

## PHOSPHORUS LEACHING FROM GRAZED PASTURE SYSTEMS IN AOTEAROA NEW ZEALAND: SOURCES, FORMS, EXTENT AND RISK FACTORS

C.W. Gray<sup>1</sup>, W.D. Talbot<sup>1</sup>, M.M. Manning<sup>1</sup>, R. Murray<sup>2</sup>, A.H.C. Roberts<sup>3</sup>

<sup>1</sup>Ravensdown, 312 Main South Road, Hornby, Christchurch 8042, New Zealand

### Abstract

The diffuse loss of phosphorus (P) from agricultural land poses a threat to freshwater quality. While past research has focused on measuring P loss in surface pathways, less attention has been given to subsurface loss (*viz* leaching), probably because many soils have a moderate-high capacity to retain P. Research over the last two decades has challenged this assumption, revealing that P leaching loss can be important for some soils and land management practices. However, the impact of P in drainage on freshwater depends on its connectivity to freshwater and form of P leached. This paper summarises research on P leaching from grazed pasture systems in New Zealand, reporting on the extent and risk factors affecting P loss. Landowners, advisors and regulators can use this information to help minimise P leaching loss and its impact on freshwater quality.

Research has identified several often-interacting factors that increase the risk and extent of P leaching.

- Phosphorus leaching is often proportional to the soil P status. This is because it affects the extent of mobilisation of dissolved and particulate P into soil solution, which subsequently can be leached.
- The anion storage capacity (ASC) is important, because low ASC soils have limited capacity to retain P during subsurface flow, resulting in greater P leaching.
- Phosphorus loss can be higher in soils that contain preferential flow pathways or artificial drains that enable P in drainage to bypass retention by the soil matrix.
- Continuous P inputs to soils can saturate P sorption sites, especially the walls of macropores or very low ASC soils, reducing their ability to retain P from drainage water, resulting in greater leaching.
- The source of P can impact leaching e.g., FDE, rich in P particles, are more susceptible to leaching than P fertilisers containing orthophosphate.
- The timing of P application can be critical, as sources such as soluble P fertilisers can be lost if large drainage events occur shortly after application.
- Selecting the appropriate P fertiliser product can affect P loss, particularly when soluble P products are applied to low ASC soils or high-rainfall environments.
- Irrigation management can impact P leaching, so adjusting irrigation based on soil type may reduce losses.

### Introduction

The diffuse loss of nutrients such as phosphorus (P) from agricultural land can negatively impact freshwater quality (Parliamentary Commissioner for the Environment 2015). Despite P concentrations improving in some monitored New Zealand streams and rivers (McDowell et al. 2019) it is recognised there are still opportunities to further reduce P loss through implementation of mitigation measures, supported by voluntary guidelines and regulation. A key piece of information required to ensure mitigation measures are successful, is knowledge of the different pathways of P loss from agricultural land. Historically, the majority of studies investigating P loss from soils have focused on surface and near surface pathways (Heathwaite and Dils 2000). In comparison, there has been much less research on subsurface (*viz* leaching) P loss, probably because of the assumption that many subsoils have a moderate to high capacity to retain P (Correll 1998). However, research over the last couple of decades in Aotearoa New Zealand and elsewhere has challenged this assumption, demonstrating that P from leaching can be an issue for some soil types and conditions and specific land management practices. Further, if there is connectivity between groundwater and surface water or a direct discharge of water via artificial drains (e.g., mole-tile) to receiving waterways, the P in the drainage water may also contribute to the enrichment of P in freshwater (McDowell et al. 2015; Monaghan and Smith 2004). Despite the work over the last couple of decades, many people are unaware that P leaching loss can be an important loss pathway for some soils and conditions. The aim of this paper is to therefore provide a brief summary of research undertaken on P loss via leaching in grazed pasture systems in New Zealand, reporting on the sources of P, forms of P in drainage, the extent of P loss, but importantly highlighting the main risk factors affecting P loss. This information can be used by landowners, advisors and regulators to assist in the management of P in grazed pasture systems to help minimise P loss via leaching from land and reduce its impact on freshwater quality.

### *Sources of P in grazed pasture systems*

Phosphorus loss from grazed pasture systems comes from a combination of sources including the soil, P fertilisers, animal dung, farm dairy effluent (FDE), and pasture plants (McDowell et al. 2007). Soils supply plants and soil organisms with P but are also often the principal source of P loss (McDowell et al. 2007). Different types of P fertilisers are applied to soil to replenish plant-available P, but some dissolved fertiliser-P may be lost through subsurface flow before it can be retained by the soil or used by plants and soil organisms (McDowell and Monaghan 2015). Farm dairy effluent contains a range of essential plant nutrients, including P, that can be lost through subsurface flow before it can be used by plants and soil organisms (McDowell et al. 2019). Dung from grazing animals contains P, although the amount returned to the soil and therefore the amount of P that potentially could be lost depends on animal type and diet (Haynes and Williams 1993). Plants can also be an important source of P loss when grazing animals tear forage (Mundy et al. 2003), releasing the soluble P that is stored in cell vacuoles (Pate 1976).

