Nash, D.M., Mc Dowell, R.W., Condron, L.M., and McLaughlin, M.J., 2020. Quantifying the direct contribution of fertilizers to phosphorus exports from pastures. In: *Nutrient Management in Farmed Landscapes*. (Eds. C.L. Christensen, D.J. Horne and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

QUANTIFYING THE DIRECT CONTRIBUTION OF FERTILIZERS TO PHOSPHORUS EXPORTS FROM PASTURES

D. M. Nash[1, 2*]

R. W. Mc Dowell[3, 4]

L. M. Condron[4]

M. J. McLaughlin[5]

[1]Soil and Allied Services Pty. Ltd., 1500 Warragul Road, Strzelecki, Victoria, 3950, Australia.

[2]School of Agriculture and Food, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Parkville, Victoria, 3010, Australia.

[3]AgResearch, Lincoln Science Centre, Private Bag 4749, Christchurch, 8140, New Zealand.

[4]Faculty of Agriculture and Life Sciences, P O Box 85084, Lincoln University, Christchurch, 7647, New Zealand.

[5]School of Agriculture Food and Wine, Waite Research institute, The University of Adelaide, PMB 1, Glen Osmond, SA, 5064, Australia

** Email: soilandalliedservices@gmail.com*

Introduction

Why is phosphorus important?

Phosphorus (P) is the sixth most abundant element in living organisms. Since its discovery in 1669, P has become an essential input for agriculture. However, the use of P in agriculture has increased the risk of P in drainage adversely affecting downstream water resources.

How much phosphorus do land plants need?

Both terrestrial and aquatic organisms extract the P they need from water. They take it up as orthophosphate anions ($H_2PO_4^-$/HPO_4^{2-}). The total P concentration needed in soil water for optimum agricultural production is often cited as >0.2 mg/L (Pierzynski *et al.* 2005). However, a soil water P concentration of approximately 0.9 mg/L was required for maximum pasture productivity in New Zealand field trials (Wheeler and Edmeades 1995).

How much phosphorus is too much in rivers and streams?

The P concentration that would result in natural waters being classed as degraded is relatively small. Some water resources are considered degraded or poor when the total P concentration exceeds 0.050 mg/L (Cottingham *et al.* 1995) or about 75 g or 35 cm^3 (a matchbox full!) of P in an Olympic sized swimming pool.

Can we stop phosphorus being exported in agricultural drainage?

No! Given that some P is always present in soil water, it follows that transfers from land to water (i.e., P exports) are an inevitable consequence of drainage from any terrestrial production system. Unfortunately, streams draining agricultural catchments often suffer "impaired" water quality.

Are grazed pastures in Australia and New Zealand any different?

In Australasia (i.e., Australia and New Zealand) intensive pasture-based grazing is often the primary land use in catchments with impaired water quality. Although some aspects of water quality may be improving in New Zealand (Larned *et al.* 2016), P exports from pastures remains a concern and the New Zealand government has responded to concerns about water quality and use with its National Policy Statement for Freshwater Management (NZ Government 2017) and proposals for further reform released in September 2019. Water quality in streams draining grazing catchments is a similar concern in Australia (Turral *et al.* 2017).

Is there any structure to phosphorus exports from grazing systems?

Phosphorus exports to water from pasture-based grazing systems can be conveniently divided into "systematic" (i.e., base or background) and "incidental" (i.e., management) components (Haygarth and Jarvis 1999). Background exports are attributable to the production system and local conditions. Management decisions and critical incidents can increase P exports over and above those that would have otherwise occurred. They include the application of inorganic fertilizer, spreading of manure, the timing of grazing and grazing management that affects soil erosion.

Are phosphorus exports from fertilizers only a problem soon after they are applied?

No. Mineral fertilizers are highly concentrated sources of P that may contribute directly to "incidental" P exports soon after their application. But, because fertilizers increase P cycling and general soil fertility they can also contribute to "systematic" (i.e., background) exports in subsequent years.

How do you manage fertilizer applications to minimise their environmental impact?

The 4R Nutrient Stewardship concept has been used by the fertilizer industry to guide the development of fertilizer "Best" or "Good Management Practices". The 4R concept is to apply the Right Source of nutrients, at the Right Rate, at the Right Time and in the Right Place (Bruulsema 2018). Good management practices consider the individual attributes of each farm and try to optimize nutrient use efficiency and environmental sustainability, while supporting farm profitability. On well-managed farms, practices are adopted that address a range of soil, fertilizer, effluent management and irrigation issues (Dairy Australia 2018).

So, now you have depressed us, what is this paper about?

