Chapter 2

Factors influencing phosphorus loss from grazed pastures

OVERVIEW

1. Introduction

Losses of phosphorus (P) from land, an essential nutrient for crop and animal production, have caused major problems world-wide in streams, rivers and lakes through the effects on aquatic ecosystem production (Carpenter et al., 1998; Sharpley, 2000). Although these losses might be minor compared with the amount of fertiliser applied to land, aquatic primary producers can be extremely sensitive to even minor increases in P. For example, freshwater algae can sequester P at the picomolar level and thus even very minor increases in P concentrations can potentially stimulate algal production (Hudson et al. 2000). Thus, in waterways where primary production is P-limited, increasing P supply to concentrations in the low parts per billion has led to high growths of algae and associated eutrophication (e.g., Bothwell 1985, Biggs 2000a). The outcome of such anthropogenic eutrophication is that water use for fisheries and recreation is restricted due to the increased growth of undesirable (and sometimes toxic) algae and aquatic weeds, and oxygen shortages caused by the decomposition of plant matter (e.g., Cyanobacteria and *Pfiesteria*). Such blooms contribute to summer fish kills, unpalatability of drinking water, the formation of carcinogens during water chlorination, and have been tentatively linked to neurological impairment in humans (Burkholder and Glasgow, 1997; Kotak et al., 1993).

Attention has centred on agriculture as a primary source of P loss to surface waters and thereby eutrophication. This is due to an extensive number of catchment-scale studies that have shown much higher concentrations of P in streams draining areas of agricultural land compared with undeveloped areas (e.g., Cooper and Thomsen 1988, Smith et al. 1993). Also, it is easier to identify and mitigate sources of P than nitrogen (N, another limiter of eutrophication), although there are some uncontrollable P inputs via precipitation (c. 0.1 - 6.5 kg ha^{-1} yr^{-1}; Newman, 1995). In pastoral systems, concentrations and loads of P vary between industries. In general, dairying emits more P than deer farms, which in-turn lose more P than sheep and beef farms. However, there are exceptions to this rule and some anecdotal evidence would suggest that high-intensity beef farming can be a significant source of P loss to surface waters.

2. The sources of P loss in grazed pastures

2.1. Soil P

2.1.1 *Dissolved P*

The loss of P from soils occurs in dissolved and particulate forms. Usually in grazed pastures, most P loss occurs as dissolved P (up to 90%; Nash et al., 2000). However, factors such as treading damage can increase the proportion of particulate P lost (see section X.X).

In acidic soils, P occurs largely as Al- and Fe-phosphates, whereas in neutral to alkaline soils P occurs largely as Ca- and Mg-phosphates sorbed onto the surface of Ca and Mg carbonates (Lindsay, 1979). Phosphorus is most available and mobile at pH 6-7. However, combinations of Al-, Fe-, Ca- and Mg-P can occur in most agricultural soils. Organic P also forms a significant part of soil P especially in acidic soils and soils that contain much organic matter and N. Landuse can have a significant impact on the quantity of P in organic forms with the ratio of organic P to inorganic P decreasing from forest to grassland to arable systems.

The solubility of soil P is controlled by three characteristics: (i) concentration of P in solution; (ii) quantity of soil P in equilibrium with soil solution; and (iii) buffering capacity of the soil controlled by sorption strength and the saturation of sorption sites with P. Coupled with soil P solubility, the release of P into flow varies with time. Kinetic exchange experiments using ^{33}P, have confirmed that rapidly exchangeable soil P (within 60 seconds) is closely related to P in overland or subsurface flow (McDowell et al., 2001a). With time, P transport in overland flow becomes less related to this pool and more dependent upon the slow diffusion of P from the inside of the soil aggregate (McDowell and Sharpley, 2003; Sharpley and Ahuja, 1983).

At any one time characteristics (i) and (ii) are represented in practice by, the concentration of dissolved P in flow (overland or subsurface) and soil test P (STP; such as Olsen P), respectively. A recent paper by Koopmans et al. (2002) showed that in theory all relationships between DRP in flow and STP will be curvilinear. However, the degree of curvature is dependant upon the range of STP measured, whereby the likelihood of detecting a curvilinear relationship decreases with the range of STP measured and the soil to solution ratio, whereby curvature increases as soil to solution ratio decreases. In general, less soil is in contact with overland flow than with subsurface flow, and hence the relationship between STP and DRP in overland flow can appear linear.

The third characteristic, buffering capacity is affected by factors such as soil texture (P is more mobile in sandy soils), the concentration of Fe and Al oxides, pH, waterlogging and redox conditions. These factors can be described by a soils' P retention; a measure of how much P is retained from a P-rich solution at a constant pH. Recent work has shown that P loss in overland or subsurface flow can be estimated provided Olsen P and P retention are known (see section X.X for more details).

Some organic P forms are more mobile than inorganic P forms. For example, Chardon et al. (1997) showed the enhanced downward movement through soil of organic P forms to depths of 70 cm or more following several years of application of swine manure to a sandy soil in the Netherlands. Studies using known organic P compounds such as deoxyribose Nucleic Acid, adenosine 5'-triphosphate and phospholipids have demonstrated their lesser affinity with soil compared to orthophosphate (Stewart and Tiessen, 1987; Leytem et al., 2002). A notable exception is inositol hexaphosphates, which tend to be more strongly bound to the soil than orthophosphate (Turner et al., 2002a). Some of these compounds are also available for use by algae (via exocellular enzymes) and thus can pose a problem in surface waters (Whitton et al., 1991). At present, studies relating the loss of organic P species to specific soil characteristics are few. While most identify that the source of organic P is largely manurial in origin, and thus subject to manure management, the background contribution of plant and soil is less well understood and the subject of much ongoing research (see section X.X).

2.1.2 Erosion and particulate P

There is potential for much P loss can occur in particulate form – although this is generally associated with bad pasture management such as overgrazing. Eroded particulate material is enriched with P compared to surface soil, due to the preferential transport of light and highly P-sorptive fines compared to coarse-sized particles. Sharpley (1985b) found that the STP content of suspended sediment was, on average, three times greater than bulk soil (0-5 cm depth) and 1.5 times greater in terms of TP. The degree of P enrichment (ER) is expressed as the quotient of P concentration of sediment in flow and in the contributing soil. Menzel (1980) concluded that, for PP, a logarithmic relationship (Ln ER = 2.00 – 0.16 Ln Sediment discharge) was appropriate for a wide range of vegetative conditions (e.g., Figure X). Based on TP concentrations for several catchments (see Figure X), ER decreases with increasing erosion.

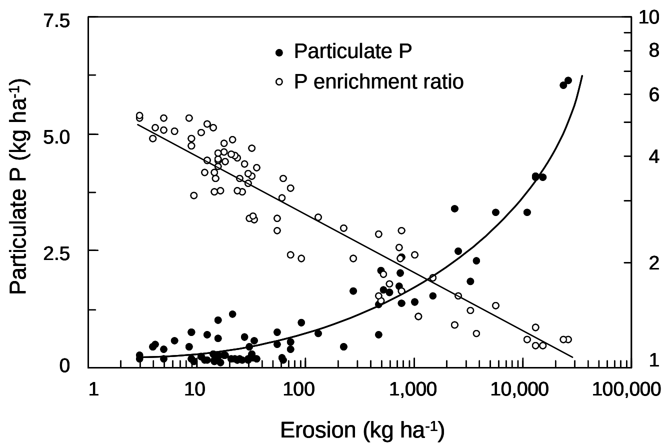

Figure X. Particulate P loss and enrichment ratio of eroded sediment as a function of erosion in overland flow from catchments at El Reno, OK (adapted from Smith et al., 1991)

Assuming an equal rainfall distribution then the load of P as PP in overland flow should increase with plot length (McDowell and Sharpley, 2002a). However, this can change if effluent or manure has been freshly applied. Here, the preferential loss of effluent or manure, which moves in lighter particles than soil, overwhelms P loss from soil (McDowell and Sharpley, 2002b). Since much P in effluent or manure is in small particulate form this means that PP can dominate P loss from paddocks where effluent or manure have been spread. In unmanured pastures, antecedent moisture conditions have a significant effect on the load and form of P lost. Soils that are wet will have a greater potential for flow and P movement than dry soils. However, due to hydrophobic conditions, slaking and dispersion effects, dry soils can produce more PP in flow than wet soils when overland flow is suddenly produced, such as could occur during infiltration-excess overland flow (Gillingham and Gray, 2006). The potential for a soil to supply flow with P was much larger at the start of flow compared to the end of the flow event. The difference is greater in those soils with poor aggregate stability and the potential for slaking and dispersion (where the aggregates break apart due to osmotic pressures) is high.

2.2. **Loss of P via fertilisers**

If best practice is followed then P losses from fertiliser is generally < 10% of total P lost from pastures. Best practice implies that fertiliser is not spread too close to waterways and is applied > 2 weeks before irrigation or at a time of year when P losses are unlikely – usually summer months when rainfall and overland flow is less. However, if this advice is not followed then P losses from fertilisers can account for the majority of P losses from the farm (Hart et al., 2004). For instance, applying superphosphate in winter caused from 2.3 to 6.7% of superphosphate applied at 50 kg P ha to be lost in either overland flow or drainage (Sharpley and Syers, 1979): 66 to 93% of annual P export from plots and catchments. Bush and Austin (1998) found up to 30% of superphosphate applied (22 kg P ha^{-1}) was lost from 240 m^2 border-dyke irrigation bays when irrigation was applied within a few days of application.