### *Forms of P measured in drainage water*

Along with total P (TP), typically three forms of P are measured in drainage water: Dissolved Reactive P (DRP), Dissolved Unreactive P (DURP), and Particulate P (PP). The forms are defined by whether the P is present in the dissolved or particulate fraction (the distinction made by filtration through a 0.45 µm filter membrane), and whether the P is present in an inorganic (reactive) form (reactivity in an acid-molybdate solution) or organic (unreactive) form (Haygarth and Sharpley 2000).

Dissolved Reactive P and DURP both have P present in the dissolved fraction. Dissolved Reactive P is the most immediately bioavailable form of P in drainage water and is largely comprised of orthophosphate ions (Robinson et al. 1994). In contrast, DURP is thought to be made up of largely organic forms of P, some of which (i.e., diesters such as phospholipids) are considered to have a low sorptive capacity in soils. This means that they can have a relatively high mobility in some soils (McDowell et al. 2021; Pizzeghello et al. 2016; Toor et al. 2003). Further, some forms of organic P have been shown to be as bioavailable in water as orthophosphate (Li and Brett 2013), although other forms still require transformation by hydrolysis to orthophosphate (Thompson and Cotner 2018).

The other form of P in drainage water is PP, which, depending on its source, includes both reactive and unreactive forms that are either part of a solid or attached to a solid. Particulate P comprises crystalline P, absorbed P, and P in organic matter that requires transformation to orthophosphate before it is bioavailable in drainage water (Nash et al. 2019). The enrichment of drainage with PP is indicative of preferential flow in soils via macropores (fissures or biopores > 0.03 mm in diameter). This is because PP is usually filtered out during matrix flow conditions (Dils and Heathwaite 1999). It has been found enrichment of PP in drainage is particularly important at the start of the drainage season (Gray et al. 2020), mostly after prolonged dry periods where soil can be washed or slaked from the sides of macropores or other preferential flow pathways e.g. mole fissure and channel network (Monaghan et al. 2005). Particulate P has also been found to be the dominant form of P in drainage from soils amended with FDE (McDowell et al. 2019; Toor et al. 2005), thought to be related to the high proportion P-rich particles (> 60% of TP) that have been measured in FDE (Houlbrooke et al. 2008) and from soils receiving cattle dung (McDowell et al. 2021; McDowell 2008).

### *How much P is lost via leaching?*

A focus of research has been around quantifying how much P is lost via leaching from grazed pasture systems and the factors that affect loss. This has been undertaken in laboratory to field scale studies, measuring P in drainage collected using a range of methods including lysimeters (different sizes and depths), mole and pipe drains and to a lesser extent Teflon cups.

A wide range of P concentrations and loads has been reported (Table 1), although the variation in P loss is not unexpected given that often a combination of different interacting factors can contribute to P loss at any one time in a farm system. What is apparent from these studies is that in general, P loss from grazed pasture systems in relative terms tends to be greater from surface than from subsurface pathways. Although as will be described in the next section, within subsurface pathways, the risk of P loss is greater in soils dominated by preferential (macropore) flow than matrix (through soil aggregates) flow. This is related to the effect soil properties and the contact time between the drainage water and the soil have on P loss.

In addition, despite lower P losses in subsurface flow, studies have reported that DRP and TP concentrations sometimes exceed guidelines recommended for good surface water quality in lowland New Zealand rivers, which

are  $10 \mu\text{g DRP L}^{-1}$  and  $33 \mu\text{g TP L}^{-1}$  respectively (ANZECC, 2000) or the proposed National Policy Statement on Fresh Water standard for New Zealand for DRP of  $18 \mu\text{g L}^{-1}$  (Ministry for the Environment 2019). However, it is important to note that despite P being detected in drainage water, the potential for the P to then impact on freshwater is contingent on several factors. The transfer of P into surface water via groundwater relies on deep drainage of leachate through the soil and vadose zone, and a good connectivity between ground and surface water bodies (McDowell et al. 2015). Or for soils where there are artificial drains (e.g., mole-tile) in place, a connectivity to the receiving waterway (Monaghan and Smith 2004). Even then, the form of P in surface water i.e., inorganic or organic P, dissolved or particulate, along with in-stream physical characteristics, will determine its bioavailability and potential effect on water quality.