In this paper we ask the question: How much of the P exported from grazing systems in Australasia comes directly from recently applied fertilizers? In terms of 4R Nutrient stewardship it's about applying fertilizer at the "Right Time". Our second paper from this conference will discuss choosing the "Right Source" of nutrients.

Key take home messages:

- *Phosphorus is essential for life and biological organisms take up P from water.*
- *Phosphorus exports are a natural consequence of any plant production system or land-use.*
- *In productive grazing systems the concentration of P in soil water is usually higher than water quality targets.*
- *Fertilizers are only one of many sources of the P lost from our grazing systems.*
- *The 4R Nutrient Stewardship concept (e.g., apply the Right Source of nutrients, at the Right Rate, at the Right Time and in the Right Place) can help guide the development of "Good fertilizer management practices" for different farms*

Background

Is all the phosphorus we lose from our farms the same?

Phosphorus is exported in pasture drainage either as part of a solid, attached to a solid, or dissolved in water (i.e., as a solute). Size is usually used to differentiate between different types of P. The terms "dissolved" and "particulate" are commonly used to define P materials that pass through or are retained by a 0.45 µm filter (i.e., about the size of a virus or smaller). Phosphorus forms are further differentiated by their reactivity in an acid-molybdate solution (i.e., the depth of colour when the water and the acid-molybdate are mixed). The most reported forms of P exported from pastures are Total P (TP), Total Dissolved P (TDP) and Dissolved Reactive P (DRP).

Do phosphorus forms matter?

Phosphorus forms influence the effectiveness of mitigation strategies. For example, vegetative filter strips (i.e., buffer strips) can help remove particulate P from overland flow (e.g., by sedimentation) but are less effective removing dissolved forms (e.g., TDP or DRP) forms. Further, the form in which P is exported also influences its impact on receiving waters. Particulate P (i.e., >0.45 µm) needs to be released before aquatic plants can use it. On the other hand, orthophosphate, a major component of dissolved P (i.e., <0.45 µm), is immediately bioavailable.

What do the forms of phosphorus tell us about how phosphorus gets into water?

Exports of particulate P (i.e., solids) usually start with detachment of fine particles (sediments) and associated P from aggregates and other soil materials. The term "erosion" is commonly used to refer to a process where detachment is followed by entrainment of particulate materials in flowing water.

Raindrop impact, cultivation, cattle treading, flowing water, slaking and dispersion can all contribute to releasing particulate P from soil. Factors that increase water velocity (e.g., slope) and turbulence (e.g., obstructions) generally increase detachment and transport rates. Erosion processes are well reviewed elsewhere.

The processes affecting the export of dissolved P are more complex. They include:

- The availability of soluble P sources.
- The ability of the soil in the immediate vicinity of P sources to hold P.
- The presence or absence of substances that interfere with the soil's ability to hold P.
- The time available for soil and water to mix.

So, is particulate or dissolved phosphorus lost from grazed pastures?

Both. However, in well-managed pastures where this is no predisposition to erosion (i.e., high rain intensities, pugging, bare soil) and good groundcover, dissolved P is generally responsible for most P exports.

Does that mean we find lots of dissolved phosphorus in streams draining agricultural catchments?

Not necessarily. Sheet erosion and erosion of gullies and streambanks can contribute P to steams. Moreover, dissolved P (especially orthophosphate) attaches to soil particles in transit. So, what started out as dissolved P can appear to be particulate P in a stream.

Can I see the water and phosphorus leaving my pastures?

Not always. Waterborne P exits fields though several interrelated pathways (Figure 1) that can be difficult to distinguish (Nash and Halliwell 1999).

There are two main types of surface flow.

- **Infiltration-excess overland flow occurs** where water additions exceed vertical drainage. Infiltration-excess overland flow is affected by factors that affect water entry into surface soil such as water-repellency, slaking and dispersion, and water passage through the soil such as soil compaction and structural deterioration. Infiltration-excess overland flow tends to increase down slopes as run-on from higher areas accumulates.

- **Saturation-excess overland flow** is characterized by saturation of the subsoil. Infiltration may be occurring, but at a negligible rate due to the low hydraulic conductivity of an underlying layer. Saturation-excess overland flow also occurs where ground water rises to the surface in discharge zones, often at the break of slope.

Once P is mobilized into surface flow there are limited opportunities for stopping it leaving a farm.