Generally, the potential for superphosphate to be lost in either overland flow or drainage decreases exponentially with time such that the concentration of P lost from plots with superphosphate will equal the concentration of P lost from plots without superphosphate after 30-60 days (McDowell et al., 2003a). However, the potential soon after application is directly related to the solubility of the fertiliser applied with superphosphate > serpentine super > reactive phosphate rock (McDowell and Cato, 2005). If superphosphate cannot be applied at a time when P loss is unlikely or soils are hydrophobic, such as in summer dry country on the east coast of the North Island, then consideration should be given to applying a lower solubility P fertiliser to minimise losses.

The variability and contribution of P loss from a typical grazed pasture is probably best illustrated in Table X, which shows the contribution to farm P losses from various forms of P fertiliser applied at 30 kg P ha^{-1} at times when overland flow was likely (June) and unlikely (December) in Southland. Losses from the farm were on average 1 kg P ha^{-1} yr^{-1} for the two years of monitoring. This means that following good practice, superphosphate contributed a maximum of 9% of farm P losses, but 24% if advice was not heeded and superphosphate was applied in June.

TABLE X Mean load (± 0.02 kg ha^{-1}) of P loss estimated via application of P fertilisers in either June or December for two years via overland flow from a grazed pasture in Southland, New Zealand (from McDowell and Cato, 2005).

Application date	Superphosphate	Pasture-Zeal®	Serpentine super	Reactive phosphate rock
2002				
June	0.24	0.16	0.14	0.01
December	0.04	0.02	0.01	0.01
2003				
June	0.23	0.14	0.11	0.01
December	0.09	0.04	0.01	0.01

2.3. The loss of P via dung or manure

There are numerous systems that have P losses from dung as a component. In dairy or beef farming with a component of pastoral grazing the loss of dung or manure-P can make up a considerable component of P lost from the farm. Excluding effluent blocks or fields that have had manure spread on them P loss from cattle dung on grazed pastures stocked at 3 cows ha^{-1} can expect to contribute about 30% of annual P losses. However, this varies greatly depending soil conditions (i.e. treading damage), and the interaction of grazing events, soil conditions and rainfall events. For instance, in warmer climates cattle will graze outside throughout the year, but in winter soils can be very wet leading to increased risk of P loss due via dung deposition. The occurrence of a highly concentrated source of P with a rainfall event has been termed an incidental transfer and can cause large (e.g., 30 mg P L^{-1}) amounts of P loss (Haygarth et al., 2000; Withers et al., 2001).

In systems where animals spend part of the year indoors animal excreta, termed here as manure, is usually stored until it can be spread on fields. Depending on the resources available this can be spread throughout the farm or restricted to fields closest to the barn. This can lead to elevated soil P concentrations since inputs are seldom matched by product outputs from the field, thus resulting in an increased risk of P loss. For dairy farms, where excreta is washed from the milking parlour, now termed dairy shed effluent, and stored in a pond until spread onto fields, there can be a risk of P build-up since these fields are commonly closest to the milking parlour. Fortunately, the P concentration of effluent is usually less than manure meaning the likelihood of P build-up is lower unless fertiliser additions are not adjusted for P in effluent.

Equally important is the method of manure or fertiliser application (Mueller et al., 1984; Zhao et al., 2001). Surface application or high rates of application can lead to increased risk of P loss in overland flow either by saturating the soil or concentrating P in the topsoil (see section X.X. for more details. To alleviate enrichment of the very top 2 cm of soil and vulnerability to loss by overland flow, manure and indeed fertilisers can be applied below the soil surface (e.g., by direct drilling; Sharpley et al., 1984; Eghball and Gilley, 1999). Depending upon rainfall intensity and slope gradient, the effective depth of interaction (EDI) between overland flow and P in topsoil ranges from approximately 1 to 40 mm

(Sharpley, 1985a). Hence, injection, knifing or incorporation by cultivation removes P from the EDI.

Modifying the timing of application relative to likely flow events can significantly alter P concentrations in flow (Sharpley, 1997; Westerman and Overcash, 1980). Following application, the potential for P loss is large and declines exponentially with time as P interacts with the soil and is converted to increasingly recalcitrant forms and a crust forms on top of the manure or dung patch (Edwards and Daniel, 1993; McDowell et al., 2006). Sharpley and Syers (1979) reported declining DRP (from > 250 μg L^{-1} to <100 μg L^{-1}) and TP concentrations (from > 700 μg L^{-1} to 100 μg L^{-1}) in tile drainage over one month following temporary, intensive grazing of paddocks by dairy cattle. Similarly, Gascho et al. (1998) observed exponential declines in DRP concentrations in overland flow (from > 5000 to < 1000 μg L^{-1}), roughly one month after fertiliser application. Equations generated from the decline in P concentrations lost in overland flow with time since deposition from dung can be used to model the contribution of dung-P to overall P losses from a grazed field. This is explored further in section X.X.

3. The Transport and variability P loss from pastures

While we must consider sources of P such as soil, fertiliser and dung/manure/effluent, the load of P lost from grazed pastures will be dictated by the volume of runoff. In other words, the transport of P in flow determines whether potential losses are translated into actual losses.

Rainfall is the primary driving force behind transfer, although some movement of P via wind erosion is also likely to occur in some regions. Rainfall events can be classified as those of:

- Low intensity and high frequency that tend to move P either in subsurface flow or overland flow in saturated areas.
- High intensity and low frequency that tend to move P by exceeding the soil's infiltration capacity and producing overland flow from a thin layer of P-rich topsoil (Figure X).

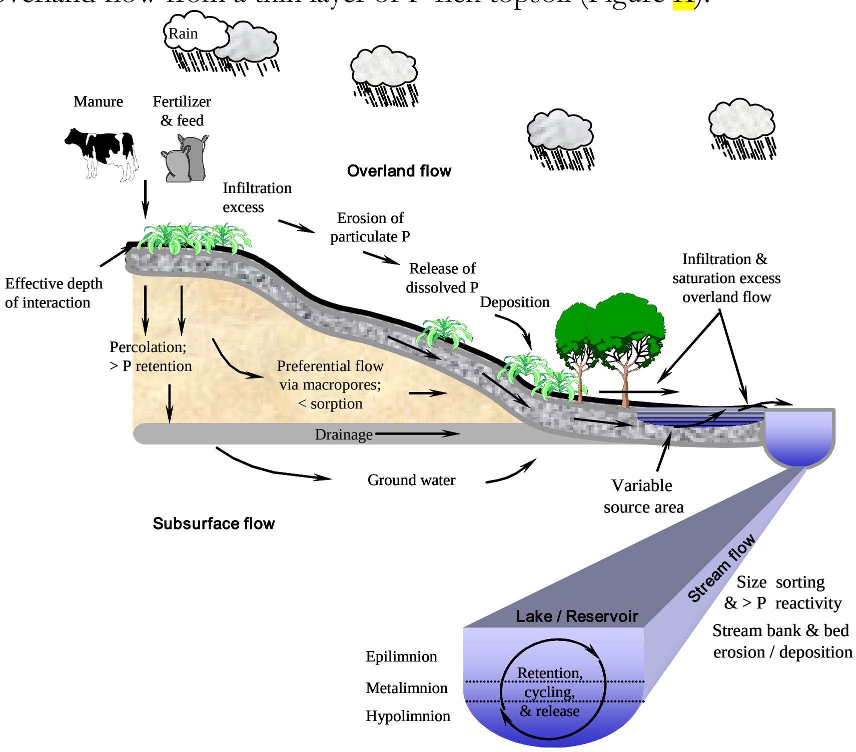

Figure X. Conceptual diagram of processes that transport P from the landscape to surface water (adapted from McDowell et al, 2004).

Due to the greater kinetic energy and erosive power of high frequency storms, more P is lost during overland flow in particulate forms than in subsurface flow. For example, Pionke et al. (1996) showed that a few short, intense storms accounted for about 90% of the annual P export from an upland pasture catchment. Similarly, Hortonian overland flow (limited by infiltration rate) will likely have a greater capacity to detach and move soil particles than overland flow caused by saturation-excess conditions (limited by soil water storage capacity).

In humid and temperate climates, saturation-excess overland flow is described by variable source area (VSA) hydrology (Ward, 1984). Flow from these areas varies with time, expanding and contracting rapidly during a storm as a function of precipitation, temperature, soil-type, topography, ground water and moisture status over the catchment. The onset of flow from these areas is limited by soil water storage capacity and thus usually results from high water tables or soil moisture contents in near-stream areas. During a rainfall event, area boundaries will migrate upslope as soils saturate. In dry summer months, overland flow will come from areas closer to the stream than during wetter winter months, when the boundaries expand away from the stream channel. In catchments where infiltration-excess overland flow dominates, areas of the catchment can alternate between sources and sinks of overland flow, as a function of soil properties (largely infiltration rate), rainfall intensity, duration and antecedent moisture condition.

Transport and loss of P generally occurs from areas where overland flow contributes to stream flow, although some subsurface flow pathways may be important under certain hydrologic conditions. Loss of P in subsurface flow is generally less than that in overland flow, and will decrease as the degree of soil-water contact increases, due to sorption by P-deficient subsoils (Haygarth et al., 1998). Exceptions occur where organic matter may accelerate P loss together with Al and Fe, the soil has a small P sorption capacity (e.g., some sandy soils), or where subsurface flow travels from P-rich topsoil via macropores or is intercepted by artificial drainage (Figure X).

The importance of hydrology, and in-turn P losses, varies with scale. While laboratory studies using repacked or intact soil boxes have elucidated many mechanisms involving P losses in overland flow, the relevance of these to field losses *per se* is unclear (e.g., Sharpley, 1985a; 1995; Srinivasan et al., 2002). In plot studies, the hydrologic response time or the time taken for flow from the farthest point of the plot to reach the monitoring point is smaller compared to field scale studies. Furthermore, rainfall intensity declines logarithmically with time meaning that we can approximate peak flow from a plot as proportional to the contributing area (Smith, 1992; Nash et al., 2002). As such, peak flows per unit area from a plot are likely to be greater than from a field. This is commonly found when sediment loads from small plots (20 m^2) are upscaled and found to be much larger than that from much larger plots (500 m^2) (Le Bissonnais et al., 1998). However, when rainfall and overland flow are constant, longer flow paths will tend to have greater and faster flow volumes and erosion than smaller plots, but also more opportunity for the selective erosion of P-rich fines.