#### *What factors affect the risk of P leaching loss?*

Phosphorus loss in runoff is reported as occurring from a combination of background or soil losses and incidental losses (Haygarth et al. 2000). Background losses are P that has had an opportunity to react with the soil and is lost in both surface and subsurface flow events that occur throughout the year. Incidental P losses occur when a concentrated source of available P (e.g., fertiliser, FDE application) and a flow event coincide, sometimes leading to a large but often short-term P loss. Incidental P losses are affected by management decisions such as the concentration, rate and timing of fertiliser/FDE application, the form of P fertiliser applied, source of P, the depth/rate of FDE application, type and rate of irrigation. Both background and incidental P losses are also affected by factors such as rainfall and soil properties which affect the transport of P from the soil to water (McDowell et al. 2005).

#### *Soil P status*

Soil fertility is often the biggest factor affecting P loss, with the risk proportional to the soil P status (e.g., Olsen P concentration) (McDowell et al. 2021). This is because it affects the extent of mobilisation of dissolved and particulate forms of P into soil solution, which subsequently can be lost in surface or subsurface runoff. However, while there are New Zealand studies that have related soil Olsen P concentrations to P loss in surface runoff (e.g., Gillingham and Gray 2006; McDowell et al. 2003a,b), we are unaware of New Zealand studies that have investigated this with respect to P leaching, although there are overseas examples (e.g., Djodjic et al. 2023; Nigon et al. 2022; McDowell and Sharpley 2001; Smith et al. 1998; Heckrath et al. 1996).

#### *Anion storage capacity*

One of the most important soil properties affecting the mobility and potential loss of P is the anion storage capacity (ASC) (i.e., amount of Fe and Al oxides in the soil). This is particularly important in soils where subsurface flow moves through soil aggregates i.e., matrix flow (Carrick et al. 2014). This is because soils with low ASC (i.e., <15%) such as sands or organic soils only have a limited capacity to sorb orthophosphate during subsurface flow. This was highlighted in a study by McDowell and Monaghan (2015) that compared P leaching losses in drainage collected to 35 cm from three grazed sites in Southland, that had soils with different ASC (Table 1). Over an 18-month period, the drainage volume was similar among all three sites (521–574 mm) however, the dissolved P load leached from a Podzol (ASC 55%) was  $1.7 \text{ kg P ha}^{-1}$ , compared to  $87 \text{ kg P ha}^{-1}$  from an Organic soil (ASC <5%) (Table 1).

#### *Preferential flow pathways*

Subsurface P loss has been found to be important in soils that have coarse textures and high stone contents (Carrick et al. 2013), and in some soils with high subsurface clay content (Cox et al. 2000; Jensen et al. 1998), particularly if drainage occurs soon after P application (Nash et al. 2019). The presence of stable macropores in these types of soils can enable preferential flow of drainage, bypassing the soil matrix, resulting in less opportunity for sorption and retention of P from drainage water (McDowell et al. 2019b; Toor et al. 2005; Cox et al. 2000). Carrick et al. (2014) for example reported strong preferential flow and leaching of P (up to  $1.4 \text{ kg TP ha}^{-1}$ ) from a young stony soil that had a subsoil dominated by stones (>60% below 15 cm depth) that received constant-rate irrigation (Table 1). Losses can also be important in soils that have an artificial drainage network (i.e., mole-pipes) that can intercept vertical preferential flow from macropores and transport the P directly into waterways (Monaghan and Smith 2004). Houlbrooke et al. (2008) reported in a study carried out in the Manawatu  $2.55 \text{ kg P ha}^{-1}$  was lost in drainage from a mole-pipe that included a badly timed FDE irrigation event under 'standard' practice when the soils were wet, compared to  $1.68 \text{ kg P ha}^{-1}$  lost via deferred irrigation that excluded the badly-timed event.

### *Saturation of P sorption sites*

There is evidence that long-term inputs and sorption of P in the subsoil of very low ASC soils and the walls of soil macropores (e.g., Sinaj et al. 2002) can lead to sorption sites becoming saturated in P, reducing their ability to sorb P from drainage water, resulting in enhanced P losses (Hooda et al. 2001). Several overseas studies have shown this to be particularly important for soils that have received inputs of organic P such as manure (Liu et al. 2015). In a trial at the Lincoln University dairy farm, McDowell et al. (2019b) showed over a 14-year period, annual application of 30 kg of P ha<sup>-1</sup> from SSP + 10 kg ha<sup>-1</sup> of P from FDE to a free draining, low ASC soil greater P loss (1.461 kg ha<sup>-1</sup> yr<sup>-1</sup>) than from the same soil that received the same amount of P but only from SSP (0.245 kg ha<sup>-1</sup> yr<sup>-1</sup>). Losses were also much higher than from a moderately well-drained soil located at the trial site that received the same rates of either SSP or FDE + SSP (0.12 kg ha<sup>-1</sup> yr<sup>-1</sup>, for both treatments) (Table 1). The enhanced P loss was attributed to several factors including high preferential flow rates through soil macropores, but also due to a gradual saturation of P sorption sites on the walls of the macropores over the 14 years of P from FDE application.