Water can also drain through the soil:

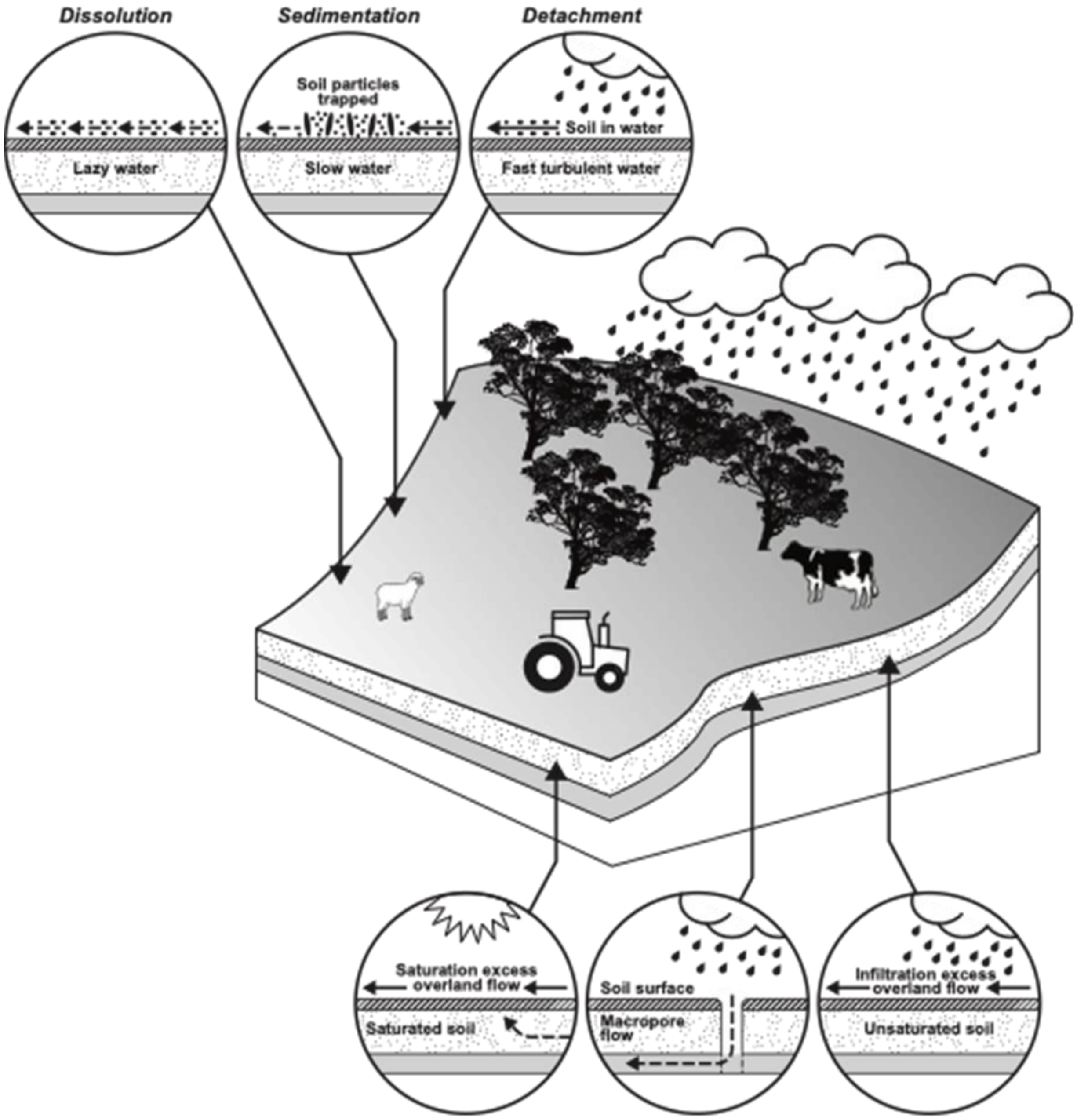
- **Matrix flow** describes water moving vertically through the soil fabric.

- **Macropore flow** also describes water moving vertically through the soil fabric but in large pores (e.g., fissures or bio-pores with diameters around 0.075mm or larger).

- **Interflow** describes water moving into soil and then laterally without reaching ground water.

Depending on soil attributes (e.g., soil structure, P buffering capacity) and the intimacy (i.e., proximity and time) of the drainage and soil contact, P can be removed from water that drains through soil. However, dissolved P moving through macropores, can effectively by-pass the soil, especially if it enters sub-surface drains.

Figure 1. Hydrology and phosphorus mobilization processes at the field-scale.



Adapted from (Nash *et al*. 2002)

We all know what causes erosion and how to limit it, how does dissolved phosphorus get into water?