We have begun to realize that P loss does not occur from the entire catchment and small areas within the catchment can dominate P losses to streams. The dominance of these small areas, termed critical source areas (CSAs), is dependant upon many factors, including soil type, topography, management (e.g., inputs of fertiliser and manure/effluent, and off-takes in crops or forage), and transport processes that are dependant upon environmental and hydrological conditions. The interaction between these factors is complex and varies spatially and temporally. However, in general, CSAs are defined by a high concentration of P available to flow and a high potential for flow, equating to a high potential for loss. Mapping these areas in a geographic information system enables the user to better target best management practices to get the maximum P loss mitigation (this will be explored in more detail in section X.X).

4. **Management to decrease P loss**

Effective nutrient management ultimately aims to balance farm P inputs with off-takes in produce, while efficient mitigation of P loss from the landscape involves placing P away from CSAs likely to lose much P. There are numerous options available to pastoral farmers to mitigate the potential for P loss, which include:

- Use of soil testing to guide future P application.
- If excessive soil test P concentrations exist, have a negative P balance to decrease them to the agronomic or economic optima.
- Establishing riparian or buffer strips in near stream areas to prevent P loss by overland flow. No grazing should be allowed in these areas, but hay or silage should be cut to harvest nutrients. The effectiveness of buffer strips depends on their width, vegetation density, soil characteristics (e.g., water infiltration rate and P sorption capacity), vegetation type, placement within the landscape, and slope (Fennessy and Cronk 1997). Quinn et al. (1993) estimated a dense grass buffer strip of 10-20 m wide (5-10% hillslope length) was sufficient to remove 60-75% of P from overland flow in areas of medium (15-20°) slope and low (4 mm hr^{-1}) drainage rate. However, the effectiveness of buffer stips decreases with time. Cooper et al. (1995) noted a riparian pasture that had been set-aside for 12 years acted as a source rather than a sink of DRP to receiving waters.
- Fencing off streams and waterways.
- Drainage networks connecting open ditches and mole and tile drains act as a conduit of nutrients to streams bypassing riparian buffers. To minimise this, constructed wetlands could be located at the end of tile and mole drains and vegetation management implemented in open ditches (Raisin and Mitchell, 1995). Alternatively, if it is known that sediments in drains are P saturated then periodic drain clearance (*c.* 5 years) will clear this source and also improve water flow.
- Minimising treading damage on wet soils by using feedpads or on-off grazing strategies.
- Feeding supplements to animals that contain no more P than they need
- Avoiding application of fertiliser-P in near stream areas or areas likely to be connected to a stream either by a culvert or natural topography (e.g., an erosion gully, drainage depressions).
- Manure/effluent and soil treatment with amendment to decrease P solubility and potential release to overland flow.
- Decreasing P lost in overland flow, and in most soils decreasing overall P loss (even though subsurface losses are increased) by installing drainage in wet areas.
- Channelling flow from bridges and laneways away from the stream.
- Constructing or channelling flow into wetlands. However, P removal by wetlands declines after a few years or decades depending on loading rates, hydraulic retention time, wastewater characteristics, wetland substratum and wetland areas (Reddy et al., 1995; Fennessy and Cronk, 1997). Removal processes include, sorption-precipitation of DRP by wetland substrate (e.g., soil, gravel, minerals and peat), sedimentation-deposition of PP, and P assimilation by microbial and plant biomass (Reddy et al., 1999).
- For dairy farms: installing an effluent storage system so effluent can be applied in areas unconnected to the stream at times of the year when P loss is less likely (e.g., late spring and summer for most soils, except cracking soils), and distributing manure/effluent over a large area so soil P doesn’t build-up.

- For dairy farms: point sources such as dairy shed effluent can be controlled by treating wastewaters in a two-staged waste stabilisation pond (WSP) system before applying to agricultural land or discharged into receiving waters. Such WSP systems consist of an anaerobic pond and an aerobic pond, which together remove 40-65% of the P (Nguyen and Davies-Colley, 1998). To enhance P removal, wetlands (Cooke et al., 1992; Tanner et al., 1995; 1998) and high rate algal ponds (HRAP), maturation ponds and algae settling ponds could also be used. The high pH (9-11) in HRAP, resulting from algal photosynthesis (Nurdogan and Oswald, 1995; Green et al., 1996) enhances P removal via chemical precipitation with calcium in pond waters.

DETAILED ANALYSIS

5. Estimating P loss from grassland soils

(summarized and adapted from McDowell and Condron, 2004)

5.1. Introduction

There is a need to estimate the potential for a soil to contribute P to overland and subsurface flow from easily measured parameters. Worldwide, work 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 (Breeuwsma & Silva 1992; McDowell & Condron 1999; Pote et al. 1996). However, while such methods have management potential for soils where this relationship is known, it cannot at present be extrapolated with certainty to all soils. This study designed 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.

5.2. Materials and methods

5.2.1 *Soil extractions*

Samples (0-7.5 cm) of 44 soils currently under grassland were collected (Table X), 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: Olsen P, $CaCl_2$-P (McDowell & Sharpley 2001); H_2O-P (an estimate of P in overland flow), determined using a soil to deionised water ratio of 1:300 and a shaking time of 45 minutes before measuring DRP; PSI (P sorption index) (Bache and Williams 1971); Percent P retention (%P remaining after equilibration with a soil P saturating solution, buffered at pH 4.6) according to Saunders (1964); Total P (Crosland et al. 1995).

5.2.2 *Additional analyses*

Laboratory tests to estimate overland and subsurface flow were calibrated against literature data and rainfall simulation studies of 11 intact pasture soils (Woodlands (Dystrochrept); Waikiwi (Dystrochrept), Mataura (Orthent), Northope (Aquept), Pukemutu (Fragiudalf), Waikoikoi (Fragiudalf), Waitahuna (Fragiudalf), Lismore (Ustochrept), Rotoiti silt loam (Vitrand), Taupo sandy silt (Vitrand) and Ngakuru loam (Udand)) soils (Table X). All soils were taken in triplicate from to a 5-cm depth using either a turf cutter. 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 6 small (2 mm diameter) holes drilled for some drainage. 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 one week of collection. Additional data for DRP loss in subsurface flow from Woodlands silt loam soils were taken from McDowell & Monaghan (2002).

5.3. Results and discussion

5.3.1 *Laboratory extractions for P loss estimations*

Soil chemical data are given in Tables X and X. 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 X). The soils selected to evaluate a quick laboratory test to predict P in overland flow represent a wide ranging sub-set 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).

Table X Range of physiochemical parameters among the different soil orders used in this study.

Classification	pH	Organic C (g kg^{-1})	Olsen P (mg kg^{-1})	Total P (mg kg^{-1})
Udands	5.7-6.5	35-103	7-57	573-2746
Dystrochrepts	5.1-7.0	25-86	8-46	341-1169
Aquepts	5.7-6.5	17-40	10-54	633-1218
Humults	5.7-6.8	43-50	11-19	938-1559
Ustoll	6.8	43	92	1291
Udox	5.7	102	10	1413
Fragiudalfs	5.6-6.2	18-43	16-88	390-1236
Ustochrepts	5.5	38-49	15-18	524-707
Orthod	5.4	130.4	37	597
Vitrands	5.1-5.7	51-93	14-80	560-1585
Orthents	5.3-6.1	31-54	11-16	560-1255
Hapludults	5.2-5.4	20-34	10-18	116-439

Table X 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
$CaCl_2$-P (mg $litre^{-1}$)	0.143	0.032	0.003	0.944
H_2O-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

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 (Beauchemin et al. 1996; Ryden & Syers 1975). Thus for subsurface flow, a short-term (30 min) extraction of soil with 0.01*M* $CaCl_2$ 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 recently used for the prediction of P behaviour and concentration in subsurface flow in the UK, USA and New Zealand (McDowell unpublished; McDowell & Condron 1999; McDowell and Sharpley 2001; McDowell & Monaghan 2002; Blake et al. 2002). The data for these studies is plotted in Figure X and shows a good relationship between P in subsurface flow and $CaCl_2$-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 to subsurface flow. Rainfall simulation data from Sharpley & Smith (1989), Pote et al. (1999), McDowell & Sharpley (2001) and McDowell et al. (2003b) was used to calculate the mean likely enrichment ratio (degree of P enrichment of sediment in overland flow compared to source soil) for more than 200 soils under pasture. This was calculated as approximately 3 for a 45 minute 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 to USA studies that commonly use > 5 cm h^{-1}) a soil to water ratio of 1:300 was derived (McDowell et al. 2003b). Once filtered, the P measured in this extract was termed H_2O-P.

Using this laboratory extraction procedure, H_2O-P in surface soil was estimated and compared to that generated from a 45-minute rainfall simulation of eleven intact grassland soils (each with 3 replicates) from across New Zealand with a range of P concentrations in topsoil. As with the relationship between $CaCl_2$-P and DRP in subsurface flow, a good relationship was gained between DRP in overland flow and H_2O-P (Table X; Figure XB).