### *Source of P*

There is evidence that the source of P applied can affect the amount of P loss in subsurface flow. Several studies have reported greater P loss from soils amended with FDE compared to water-soluble P fertiliser (McDowell et al. 2019; Carrick et al. 2014). Toor et al. (2004) for example reported the average TP load in drainage measured over two years from a flood irrigated stony silt loam soil under pasture, amended with SSP (45 kg P ha<sup>-1</sup>) and FDE (45 kg P ha<sup>-1</sup>) was 1.95 kg ha<sup>-1</sup> yr<sup>-1</sup>. This compared to 1.10 kg ha<sup>-1</sup> yr<sup>-1</sup> for the same soil amended with only SSP (90 kg P ha<sup>-1</sup>) (Table 1).

Comparison has also been made of the relative loss of P from soils amended with cattle dung and SSP (e.g., McDowell et al. 2008) (Table 1). McDowell et al. (2021) for instance compared P loss from a stony soil with a low ASC (<15%) that had been amended with dung or SSP fertiliser at 45 kg P ha<sup>-1</sup>, and SSP and dung at 90 kg ha<sup>-1</sup>. Higher P losses were measured from the soil amended with dung than SSP, largely due to the greater leaching of P as DURP and PP in the dung treatment. It was suggested this was because the DURP and PP contained in dung have a lower affinity for soil P sorption sites than the orthophosphate, the main form of P in SSP fertiliser, and when applied at the same rate, DURP will be preferentially leached. The study also measured the relative movement of different species of organic P through samples of the aquifer gravels which underlaid the site the soil was located. It found most species of organic P were poorly sorbed and leached at a faster rate than orthophosphate, increasing their risk of enriching groundwater. As previously discussed, many species of organic P are as bioavailable as orthophosphate, hence may present a risk to water quality.

### *Timing of P application*

The application of P fertiliser is obviously critical in maintaining fertility in soils. When applied using best practice (e.g., 4R Nutrient Stewardship; (FANZ 2023)), the direct loss of fertiliser P from grazed systems have been estimated to be small (<10%) (Nash et al. 2019; McDowell et al. 2007). One of the 4Rs is the application of P fertiliser at the right time. Although timing has been shown to be important in affecting P loss in New Zealand systems where surface flow dominates, timing of P fertiliser application in relation to drainage will also undoubtedly be important in determining how much P potentially could be lost, especially from P fertiliser applied to soils where preferential flow through macropores is important, or soils have very low ASC. This is because orthophosphate contained within P fertilisers such as SSP is highly water soluble. So while the P contained in fertiliser after application is diffusing into soil solution and eventually into the soil matrix, which is a relatively quick process occurring within a couple of days (Degryse and McLaughlin 2014), there is a risk of P loss should a large drainage event occur, resulting in preferential flow in soil macropores (Nash et al. 2019). Several authors have defined this risk period to last from 7 to 60 days (with a mean of 21-days) depending on the soil type and climatic conditions, and the loss is exponential (McDowell and Catto 2005). But typically, the longer the interval between the application of P fertiliser and a drainage event, the smaller the P loss.

As noted already, the application of FDE to soils at times when they are wet particularly at high rates, may lead to preferential flow and significant P loss, especially if the soils have mole-pipe drains (Houlbrooke et al. 2008; Monaghan and Smith 2004).

### *P fertiliser product*

Another one of the 4Rs is the application of the right product. In unavoidable situations where soils are located in high rainfall environments, soils are dominated by macropores or have very low ASC, the use of less water-

soluble P fertilisers (e.g., RPR, serpentine super) may well be appropriate to help minimise P leaching from soil. This was investigated by Simmonds et al. (2016), who found significantly smaller losses of both DRP and DURP in drainage from a very low ASC (<2%) acid Organic soil that had been amended with RPR instead of SSP when it been limed to > pH 5.5.

#### *Irrigation management*

Another management factor that can influence subsurface P loss from soils is irrigation (Carrick et al. 2014; Toor et al. 2004). Irrigation increases soil moisture and the likelihood of drainage if the soil's water holding capacity or consideration of subsequent rainfall or irrigation events are not taken into account after P application (Trout et al. 2007). A study conducted in Central Otago examined P loss in drainage over three years on a stony fine sandy textured soil with low ASC (<15%) under uniform irrigation (McDowell 2017). Following soil mapping at the site and adjustment of irrigation rates to match the soil types beneath the irrigator (variable rate irrigation), P loss decreased by about 80%, highlighting the role appropriate irrigation management can play in mitigating subsurface P loss (Table 1).

#### **Summary**

Over the past two decades, research has revealed the potential risk of P loss from land to water through leaching in grazed pasture systems. The extent of this loss is influenced by various interacting factors, such as soil P status, the soil ASC, flow pathways (i.e., matrix, preferential), presence of artificial drainage, extent of P saturation, source of P, timing of P application, types of P fertilisers used, and irrigation practices. The extent of P loss is variable, although typically lower than P losses in surface flow. Despite this, effective management of P loss through leaching in grazed pasture systems is crucial for safeguarding freshwater quality in New Zealand. An understanding of the sources, forms, and influencing factors of P leaching can aid landowners, advisors, and regulators in developing strategies to minimize P loss and mitigate its impact on water quality.

