5	130.4
Olsen P (mg kg^{-1})	30	3.9	7	117
Total P (mg kg^{-1})	866	78.0	116	2746
$\text{CaCl}_2\text{-P}$ (mg litre^{-1})	0.143	0.032	0.003	0.944
$\text{H}_2\text{O-P}$ (mg litre^{-1})	0.068	0.010	0.011	0.338
P retention (%)	33	3.1	7	85
PSI	677	65.1	144	2123

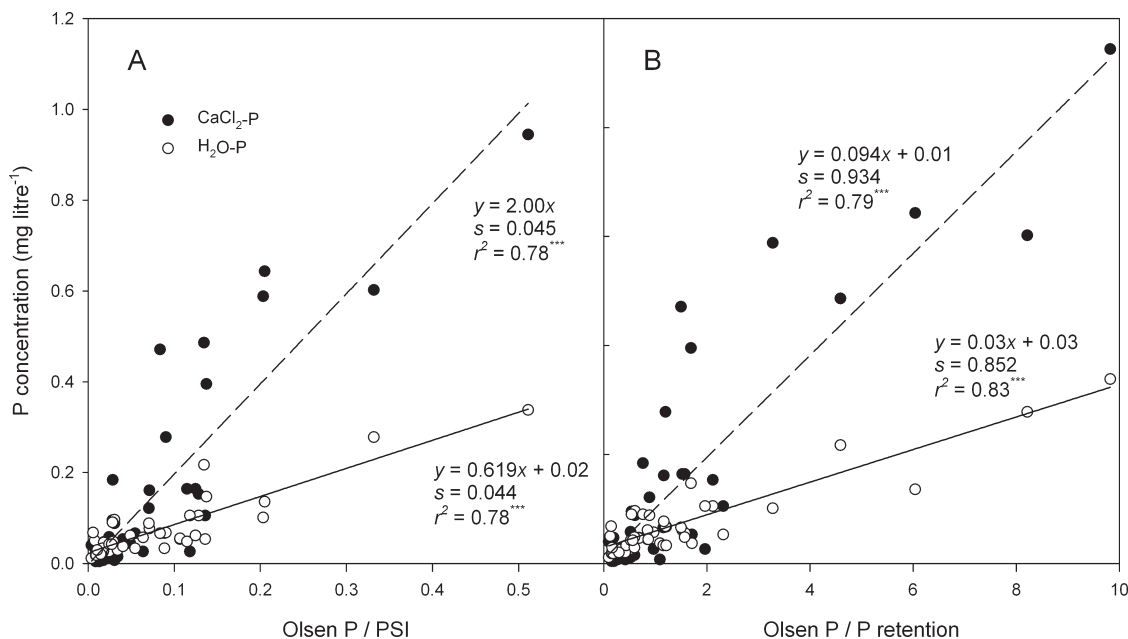


Fig. 2 Linear regressions for the relationships between dissolved reactive P (DRP) concentration in CaCl₂-P or H₂O-P and the quotients of Olsen P and PSI (A), and Olsen P and % P retention (B), for 44 New Zealand grassland soils.

($P < 0.001$) with the added benefit of simplicity and no superfluous terms. We therefore propose this as an easy method of predicting CaCl₂-P or H₂O-P (Fig. 2A). However, the linear regression shown in Fig. 2A is dependent upon a few data points with much leverage, especially for CaCl₂-P data. As such, the relationships are preliminary (note standard errors, s).

In New Zealand, the P retention test developed by Saunders (1964) has been widely used in soil classification and agronomic advice. As expected, the PSI and P retention values were closely correlated ($r = 0.905$; $P < 0.001$), and hence the quotient of Olsen P and P retention is also a suitable method for the prediction of CaCl₂-P or H₂O-P (Fig. 2B). Although some attempts to use P retention for the prediction of P loss have been made, they either involve complex equations, only relate to one flow pathway, or have thus far been without validation (Hart et al. 2002; Hedley et al. 2002).

The choice between using the Olsen P and PSI or P retention quotient to estimate CaCl₂-P or H₂O-P is almost arbitrary; both are simple measures that are either easily adopted or used. However, in New

Zealand many soils already have their P retention values determined. The quotient of Olsen P and P retention could thus provide the most useful method of determining the potential concentration of H₂O-P and CaCl₂-P. However, caution should be employed when extrapolating this to P in overland and subsurface flow for New Zealand pastoral soils. Recent evidence by Koopmans et al. (2001, 2002) and McDowell & Sharpley (2001) indicates that differing rainfall intensity could affect the concentration of P in flow. We have only demonstrated the relationship and link between H₂O-P and P in overland flow for one rainfall intensity. Although work over the last 30 years has shown that the difference in concentration in soil solution ratios above 1:100 is small, there is still potential for some differences to occur (Ryden et al. 1971a,b). Furthermore, we have demonstrated that the results presented here pertain to P loss at one scale, overland flow boxes 1-m long. Recent work has shown that scale can affect the concentration of P in flow (McDowell & Sharpley 2002). Additional work is required to see by what degree the relationships change under the

range of rainfall intensities possible in the New Zealand environment, and different scales in the field. Furthermore, the relationship is only applicable for pasture soils that have not been recently grazed (<10–15 days since grazing), since P from dung may significantly increase P loss. This work should, therefore, be considered as still evolving. In the meantime, by combining equations in Fig. 1 and 2, a preliminary relationship for the estimation of DRP in overland and subsurface flow from Olsen P and PSI/P retention data can be generated:

DRP concentration (overland flow)
 = 0.495 (Olsen P/PSI) + 0.016;
 = 0.024 (Olsen P/P retention) + 0.024.

DRP concentration (subsurface flow)
 = 1.480 (Olsen P/PSI)
 = 0.069 (Olsen P/P retention) + 0.007.

CONCLUSIONS

Dilute CaCl₂ solution and deionised water extractions can be used for the prediction of P concentrations in subsurface and overland flow, respectively. However, for subsurface flow this method pertains only to P lost from topsoil (30 cm) and has not been validated for lower depths. The laboratory test developed (1:300 soil to solution mixture, shaken for 45 min) appeared to estimate well the DRP in overland flow from 11 soils generated by simulated rainfall from 1-m long boxes. These data were used to derive relationships between DRP in overland and subsurface flow from soils that have not been recently grazed and selected soil chemical parameters (Olsen P, PSI/P retention).

However, caution should be employed when using these relationships as they are likely to change as additional soils become available for validation and they are tested under different rainfall regimes (which would likely alter the soil to solution ratio) and scales. Consequently, further work should be directed at determining the likely influence of these parameters, and these relationships should be viewed as preliminary.

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