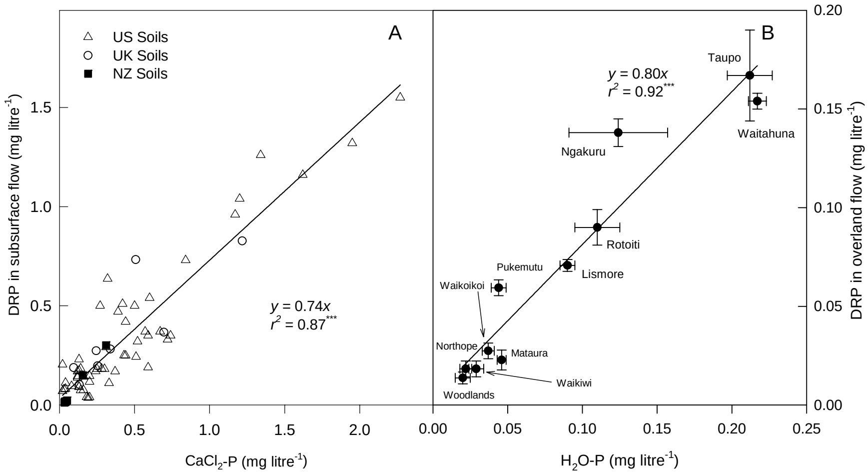

Figure X Relationship between DRP in subsurface flow and $CaCl_2$-P for US (McDowell & Sharpley 2001), UK (McDowell & Sharpley 2001) and NZ (McDowell & Monaghan 2002; McDowell unpublished) soils (A), and between DRP in overland flow and H_2O-P for selected New Zealand grassland soils (B). Error bars are the standard errors for 3 replicates.

5.3.2 *Predicting $CaCl_2$-P and H_2O-P*

Following an analysis of the data for correlations between $CaCl_2$-P or H_2O-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 $CaCl_2$-P; 0.760, 0.387 and 0.418, respectively for H_2O-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 $CaCl_2$-P or H_2O-P was found to be highly significant ($P < 0.001$) with the added benefit of simplicity and no superfluous terms. We therefore propose this as an easy method of predicting $CaCl_2$-P or H_2O-P (Figure XA). However, the linear regression shown in Figure XA is dependent upon a few data points with much leverage, especially for $CaCl_2$-P data.

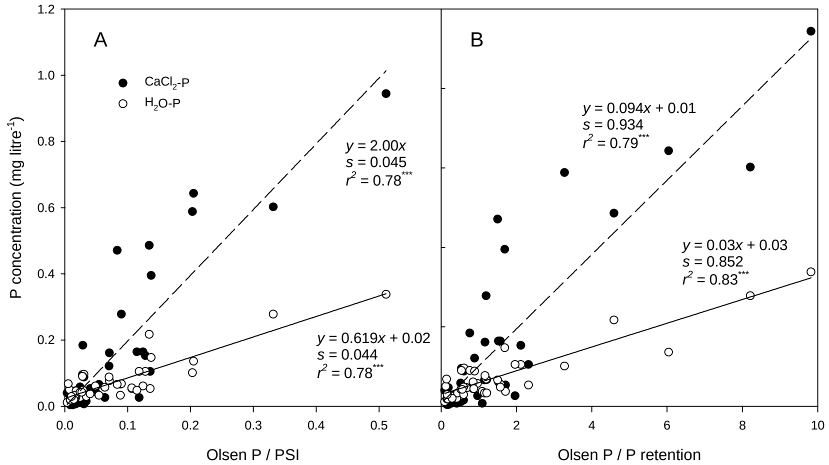

Figure X Linear regressions for the relationships between DRP concentration in $CaCl_2$-P or H_2O-P and the quotients of Olsen P and PSI (A), and Olsen P and % P retention (B) for 44 New Zealand grassland soils.

The choice between using the Olsen P and PSI or P retention quotient to estimate $CaCl_2$-P or H_2O-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. As such, the quotient of Olsen P and P retention could provide the most useful method of determining the potential concentration of H_2O-P and $CaCl_2$-P. However, caution should be employed when extrapolating this to P in overland and subsurface flow. 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 H_2O-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 to 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, soils overland flow boxes 1-m long. Recent work has shown that scale can affect the concentration of P in flow (McDowell & Sharpley 2002). By combining equations in Figs 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 or = 0.024 (Olsen P / P retention) + 0.024.
DRP concentration (subsurface flow) = 1.480 (Olsen P / PSI) or = 0.069 (Olsen P / P retention) + 0.007.

6. **Determining the soil contribution to P loss from grazed pastures**

(summarized and adapted from McDowell et al., 2007 and unpublished data)

6.1. Introduction

The sources of the P exported during and after grazing may be a combination of fertiliser, excreta, and plant and soil pools. However, data on the relative contributions of each of these sources is sparse. Several studies have shown that the P mobilised from dung is an order of magnitude greater than soil when dung or manure is wet, but declines quickly as dung dries (e.g., McDowell et al., 2006; Smith et al., 2001). The contribution from fertiliser also declines quickly with time since application. The contribution from soil to P exports varies according to the size of the pool of P available for mobilisation, which can be determined using the technique outlined in section X.X.. This pool is influenced by a number of factors such as soil moisture, soil sorption capacity and strength and treading.

Accounting for P exports from fertiliser and dung in a grazed pastoral system in Southland, New Zealand, McDowell et al. (2006) estimated that fertiliser made up 10% of exports, dung 30-40% and the remainder was from soil P. These results are consistent with other calculations for fertiliser contributions to annual P exports of < 10% (McDowell and Catto, 2005). However, a question remains around the proportion of P exported directly from soil and what is the influence of other factors such as the treading, plant damage and sources such as grazed pasture.

Pastures in Australia and New Zealand are grazed on average 14-16 times a year. Often grazing coincides with high rainfall periods and the associated overland flow (Nash et al., 2000). Without an understanding of the relative contributions of soil, pasture, and dung (assuming fertiliser losses can be minimised by good management) to the P exported from these systems, there are severe limitations on the development of effective and targeted remedial strategies. This section outlines a study that compares the relative contributions of soil, treading by cattle, dung and pasture to P losses in overland flow from a grazed pasture system.

6.2. Materials and methods

6.2.1 *Soil treatments*

The soil (Waikiwi silt loam: Typic Dystrochrept) was taken from the Woodlands research station near Invercargill, Southland, New Zealand. The site was a permanent ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture and had a moisture content of 0.43% ($v\ v^{-1}$) ± 0.02%.

One hundred intact soil blocks were taken using a 1-m long, by 20-cm wide metal cutting blade to 10-cm depth. The pasture had a 95% ground cover (*c.* 1.8 mg dry matter [DM] ha^{-1}). Soil turves were placed in boxes, 1-m long by 20-cm wide by 10-cm deep. The 100 turves were divided equally into one of four treatments:

1. grazed pasture
2. grazed pasture + soil
3. grazed pasture + soil + treading
4. grazed pasture + soil + treading + faeces

These are referred to from here as treatment 1 = pasture, treatment 2 = pasture + soil, treatment 3 = treaded, and treatment 4 = dung. Grazing was simulated on all treatments by hand pulling pasture until a cover of about 1300 kg DM ha^{-1} was reached (determined by rising plate meter). Grazed pasture in treatment one was separated from the soil surface by pouring molten petrolatum along the side of the soil and box until level with the soil surface. Treatment 2 was grazed and otherwise unaltered. Treatments 3 and 4 were each treaded upon by an artificial cow hoof eight times (20 imprints m^{-2}) to simulate treading during a 24-36 h grazing event (McDowell et al. 2003c). The artificial cow hoof was modelled on a 2 y-old Friesian cow hoof and delivered 250 kPa of pressure over a 90 cm^2 area (Di et al., 2001). Turves in treatment 4 each received a 0.5 kg dung pat (moisture content *c.* 88%) placed within a 20 cm diameter metal ring at the upslope end of each box - typical of dung deposition for a 24-36 h grazing period (Haynes and Williams, 1993). The metal rings were removed, and soils left outside and inclined at 3% slope (similar to that found at the sampling site). One set (4 boxes) of each treatment was moved into an indoor artificial rainfall facility 0, 1, 3, 7, 19 days after imposing treatments, rained upon at 25 mm hr^{-1}, and overland flow (1.5L) collected.

6.2.2 *Water, Pasture, Dung and Soil Analyses*

Water soluble P (WSP) was measured in fresh dung using the method of Wolf et al. (2005), and cut pasture (0.2 g dry weight equivalent shaken with deionised water for 60 min, filtered (0.45 µm) and WSP determined on filtrate). WSP was measured as per section X.X. Subsamples of dung, pasture and soil were also dried and ground to pass a 1-mm sieve. On these samples, total P was determined (Crosland et al. 1995). Soils were also analysed for Olsen P. Macroporosity (percentage of pores > 30 µm) measurements were made using the method outlined by Drewry and Paton (2000).

Overland flow samples were immediately filtered (< 0.45 µm) and analysed for DRP within 24 h, and total dissolved P (TDP) after acidified persulphate digestion within 48 h (Eisenreich et al., 1975). An unfiltered sample was also digested and total P measured within 7 days. Fractions defined as dissolved unreactive (largely organic P) DURP and PP were determined as TDP less DRP and TP less TDP, respectively.

6.3. Results and discussion

6.3.1 *Soil hydrology*

Among the four treatments the time taken for overland flow to begin ranged from < 1 min in the pasture treatment to about 18 min in the pasture and soil treatment (Figure X). In the pasture treatment, the use of petrolatum ensured that only infiltration-excess overland flow occurred. All other treatments presumably had a combination of infiltration-excess and saturation-excess overland flow.