## References

ANZECC 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council– Agriculture and Resource Management Council of Australia and New Zealand, Canberra, ACT.

Barkle G 2008. Evaluating strategic retention of artificial drainage flows for nitrate-N reduction under Waikato conditions © Aqualinc Research Ltd Prepared for Environment Waikato (Report No H06005/1, September 2006).

Carrick S, Cavanagh J, Scott J, McLeod M, 2014. Understanding phosphorous, nitrogen and cadmium transfer through a young stony soil In: Currie, L.D., Christensen, C.L. (Eds.), Nutrient Management for the Farm, Catchment and Community. Occasional Report No. 27. Palmerston North, Fertilizer and Lime Research Centre, Massey University.

Carrick S, Palmer D, Webb T, Scott J, Lilburne L 2013. Stony soils are a major challenge for nutrient management under irrigation development In: Currie, L. D., Christensen, C.L. (Eds.), Accurate and Efficient Use of Nutrients on Farms. Occasional Report No. 26. Palmerston North, Fertilizer and Lime Research Centre, Massey University.

Christensen CL 2013. Duration-controlled grazing of dairy cows: Impacts on pasture production and on nitrogen, phosphorus and faecal microbe losses to water. PhD thesis, Massey University, Palmerston North.

Correll DL 1998. The role of phosphorus in the eutrophication of receiving waters: a review. *Journal of Environmental Quality* 27: 261–266.

Cox JW, Kirkby CA, Chittleborough DJ, Fleming NK, Smythe LJ 2000. Mobility of phosphorus through intact soil cores collected from the Adelaide Hills, South Australia. *Australian Journal of Soil Research* 38: 973–990.

Degryse F, McLaughlin MJ 2014. Phosphorus diffusion from fertilizer: Visualization, chemical measurements, and modeling. *Soil Science Society of America Journal* 78: 832–842.

Dils RM, Heathwaite AL 1999. Phosphorus transport from diffuse agricultural sources: shallow subsurface pathways in grassland soils. In: Louise Heathwaite, editor. Impact of land-use change on nutrient loads from diffuse sources. Vol. 257. Wallingford: IAHS Publications; p. 57–64.

Djordjic F, Bergström L, Schmieder F, Sandström C, Agback P, Hu Y 2023. Soils potentially vulnerable to phosphorus losses: speciation of inorganic and organic phosphorus and estimation of leaching losses. *Nutrient Cycling in Agroecosystems* 127: 225–245.

FANZ 2023. Code of Practice for Fertiliser Nutrient Management. Published by Fertiliser Association of New Zealand. Electronic: 978-0-9951151-0-0

Gillingham AG, Gray MH 2006. Measurement and modelling of runoff and phosphate movement from seasonally dry hill-country pastures, *New Zealand Journal of Agricultural Research* 49: 233-245.

Gray CW, McDowell RW, Carrick S, Thomas S 2016. The effect of irrigation and urine application on phosphorus losses to subsurface flow from a stony soil. *Agriculture, Ecosystems and Environment* 233: 425–431.

Gray CW, McDowell RW, Graham SL, Hunt JE, Laubach J, Rogers GND, Carrick S, Whitehead D 2020. Phosphorus transport in subsurface flow from a stony soil under irrigated and non-irrigated lucerne. *New Zealand Journal of Agricultural Research* 64: 429–443.

Hanly JA 2012. Management practices and technologies for reducing nitrogen and phosphorus losses from soils receiving farm dairy effluent. PhD thesis, Massey University, Palmerston North.

Hanly JA, Hedley MJ, Horne DJ 2008. Evaluation of tephra for removing phosphorus from dairy farm drainage waters. *Australian Journal of Soil Research* 46: 542–551.

Haygarth PM, Heathwaite AL, Jarvis SC, Harrod TR 2000. Hydrological factors for phosphorus transfer from agricultural soils. *Advances in Agronomy* 69: 154–178.

Haygarth PM, Sharpley AN 2000. Terminology for phosphorus transfer. *Journal of Environmental Quality* 29: 10–15.

Haynes RJ, Williams PH 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* 49: 119–199.

Heathwaite AL, Dils RM 2000. Characterizing phosphorus loss in surface and subsurface hydrological pathways. *Science of the Total Environment* 251–252: 523–538.

Heckrath G, Brookes PC, Poulton PR, Goulding KWT 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk Experiment. *Journal of Environmental Quality* 24: 904–910.

Hooda P, Truesdale VW, Edwards AC, Withers PJA, Aitken MN, Miller A, Rendell AR 2001. Manuring and fertilization effects on phosphorus accumulation in soils and potential environmental implications. *Advances in Environmental Research* 5: 13–21.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO 2003. The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. *Proceedings of the New Zealand Grassland Association* 65: 179–184.

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA 2008. Land application of farm dairy effluent to a mole and pipe drained soil: Implications for nutrient enrichment of winter-spring drainage. *Australia Journal of Soil Research* 46: 45–52.

Jensen MB, Jorgensen PR, Hansen HCB, Nielsen NE 1998. Biopore mediated subsurface transport of dissolved orthophosphate. *Journal of Environmental Quality* 27: 1130–1137.

Li B, Brett MT 2013. The influence of dissolved phosphorus molecular form on recalcitrance and bioavailability. *Environmental Pollution* 182: 37–44.

Liu J, Kleinman PJA, Beegle DB, Weld JL, Sharpley AN, Saporito LS, Schmidt JP 2015. Phosphorus and nitrogen losses from poultry litter stacks and leaching through soils. *Nutrient Cycling Agroecosystems* 103: 101–114.

McDowell RW, Sharpley AN 2001. Soil phosphorus fractions in solution: influence of fertiliser and manure, filtration and method of determination. *Chemosphere* 45: 737–748.

McDowell RW, Monaghan RM, Morton J 2003a. Soil phosphorus concentrations to decrease potential P loss to surface waters in Southland. *New Zealand Journal of Agricultural Research* 46: 239–253.

McDowell RW, Monaghan RM, Carey PL 2003b. Potential phosphorus losses in overland flow from pastoral soils receiving long-term applications of either superphosphate or reactive phosphate rock. *New Zealand Journal of Agricultural Research* 46: 329–337.

McDowell RW, Monaghan RM, Wheeler D 2005. Modelling phosphorus losses from pastoral farming systems in New Zealand. *New Zealand Journal of Agricultural Research* 48: 131–141.

McDowell RW, Nash DM, Robertson F 2007. Sources of phosphorus lost from a grazed pasture soil receiving simulated rainfall. *Journal of Environmental Quality* 36: 1281–1288.

McDowell RW 2008. Phosphorus in humped and hollowed soils of the Inchbonnie catchment, West Coast, New Zealand: II. Accounting for losses by different pathways. *New Zealand Journal of Agricultural Research* 51: 307–316.

McDowell RW, Cox N, Daughney CJ, Wheeler D, Moreau M 2015. A national assessment of the potential linkage between soil and ground and surface water concentrations of phosphorus. *Journal of the American Water Resources Association* 51: 922–1002.

McDowell RW, Monaghan R 2015. Extreme phosphorus losses in drainage from grazed dairy pastures on marginal land. *Journal of Environmental Quality* 44: 545–551.

McDowell RW 2017. Does variable rate irrigation decrease nutrient leaching losses from grazed dairy farming? *Soil Use and Management* 33: 530–537.

McDowell RW, Hedley MJ, Pletnyakov P, Rissman C, Catto W, Patrick W 2019a. Why are median phosphorus concentrations improving in New Zealand streams and rivers? *Journal of the Royal Society of New Zealand* 49: 143–170.

McDowell RW, Gray CW, Cameron KC, Di HJ, Pellow R 2019b. The efficacy of good practice to prevent long-term leaching losses of phosphorus from an irrigated dairy farm. *Agriculture, Ecosystems and Environment* 273: 86–94.

McDowell RW, Worth W, Carrick S 2021. Evidence for the leaching of dissolved organic phosphorus to depth. *Science of the Total Environment* 755: 142392.

Ministry for the Environment 2019. Draft National Policy Statement for Freshwater Management. <https://www.mfe.govt.nz/publications/fresh-water/draft-national-policy-statement-freshwater-management>.

Monaghan RM, Horn D, Hedley M, Nguyen L 2002. Water and contaminant load from artificial subsurface drainage systems in New Zealand. Fonterra Research Centre Report.

Monaghan RM, Paton RJ, Smith LC, Drewry JJ, Littlejohn RP 2005. The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. *New Zealand Journal of Agricultural Research* 48: 227–240.

Monaghan RM, Smith LC 2004. Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research* 47: 417–429.

Monaghan RM, Smith LC, Muirhead, RW 2016. Pathways of contaminant transfer to water from an artificially-drained soil under intensive grazing by dairy cows. *Agriculture, Ecosystems and Environment* 220: 76–88.

Mundy GN, Nexhip KJ, Austin NR, Collins MD 2003. The influence of cutting and grazing on phosphorus and nitrogen in irrigation runoff from perennial pasture. *Soil Research* 4: 675–685.

Nash, DM, McDowell, RW, Condon, LM, McLaughlin, MJ 2019. Direct exports of phosphorus from fertilizers applied to grazed pastures. *Journal of Environmental Quality* 48: 1380–1396.