The mean soil macroporosity to 10 cm depth was 12% (Table X). These pores are likely to have drained at field capacity (i.e. before treatments were rained upon) and effectively form the major part of the soil's water holding capacity. To 10 cm depth there was 20,000 cm^3 of soil per turve of which 12% ($v\ v^{-1}$), or 2400 cm^3, could hold water. At a rainfall intensity of 25 mm h^{-1} this equates to about 29 minutes, meaning that under saturation-excess conditions and 100% access of water to those pores, collection of 1.5 L of overland flow would occur after 47 minutes. This was close to the results for the pasture and soil treatments (Figure X). However, as with time to overland flow, the two treaded treatments took less time and improved as the interval between treatment and experimentation increased. Such results are consistent with smearing of the soil surface restricting water infiltration and compaction decreasing macroporosity. Indeed, over a 1 hour period, McDowell et al. (2003c) noted that macroporosity affected both time to overland flow and overland flow volume (i.e. greater macroporosity caused a decrease in the overland flow produced over their 1 hour collection time).

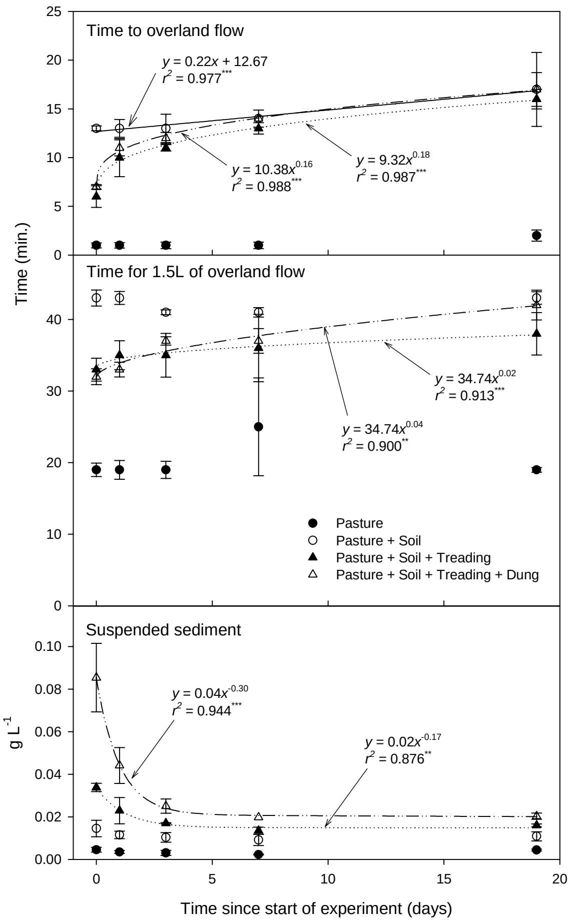

Figure X. Variation in the mean time to overland flow, the mean time taken to generate 1.5L of flow and mean suspended sediment concentration with time since the start of the experiment. Bars represent the standard error of the mean.

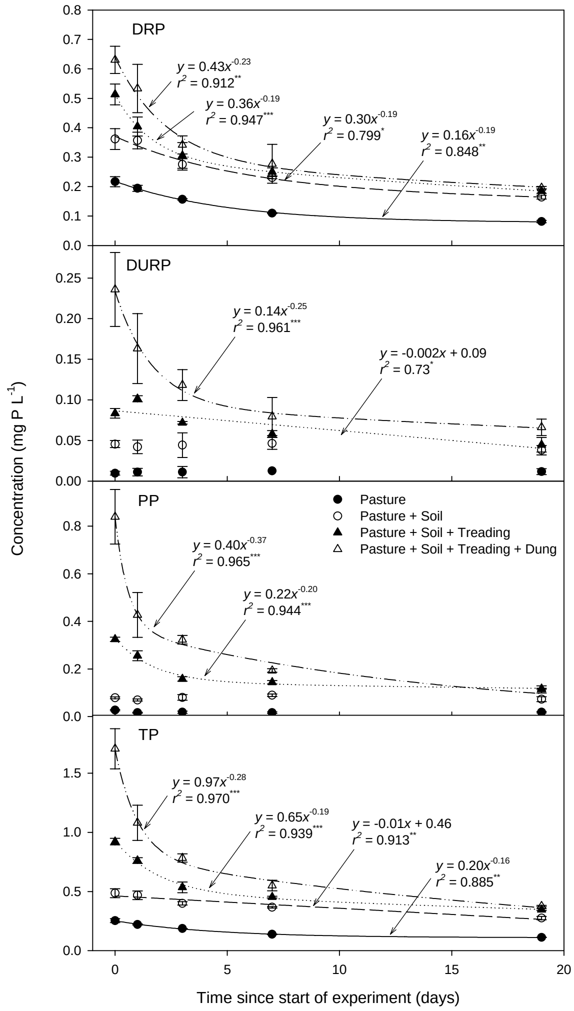

Figure X. Variation in the mean concentration of P fractions with time since the start of the experiment. Bars represent the standard error of the mean.

Table X. Mean general physical and chemical characteristics of the soil (10 cm depth unless specified), pasture and dung used in this study. Standard error of the mean is given in parentheses.

Characteristic	Sample	Concentration
Bulk density (g cm^{-3})		1.0 (0.02)
Macroporosity % (v v^{-1})		12 (0.5)
Field capacity % (v v^{-1})		49 (1.2)
Olsen P 0-7.5 cm (mg kg^{-1})		25 (2)
H_2O-P (mg kg^{-1})	Pasture (dry weight basis)	1.3 (0.23)
	Soil 0-7.5 cm	2.4 (0.13)
	Dung (dry weight basis)	626 (6.1)
Total P (mg kg^{-1})	Pasture (dry weight basis)	2600 (16.5)
	Soil 0-7.5 cm	703 (21.9)
	Dung (dry weight basis)	4567 (179.0)

6.3.2 *Phosphorus losses*

Data for the mean concentration of P fractions lost during each event are given in Figure X. Without exception, the mean concentration of P fractions declined with time in the two treaded treatments. However, of TP fractions, only DRP showed any significant decline with time in the pasture and pasture and soil treatments. The trend has been attributed to dung drying which decreases P desorption and access of rainfall to wet dung when a crust forms (McDowell, 2006) and may also affect the rate of P diffusion from internal to external surfaces.

The greatest loss of P fractions among treatments generally occurred from the treaded and dung treatment followed by the treaded > pasture and soil > pasture treatments. To determine the relative difference among treatments a potential load for P loss was calculated assuming 1 L of overland flow for 30 days – a common period between grazing in these regions. The results in Table X compare the relative load among treatments, the contributing percentage of each P fraction to load (vertical), and the percentage of each P fraction lost from pasture, soil, treading and dung for each P fraction (horizontal) – obtained from treatment 1 = pasture and by subtracting treatments 2 from 1 = soil, 3 from 2 + 1 = treading, and 4 from 3 + 2 + 1 = dung. In general, DRP accounted for most TP in all treatments. However, due to more PP in the treaded and dung treatments, DRP accounted for less TP than in the pasture or pasture and soil treatments. This implies that as a proportion of TP very little DURP was lost in overland flow.

Table X. Matrix of relative risk for each treatment and P fraction, and the percentage of P fractions in each treatment relative to total P and P fractions due to pasture, soil, treading and dung (e.g., by difference of contribution from pasture = P+S – P treatments).

	Estimated relative risk				Contributed proportion to risk			
	P*	P+S	P+S+T	P+S+T+D	Pasture	Soil	Treading	Dung
					%			
DRP	3.4	6.4	7.7	8.7	39	35	15	11
DURP	0.3	1.3	1.9	2.8	12	36	20	32
PP	0.6	2.4	2.4	7.2	8	25	31	36
TP	4.5	9.6	9.6	18.5	24	28	20	25
	Contributed % for each P fraction							
DRP (%)	86	61	55	46				
DURP (%)	8	14	13	15				
PP (%)	6†	15	33	39				

*Codes for treatments are: P = pasture, P+S = pasture and soil, P+S+T = pasture and soil and treading, P+S+T+D = pasture and soil and treading and dung.

†Percentage = 100. Note due to rounding that the sum total of P fractions may not equal 100%.

The DRP in the pasture treatment was about half that in the pasture and soil treatment, (Table 2). This suggests that a significant proportion of P mobilised following grazing could originate directly from the plants (excluding treading or dung deposition). This P may come directly from P stores in the plant or from disrupted cells and xylem and phloem exposed to overland flow. Studies of decomposing residues and hayed-off pastures (*Phalaris tuberose*; *Trifolium subterraneum* mix) have shown from 68-90% of total P leached is water soluble molybdate reactive (inorganic) P (Sharpley and Smith, 1981, Bromfield and Jones 1972). Using these data, and a P concentration in pasture of 2.5 to 4.5 g kg^{-1}, Nash and Halliwell (1999) estimated that the pastures studied by Bromfield and Jones (1972) contained between 15-56 kg WSP ha^{-1}. If the soil P concentration is maintained within the optimum range for maximum potential pasture production then a ryegrass and white clover pasture should typically contain 3 g P kg^{-1} dry matter (Cornforth, 1984). This means that for a pasture producing 15 Mg dry matter ha^{-1} y^{-1} and a mean water soluble P concentration of 75%, an average WSP of 34 kg P ha^{-1} is potentially available for mobilisation. Clearly, not all of this will be available to overland flow as diffusion from the internal store to the plant surface will limit supply (i.e. rate of P availability). Field data on flood irrigation of bays published by Nexhip et al. (1997) and Mundy et al. (2003) have shown that P exports in surface drainage from mown control bays under flood irrigation were greater than exports from bays that had cattle grazing at 100 and 200 cows ha^{-1}. In contrast, our data indicated that in our cattle grazed pasture (dung treatment) the influence of P from the pasture was less. This may be due to the resorption of P from overland flow either by SS (Sharpley et al., 1981) or the soil itself.