Nigon LML, Kaiser DE, Feyereisen GW 2022. Influence of soil test phosphorus level and leaching volume on phosphorus leaching. *Soil Science Society of America Journal* 8: 1280–1295.

Parliamentary Commissioner for the Environment. 2015. Update report: water quality in New Zealand: land use and nutrient pollution. Wellington: Parliamentary Commissioner for the Environment. p. 29.

Pate JS 1976. Nutrients and metabolites of fluids recovered from xylem and phloem significance in relation to long distance transport in plants. In: IF Wardlaw, Passioura JB, editors. *Transport and transfer processes in plants*. New York (NY): Academic Press; p. 253–381.

Pizzeghello D, Berti A, Nardi S, Morari F 2016. Relationship between soil test phosphorus and phosphorus release to solution in three soils after long-term mineral and manure application. *Agriculture, Ecosystems and Environment* 233: 214–223.

Redding M, Ghani A, Kear M, O'Connor M, Catto W 2006. Phosphorus leaching from pastures can be an environmental risk and even a significant fertiliser expense. *Proceedings of the New Zealand Grassland Association* 68: 293–296.

Simmonds B, McDowell RW, Condon LM, Cox N 2016. Can phosphorus fertilizers sparingly soluble in water decrease phosphorus leaching loss from an acid peat soil? *Soil Use and Management* 32: 322–328.

Sinaj S, Stamm C, Toor GS, Condon LM, Hendry T, Di HJ, Cameron KC, Frossard E 2002. Phosphorus exchangeability and leaching losses from two grassland soils. *Journal of Environmental Quality* 31: 319–330.

Smith C, Monaghan R, McDowell RW, Carrick S, 2016. Nitrogen and phosphorus leaching losses from pasture, winter forage crop and native bush sites in the West Matukituki Valley. AgResearch report prepared for Otago Regional Council. RE500/2016/013.

Thompson SK, Cotner JB 2018. Bioavailability of dissolved organic phosphorus in temperate lakes. *Frontiers in Environmental Science* 6 (62).

Toor GS, Condon LM, Di HJ, Cameron KC, Cade-Menun BJ 2003. Characterization of organic phosphorus in leachate from a grassland soil. *Soil Biol. Biochemistry* 35: 1317–1323.

Toor GS, Condon LM, Di HJ, Cameron KC, Sims JT 2004. Seasonal fluctuations in phosphorus loss by leaching from a grassland soil. *Soil Science Society America Journal* 68: 1429–1436.

Toor GS, Condon LM, Cade-Menun BJ, Di HJ, Cameron KC 2005. Preferential phosphorus leaching from an irrigated grassland soil. *European Journal of Soil Science* 56: 155–168.

Trout TJ, Steele DD, Eggleston KO 2007. Environmental considerations. In: *Design and operation of farm irrigation systems* (eds G.J. Hoffman, R.G. Evans, M.E. Jensen, D.L. Martin & R.L. Elliot), pp. 77–107. American Society of Agricultural and Biological Engineers, St. Joseph, MI.

**Table 1.** Summary of subsurface phosphorus (P) losses from grazed pasture soils in New Zealand.

Soil properties	Soil Order (NZSC)	Trial type	Date	P inputs (kg ha <sup>-1</sup> yr <sup>-1</sup> ) and/or treatment	Drainage (mm)	DRP conc. (mg L <sup>-1</sup> )	TP load/loss (kg ha <sup>-1</sup> yr <sup>-1</sup> )	TP conc. (mg L <sup>-1</sup> )	Reference
ASC 30%; very stony	Brown	Lysimeter	2018	14 P fert, Lucerne dryland	307	0.006	0.120	0.043	Gray et al. 2020
			2019	9 P fert, + 14 dung, Lucerne dryland	124	0.015	0.044	0.038	
			2018	11 P fert, 28 FDE, 6 dung, Lucerne irrigated	493	0.008	0.207	0.046	
			2019	36 P fert, 62 FDE, Lucerne irrigated	252	0.011	0.055	0.031	
ASC 21%	Recent	Lysimeter	2001-14	40 P fert	285	0.019*	0.245	0.057*	McDowell et al. 2019b
ASC 25%	Recent			30 P fert + 10 FDE	319	0.050*	1.461	0.171*	
ASC 16%	Pallic			40 P fert	231	0.007*	0.117	0.032*	
ASC 19%	Pallic			30 P fert + 10 FDE	204	0.010*	0.122	0.037*	
ASC <20%; >60% gravels at 40	Recent	Lysimeter	2015	30 P fert, low irrigation + urine	289	0.003	0.070	0.024	Gray et al. 2016
				30 P fert, low irrigation - urine	352	0.006	0.124	0.035	
				30 P fert, med irrigation + urine	316	0.010	0.087	0.029	
				30 P fert, med irrigation - urine	372	0.003	0.153	0.041	
				30 P fert, high irrigation + urine	324	0.003	0.093	0.029	
				30 P fert, high irrigation - urine	367	0.010	0.167	0.045	
ASC 23%; stone content 10% in topsoil and 46% in subsoil	Brown	Lysimeter		Received flood irrigation 92 mm 8 times/yr 45 P fertiliser (superphosphate)	836		0.76		Toor et al. 2004
				Received flood irrigation 92 mm 8 times/yr 90 kg P fertiliser (superphosphate)	854		1.10		
				Received flood irrigation 92 mm 8 times/yr 45 kg P fertiliser (superphosphate) + 45 kg FDE	850		1.95		
ASC 4%; stone content of 54% in topsoil and 64% in subsoil	Recent	Lysimeter		28 FDE, constant-rate irrigation	c. 170	-	0.3 - 1.4	-	Carrick et al. 2014
				95 P fert, 8.8 FDE + cow urine, periodic irrigation	c. 900	-	0.2 - 0.4	-	
ACS 12%; >35% gravels within 50 cm	Recent	Lysimeter	2012-14	Grazed, dairy; 45 kg P/ha/yr; irrigated (700mm), 5 mm every 4-5 days over 6 months	c. 500		1.69 – 2.1#		McDowell et al. 2021
	Recent	Lysimeter	2015	Control	200		0.71		McDowell et al. 2021

				45 Dung	200		1.24		
				45 P fertiliser	200		0.86		
				90 P fertiliser + dung	200		2.43		
ASC <10%	Organic	Teflon cup		Site developed out of scrub for 2 yr and used for winter forage cropping	992		87^		McDowell and Monaghan 2015
47-61%	Podzol	Teflon cup		Site developed into pasture for 10 yr	1131		1.7^		
25 – 62%	Intergrade	Teflon cup		Been in pasture for 2 yr			9.0^		
ASC 15%; Olsen P 14	Recent	Teflon cup	2015	Sheep-cattle grazed pasture; 12	1331	0.52	1.33##		Smith et al. 2016
	Recent		2015	cattle-grazed winter forage crop; 141 P	1293	0.51	1.03##		
ASC < 15%; stone content 10% in topsoil and 70% in subsoil	Semi-arid		2010-13	35 P fertiliser, uniform rate irrigation	408#	0.011	0.42	0.051	McDowell 2017
			2013-16	26 P fertiliser, variable rate irrigation	256#	0.007	0.03	0.016	
ASC 17%	Recent	Lysimeter		Control			0.128		McDowell 2008
				Dung			0.353		
				30 kg P Fertiliser			0.165		
				30 kg P Fertiliser + dung			0.692		
ASC 5%	Podzol	Lysimeter		50P and 100P from SSP			16.5 and 34.4		Redding et al. 2006
				50P and 100P from RPR			0.15 and 0.4		
Edendale	Pallic + Brown	Mole-pipe	1996-99	Nil fertiliser N	193	0.062	0.34	0.19	Monaghan et al. 2005
				100 N		0.029	0.16	0.11	
				200 N		0.041	0.43	0.17	
				400 N		0.047	0.26	0.18	
Tussock Creek	Pallic	Mole-pipe	2001-03	Control	215	0.092	0.437	0.232	Monaghan et al. 2016
				Nil grazed	225	0.033	0.247	0.135	
				Restrict grazing 4 hr	207	0.078	0.221	0.165	
Northland	Granular	Mole-pipe	2000	Irrigated + 125 N and 24-35 P	393	0.08	2.2	0.57	Unpublished data; Monaghan et al 2002
Waikato	Gley	Mole-pipe	2000	100 N and 65 P	258	0.035	0.44	0.17	Barkle 2008

Massey	Pallic	Mole-pipe	2003	0 P	220	0.06	0.65	0.29	Houlbrooke et al. 2008
				35 kg FDE	236	0.40	2.55	0.96	
Massey	Pallic	Mole-pipe	2005	control	124	0.073	0.296	0.239	Hanly et al. 2008
Massey	Pallic	Mole-pipe	2006	125 kg N	394		0.30		Hanly 2012; unpublished
			2007		117		0.11		
			2008		353		0.20		
Massey	Pallic	Mole-pipe	2009	Standard grazing (7 hr day graze, 12 hr night graze); 60 N; 60 P	373		0.89		Christensen 2013
			2010	Standard grazing (7 hr day graze, 12 hr night graze); 75 N	316		0.28		
			2011	Standard grazing (7 hr day graze, 12 hr night graze); 80 N	329		0.21		
Massey	Pallic	Mole-pipe	2009	Controlled grazing	373		0.87		Christensen 2013
			2010	Controlled grazing	316		0.39		
			2011	Controlled grazing	329		0.18		

\*Median values (mg/L)

^ total dissolved P (DRP and DURP) (kg/ha) collected over 18 months

##Total dissolved P (kg/ha) collected over 15 months