In this study, the contributions of PP to TP in overland flow were higher in the treading treatments. We used treading damage equivalent to a day's grazing. However, at higher rates of treading more PP and SS loss may occur (see section X.X). The vulnerability of soil to physical damage, and relative proportions of sediment and PP in overland flow will depend on a number of factors such as soil P concentration, erosivity and occurrence of overland flow, pasture cover, slope, stocking rate and soil type (Dunne et al., 1991). This study has also shown that dung deposited by grazing cattle increases the concentrations of DRP and PP in overland flow (Figure X), but increases PP proportionately more than DRP (Table 2).

6.3.3 *Application to source identification*

Assuming the model conditions used in this study reflect the field environment, the data from this and related studies were used to estimate P exports from a two-year trial in Southland, New Zealand. Soil on the trial site was a Pukemutu silt loam (Typic Hapludalf) grazed with dairy cattle. Phosphorus exported in overland flow from eight, 16 × 30 m hydrologically isolated plots was about 0.3 kg P ha^{-1} (12 events) in 2002, and 0.8 kg P ha^{-1} (20 events) in 2003. Runoff occurred between May and November and the mean soil Olsen P concentration averaged 30 mg kg^{-1} and ranged between 22 and 50 mg kg^{-1}.

The equation in section (X.X) was used to determine the contribution of dissolved P derived from grassland soils (soil and pasture and pasture treatments) in overland flow (Table 3, Figure X). The soil and pasture-P component included an additional 25% extra P to account for PP not estimated this equation but found to be ≤ 25% during subsequent fractionation (McDowell unpublished data). The equation derived in the present section for DRP export in overland flow from the pasture treatment was used to estimate the pasture only component. To estimate the contribution from dung the equations in Figure X were combined with those generated by McDowell et al. (2006) and McDowell (2006). Finally, the mobilisation and exports of P with time since superphosphate application was estimated with equations given in McDowell and Catto (2005). About 30 kg of P was applied to all 16 × 30 m plots in September each year (indicated by arrows in Figure X).

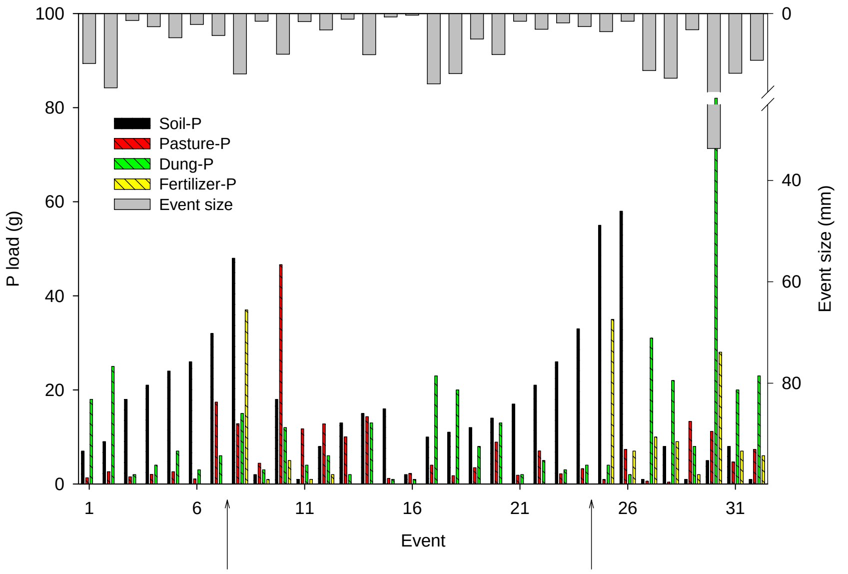

Figure X. Modelled load of P lost in overland flow from events measured during 2002 and 2003 for a dairy cattle grazed trial in Southland, New Zealand. Arrows indicate when superphosphate fertiliser was applied in September each year.

The sum of estimated total P exported was 138% of actual total P lost in 2002 (Table X, Figure X), but almost equal to TP lost in 2003 (95%). Of the estimated P losses, fertiliser comprised 11%, while dung P losses were 23-31% of the estimated TP lost. Soil-P was estimated to occupy 28-47% of total P, while the component from pasture was estimated at 15-21%. This example shows not only the application of data to indicate the potential for P losses at different times of year, but also the relative importance of each source. Since this may vary from region to region these data are invaluable for considering how to better manage P loss. In general, the data implied that to minimise P losses grazing should be timed to occur outside of periods of likely overland flow (including irrigation causing overland flow).

Table X. Modelled individual P loads (percentage of sum in parenthesis) for soil, dung and fertiliser, the sum and the actual load (all kg ha^{-1}) of total P in overland flow from a dairy grazed trial in Southland, New Zealand for 2002 and 2003.

Year	Modelled P load					Actual load*
	Soil-P	Pasture-P	Dung-P	Fertiliser-P	Sum	
2002	0.18 (45)	0.06 (15)	0.11 (28)	0.05 (13)	0.40	0.29
2003	0.22 (29)	0.16 (21)	0.29 (38)	0.10 (13)	0.77	0.81

*Load data taken from Monaghan et al. (2002) and unpublished data.

7. **Spatial management of critical sources areas to best mitigate P losses**
(summarized and adapted from McDowell et al., 2001c; McDowell et al., 2002)

7.1. Introduction

In terms of mitigating P losses the first step is to balance P inputs to farm with outputs in primary production such that no excess P is applied and soil P concentrations are kept at an optimum level for agronomic performance and minimal environmental impact. However, even with this achieved there are parts of the landscape that emit more P than others due to very active hydrology. This requires management to be adaptive and conducted with spatial variability in mind. As such this study compares three options for decreasing P loss in a small catchment; an agronomic soil test P recommendation, an environmental soil test P (STP) threshold, and a P index to rank fields according to their spatial vulnerability to potential P loss.

7.2. Materials and Methods

7.2.1 *Study Site*

The study is a 39.5 hectare sub-catchment of Mahantango Creek (FD-36), a tributary of the Susquehanna River and ultimately the Chesapeake Bay (Figure X). The dominant soils are loamy skeletal to fine loamy, mixed, mesic families of Typic Dystudepts (80% of the catchment) and Typic Fragiudults (20% of the catchment). Slopes within the catchment range from 1 to 20%. Climate is temperate and humid, with an average rainfall of 1100 mm yr^{-1}. The catchment is characterized by mixed land use typical of that found in the North East US (50% soybean, wheat or corn; 20% pasture; 30% woodland). Management of individual fields was obtained from annual farmer surveys. Fertiliser application averaged about 30 kg P ha^{-1} yr^{-1} to soybeans. Manured fields received differing rates, ranging from 60 Mg ha^{-1} yr^{-1} pig slurry (approximately 75 kg P ha^{-1} yr^{-1} and 300 kg N ha^{-1} yr^{-1}) to 5 Mg ha^{-1} yr^{-1} poultry manure (approximately 225 kg P ha^{-1} yr^{-1} and 480 kg N ha^{-1} yr^{-1}).

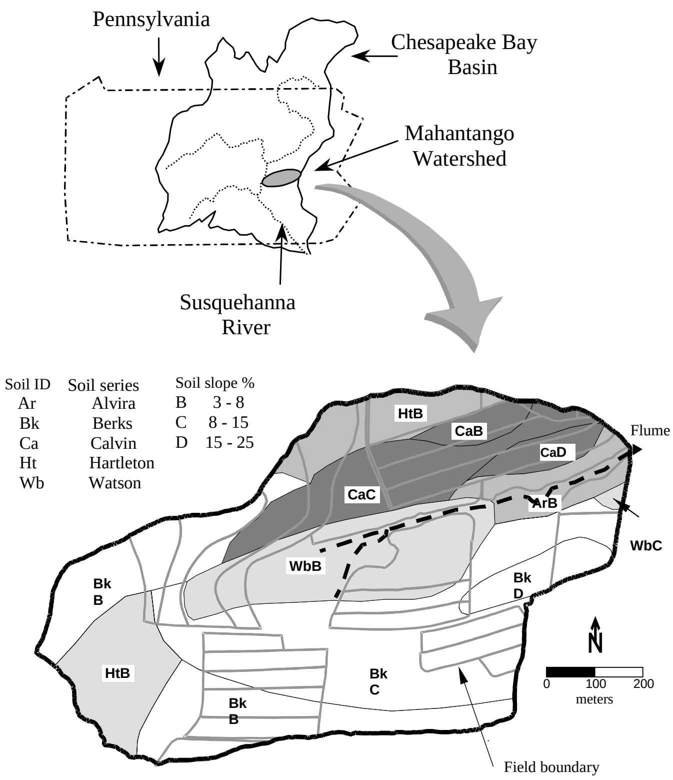

Figure X. Location and arrangement of soil and fields within the FD36 sub-catchment.

Soil samples (0-5 and 0-15 cm depth) were collected on a 30-m grid over the catchment. Soil sampling depths for the agronomic soil test strategy was 0-15 cm and for the environmental soil P test threshold and P index strategy was 0-5 cm (Beegle, 1999; Sharpley et al., 1996). Samples were air dried, ground and sieved (< 2 mm) and STP determined using the Mehlich-3 P method (Mehlich, 1984). The Mehlich-3 extractable P data within each individual field were used to generate a mean concentration for the field, and used as the basis to test each management strategy (agronomic, environmental and the source factor components of the P index).

7.2.2 *Agronomic Soil Test Phosphorus Recommendation*

In this option, manure application rates are based on the recommendations for optimum crop production as detailed in the Pennsylvania soil test program (Table X, soil test program). In other words, if the STP (0 - 15 cm depth) called for a P addition to grow the crop, manure could be applied only to supply the recommended P. If the STP did not recommend any P addition, little or no manure could be applied.

Table X. Summary of the soil test program and Animal Feeding Operations (AFO) crop soil test strategy for Pennsylvania.

	Soil Test Program		Animal Feeding Operation Strategy	
Soil test category† (mg kg^{-1})	Interpretation	Recommendation	AFO Guidance	Typical maximum manure rates for a 6 Mg bushell ha^{-1} corn crop‡
Low < 30	P deficient, high probability of an economic response to P	P recommended to build soil P into the optimum range and maintain it there	Manure rates based on the N requirement of the crop	Dairy 15 Mg ha^{-1} Swine 15,300 L ha^{-1} Poultry 3 Mg ha^{-1}
Optimum 30 – 50	P adequate, low probability of an economic response to P	P recommended to replace crop removal of P and maintain optimum soil P	Manure rates based on 1.5 x P removal by crop	Dairy 7 Mg ha^{-1} Swine 5,050 L ha^{-1} Poultry 0.5 Mg ha^{-1}
High 50 – 100	P more than adequate, no crop response expected to P	No P recommended	Manure rates based on P removal by crop	Dairy 5 Mg ha^{-1} Swine 3,365 L ha^{-1} Poultry 0.3 Mg ha^{-1}
Excessive > 100	P more than adequate, no crop response expected to P	No P recommended	No manure P applied	No manure applied

†Soil test P as Mehlich-3 P, mg kg^{-1}.
‡Uses book values for crop requirement and manure nutrient content (swine is grower pigs, poultry is layers). Assumes spring application with incorporation by tillage or rain 2-5 days after application.

7.2.3 *Environmental Soil Test Phosphorus Threshold*

In this option, a STP concentration (based on a 0-5 cm sampling depth) is established above which the enrichment of P in agricultural overland flow becomes unacceptable (Sharpley et al., 1996). Using the AFO strategy for P threshold, little or no manure or fertiliser could be applied if STP concentration > threshold. The actual thresholds (TH) will most likely be site specific and determined from research like that described below. This approach has a much stronger scientific basis for managing P to protect the environment than does the agronomic soil test option. First, sampling and extraction procedures are developed or adapted specifically for estimating P loss potential from the soil. Second, interpretations are developed based on standardized field calibration research relating the soil P concentration to P in overland flow.

One approach for determining a threshold uses a split-line model that separates the relationship between STP and P in overland flow or subsurface drainage waters into two sections, one with greater P loss per unit increase in STP than the other (Heckrath et al., 1995; McDowell and Condron, 1999). McDowell and Sharpley (2001) give a description and application of the split-line model to determine thresholds. Recent research has shown thresholds occur at the same STP concentration when plotting STP against P in 0.01*M* $CaCl_2$ extracts (0-5 cm depth), overland flow, or sub-surface drainage water (McDowell and Sharpley, 2001; Hesketh and Brookes, 2000; McDowell et al., 2001b; Figure X). Using this method it is possible to define a threshold expressed in STP concentration above which the potential for P loss increases significantly. An environmental threshold of 190 mg Mehlich-3 extractable P kg^{-1} was used in this study (Figure X).

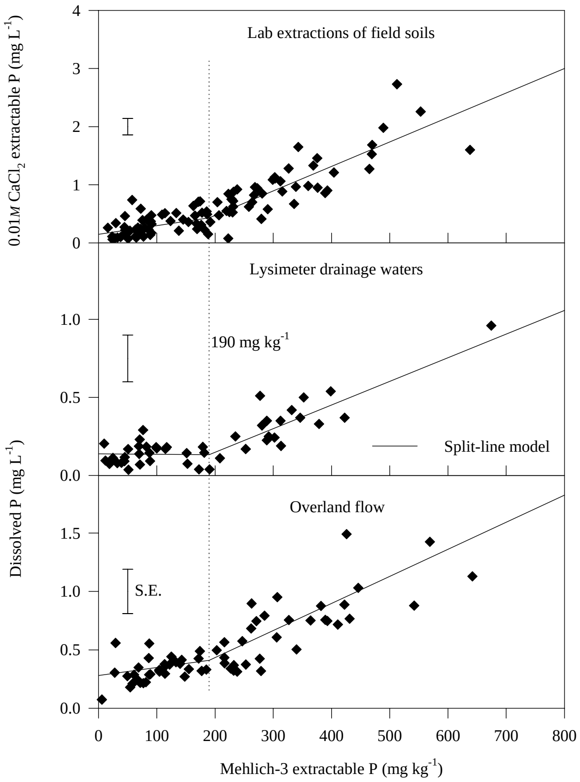

Figure X. The relationship between Mehlich-3 extractable P of surface soils (0–5 cm) and dissolved P in overland flow, subsurface drainage from 30 cm deep lysimeters and 0.01M $CaCl_2$ extractable P (0-5 cm) for soils in a central PA catchment (adapted from McDowell and Sharpley, 2001; McDowell et al., 2001b). The dashed vertical line represents the common value of the threshold at 190 mg Mehlich-3 extractable P kg^{-1}. S.E. is the standard error.

7.2.4 *The Phosphorus Index*

In this option, an index is used to define areas within the landscape that contribute to P losses to surface waters so that management of P applications and/or remedial efforts can be better targeted. Not all areas in a catchment contribute equally to P losses, and that the majority of losses come from a small area in most catchments and result from only a few storm events (Gburek et al., 2000; Heathwaite et al., 2000). For P losses to occur there must be a P source and a mechanism to transport it to surface water. Thus, effective environmental management of P losses requires information on where these two factors overlap.

Many indices have been developed to rank land units (e.g., fields). One has been developed by USDA-NRCS in cooperation with several research scientists (Lemunyon and Gilbert, 1993). An assessment of site vulnerability to P loss in overland flow is made by selecting rating values for individual transport (Table X) and site management factors (Table X) from the P index. A P index value, representing cumulative site vulnerability to P loss from each site, is obtained by multiplying summed transport, source and management factors (Table X). In this P index values are scaled so that the break between high and very high categories is 100. This is done by calculating a site P index value, assuming all transport and source factors are high (erosion is set at 7 Mg ha^{-1} considered a high value for Pennsylvania and soil test P is set at 200 mg kg^{-1} Mehlich-3 P proposed as a non-site specific threshold for Pennsylvania). The break between medium and high and low and medium is calculated using the same method and STP concentrations of 50 and 30 mg Mehlich-3 P kg^{-1} respectively. These coincide with the AFO joint strategy for a manure P applications based on crop removal (> 50 mg Mehlich-3 P kg^{-1}) and N-based manurial applications (< 30 mg Mehlich-3 P kg^{-1}). The AFO guidance based on the joint USDA-EPA strategy for the P index option is outlined in Table X.

Table X. Phosphorus loss potential due to transport characteristics in the PA P index (Part A).

Transport factor	Relative ranking					Field value
Soil erosion	Soil loss (Mg ha^{-1} yr^{-1})					
Overland flow class	0 Very Low	1 Low	2 Medium	4 High	8 Very High	
Leaching potential	0 Very Low	0 Low	1 Medium	2 High	4 Very High	
Connectivity	0 Not connected†	1	2 Partially connected‡	4	8 Connected*	
					Sum transport factors / 27	

† Field is far away from water body. Overland flow from field does not enter water body.
‡ Field is near, but not next to water body. Overland flow from the field sometimes enters water body, e.g., during large intense storms.
* Field is next to a body of water. Overland flow from field always enters water body.

Table X. Phosphorus loss potential due to source and management practices in the PA P index (Part B).

Source factor	*Relative ranking*					Field value
Soil test P	Soil test P (mg P kg^{-1} soil)					
STP rating value	*Soil test P × 0.2*					
Fertiliser P rate	Fertiliser rate (kg P ha^{-1})					
P fertiliser application method and timing	Placed with planter or injected > 5 cm deep 0.2	Incorporated < 1 week after application 0.4	Incorporated > 1 week or not incorporated following application in late spring to early autumn 0.6	Incorporated > 1 week or not incorporated following application in late autumn to early spring 0.8	Surface applied on frozen or snow covered soil 1.0	
Fertiliser rating value	*Fertiliser P application rate × Loss rating for fertiliser P application method and timing*					
Manure P rate	Manure application (kg P ha^{-1})					
P manure application method and timing	Placed with planter or injected > 5 cm depth 0.2	Incorporated < 1 week after application 0.4	Incorporated > 1 week or not incorporated following application in late spring to early autumn 0.6	Incorporated > 1 week or not incorporated following application in late autumn to early spring 0.8	Surface applied on frozen or snow covered soil 1.0	
Manure rating value	*Manure P application rate × Loss rating for manure P application method and timing*					
					Sum source factors	

Table X. Worksheet and generalized interpretation of the P index and manure management.

To solve for P loss rating - add all numbers on Part A and selected numbers on Part B. Write these numbers on the worksheet. Multiply Part A x Part B. This is your final P loss rating.

Part A Value:__________

Part B Value:__________

Multiply A X B = ____________ = _______________ P Index Rating

P index	Interpretation of the P index
Low < 60	LOW potential for P loss. If current farming practices are maintained there is a low probability of adverse impacts on surface waters. Manure applications are based on N content.
Medium 60 – 80	MEDIUM potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss. Manure applications are based on N content.
High 80 – 100	HIGH potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and P management plans are needed to minimize the probability of P loss. Manure applications limited to P removed.
Very high > 100	VERY HIGH potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss. No manure is applied.

Table X. Summary of the Animal Feeding Operations P index strategy for Pennsylvania.

P index risk rating	AFO guidance	Typical maximum manure rates for a 3 Mg ha^{-1} corn crop†
Low <60	Manure rates based on the N requirement of the crop	Dairy 15 Mg ha^{-1} Swine 15,000 L ha^{-1} Poultry Mg ha^{-1}
Medium 60 – 80	Manure rates based on the N requirement of the crop	Dairy 7 Mg ha^{-1} Swine 5,050 L ha^{-1} Poultry 0.5 Mg ha^{-1}
High 80 - 100	Manure rates based on P crop removal	Dairy 5 Mg ha^{-1} Swine 3,365 L ha^{-1} Poultry 0.3 Mg ha^{-1}
Very High >100	No manure P applied	No manure applied

† Uses book values for crop requirement and manure nutrient content (swine is grower pigs, poultry is layers). Assumes spring application with incorporation by tillage or rain 2-5 days after application.

7.3. Results and discussion

7.3.1 *Agronomic Soil Test Phosphorus Thresholds*

Soil test P, measured as Mehlich-3 extractable P on 0-15 cm samples, ranged from 7 to 300 mg kg^{-1} over the catchment, and was generally distributed as a function of land use and field boundaries. Soils in wooded areas had small Mehlich-3 extractable P concentrations (< 10 mg kg^{-1}), while cropped fields receiving manure and fertiliser applications were, in most cases, in excess of optimum crop requirements at 50 mg Mehlich-3 extractable P kg^{-1}. Using the first management strategy using an 'agronomic recommendation', future manure additions are stopped in those fields with a mean STP concentration greater than that required for optimum crop growth, i.e., > 50 mg Mehlich-3 extractable P kg^{-1}. Over the managed part of the catchment, 90% of the soils had Mehlich-3 extractable P concentrations at or greater than 50 mg kg^{-1} and 55% had concentrations > 100 mg kg^{-1} (Figure X, Table X). If P additions were restricted by an agronomic recommendation only 4% of the entire catchment would be eligible (Figure X, Table X).

Table X. Area of the managed portion of the catchment impacted by the various P management strategies.

P recommendation	P management strategy			
	Current	Agronomic soil test P	Environmental soil P threshold	P index
	hectares			
N based	22.3	1.4	3.9	19.8
1.5 × Crop Removal	0	1.6	0	0
1.0 × Crop P removal	0	7.2	11.3	2.5
0.5 × Crop Removal	0	0	6.7	0
No P applied	0	12.2	0.4	0

In addition to being restrictive in terms of limiting future P applications, there are number of problems with using the agronomic threshold approach. The most important is that soil test sampling, extraction, and interpretations were developed strictly based on crop response. In the process of developing the soil test program, no environmental P loss potentials were measured (Beegle, 1999). Therefore, there is no scientific basis for assuming that the agronomic soil test based on crop response will be correlated with environmental impact. Also, this option only measures plant-available P. It does not reflect P that is potentially available in overland flow or to soil solution percolating down the soil profile.

7.3.2 *Environmental Soil Test Phosphorus Threshold*

Assuming an environmental soil P threshold (0-5 cm depth) of 190 mg kg^{-1}, 87% of the total catchment area and 77% of the managed (cultivated and pasture) land has STP concentrations above this value. Using the AFO strategy outlined in Table X, 18% of the managed area of the catchment would be subject to manure applications based on the N requirements of the crop (Figure X, Table 9). Reduced manure applications based on crop P removal and half crop P removal would apply to 51% and 30% of the managed area of the catchment, while no P would be allowed on only 2% (Figure X, Table X).

The difference between agronomic and environmental thresholds is illustrated in Figure X. The critical level for crop response is the point on the dashed line in Figure X where the yield no longer increases as STP concentrations increase. The environmental threshold P is the STP concentration on the solid line where the potential environmental impact becomes unacceptably large. Even if the same soil test extractant is used, it cannot be assumed that there is a direct relationship between the soil test calibration for crop response to P and P loss potential. What will be crucial in terms of managing P based in part on STP concentrations, will be the interval between the threshold soil P value for crop yield and overland flow P (Figure X). However, although rare, it is possible that the critical soil test level for P loss may be above or even below the critical level for crop yield.

Table X. Summary of the Animal Feeding Operations soil P threshold strategy for Pennsylvania.

Soil P threshold level	AFO guidance	Typical maximum manure rates for a 6 Mg bushell ha^{-1} corn crop†
< .75 TH < 150 mg kg^{-1}	Manure rates based on the N requirement of the crop	Dairy 15 Mg ha^{-1} Swine 15,300 L ha^{-1} Poultry 3 Mg ha^{-1}
.75 TH to 1.5 TH 150 – 300 mg kg^{-1}	Manure rates based on P crop removal	Dairy 4.7 Mg ha^{-1} Swine 3,365 L ha^{-1} Poultry 0.5 Mg ha^{-1}
1.5 TH to 2 TH 300 – 400 mg kg^{-1}	Manure rates based on 0.5 x P crop removal	Dairy 2.4 Mg ha^{-1} Swine 1,685 L ha^{-1} Poultry 0.17 Mg ha^{-1}
>2 TH > 400 mg kg^{-1}	No manure P applied	No manure applied

† Uses book values for crop requirement and manure nutrient content (swine is grower pigs, poultry is layers). Assumes spring application with incorporation by tillage or rain 2-5 days after application

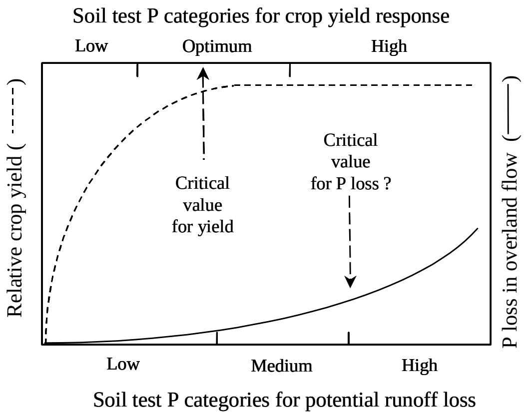

Figure X. As soil P concentration increases so does crop yield and the potential for P loss in overland flow. The interval between the critical soil P concentration for yield and overland flow P will be important for P management.

7.3.3 *The Phosphorus Index*

Applying the third management strategy a 'P index' to the FD-36 catchment identifies different areas of the catchment that represent areas with sources of P and susceptible to transport. None of the catchment is defined as of very high risk of P loss. However, 6% of the total catchment area was defined as of 'high' risk (Figure X). These areas are where high soil P, manure and fertiliser application, and the risk of overland flow or erosion coincide. Using the P index option, P applications would be managed based on the N requirements of the crop over the entire catchment, except in 2.5 ha of land which would be managed according to the P requirements of the crop. The P index management strategy is the least restrictive of the three options to farmers when considering short-term P applications (Table X). Future management to reduce P losses would need to target only 13 and 10% of the managed area of the catchment, deemed of a medium and high risk respectively to P loss (Figure X).

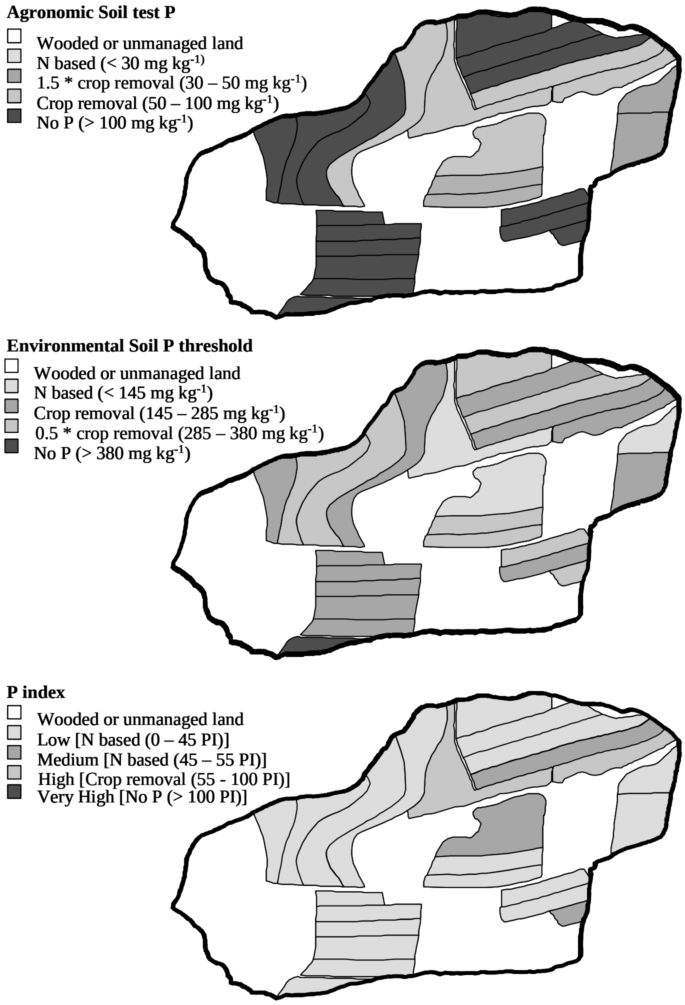

Figure X. The catchment under different strategies for targeting CSAs.

The small area of the catchment targeted for P management by the P index (23%) compared to agronomic (90%) and environmental (82%) STP strategies, is consistent with measured P losses from FD-36. The mean annual flow-weighted concentration of dissolved and total P in stream flow from FD-36 for 1996 to 1999, is 0.05 and 0.075 mg L^{-1}, respectively (Pionke et al., 1999; Sharpley et al., 1999a). These levels are below eutrophic criteria for the region established as 0.1 mg total P L^{-1} for stream or other flowing waters not discharging directly into lakes or impoundments (Dodds et al., 1998; USEPA, 1994). Based on the level of water quality impairment of FD-36, in terms of P loss criteria, there is little justification for major changes in P management at a catchment scale at the present time. Thus, the P-index strategy may be the most prudent management approach, given the relatively low concentration of P in stream flow, as long as targeted conservation measures reduce the potential for P loss during high-risk periods (e.g., storm flow and after land application of manure or fertiliser).

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