When rain falls, or irrigation water is applied to pastures, it washes over and through vegetation and onto the soil surface. It is on the soil surface that animals defecate, fertilizers are often applied and detritus from pasture plants and supplementary feed falls. It is also here, in that spongy layer that exudes water when you walk over it on wet days, that dissolved P gets into the water. That layer is referred to as the mixing layer.

How thick is the mixing layer?

Various tracer studies suggest that a mixing layer of approximately 3 mm might be expected for P in many well-managed pastures. Excessive animal traffic may well increase the "apparent" (i.e., effective) mixing depth by increasing the soil surface area and decreasing soil stability (Drewry *et al.* 2008).

Key take home messages:

- *Using filtration, water borne P is classed as particulate (>0.45 µm) or dissolved <0.45 µm).*
- *Reactivity in an acid-molybdate solution is used to further differentiate P species.*
- *Dissolved P, especially dissolved reactive P (DRP), is the most potent (i.e., has the highest concentration of orthophosphate that plants can immediately use) and generally the hardest to remove from flowing water.*
- *Dissolved reactive P accounts for most P exported from well-managed grazed pastures.*
- *The dissolved P is entrained in the spongy layer at the soil surface commonly called the mixing layer.*

Quantifying the short-term impacts of fertiliser on phosphorus exports

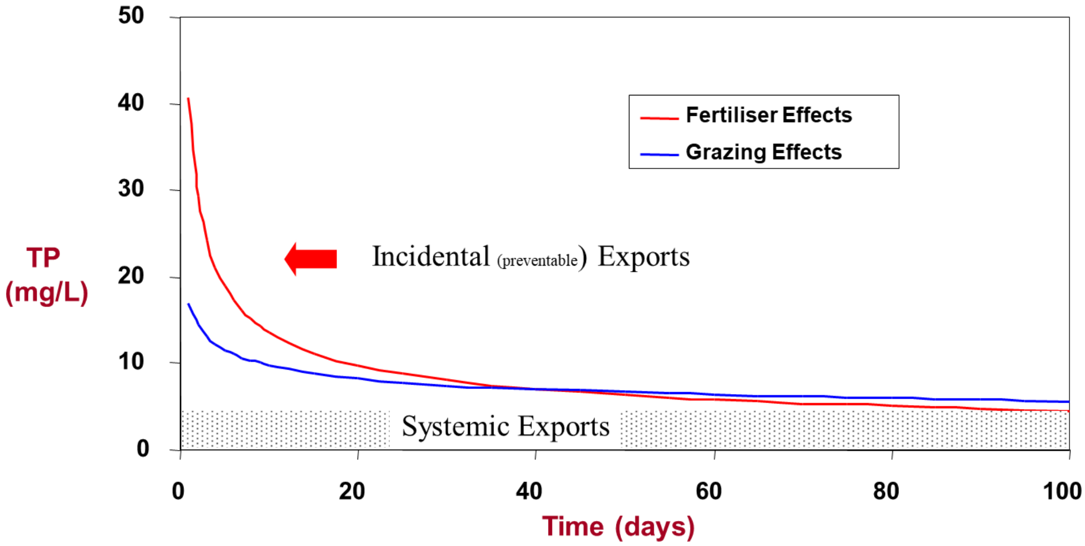
Is it possible for phosphorus from recently applied fertilizer to be responsible for most phosphorus exports from grazed pastures?

Most studies have demonstrated that it is "possible" for P exports from recently applied fertilizer to overwhelm other P sources. However, from a catchment management perspective the key question is not what is "possible", but rather what is "probable".

How long do the effects of recently applied fertilizer last?

The effects of recently applied fertilizers on P exports tend to decay very quickly (Figure 2). Field monitoring of rainfed and border-check irrigation systems in Australia suggests that the effects of fertilizer application and grazing on P exports decay with time in near-exponential fashion. For example, the initial half-life of fertilizer impact (i.e., the number of days since fertilizing to decrease the total P concentration in overland flow by half) has been estimated to be ~3 to 4 d, with 95% confidence intervals of ~3 to 8 d. These were pastures where most P was exported in overland flow as dissolved P.

Figure 2 **A diagrammatic representation of fertiliser and grazing effects on phosphorus concentrations in overland flow from the Darnum site.**



How does this happen?

The reactions of fertilizer P in soil are the subject of our second paper in this conference. Presumably, P from water-soluble fertilizers quickly moves into the soil, away from the mixing layer (i.e., soil surface), and this, along with other soil processes, results in that P rapidly becoming less accessible to overland flow.

Is that why it is important to maximize the time between fertilizer is applied and overland flow occurs?

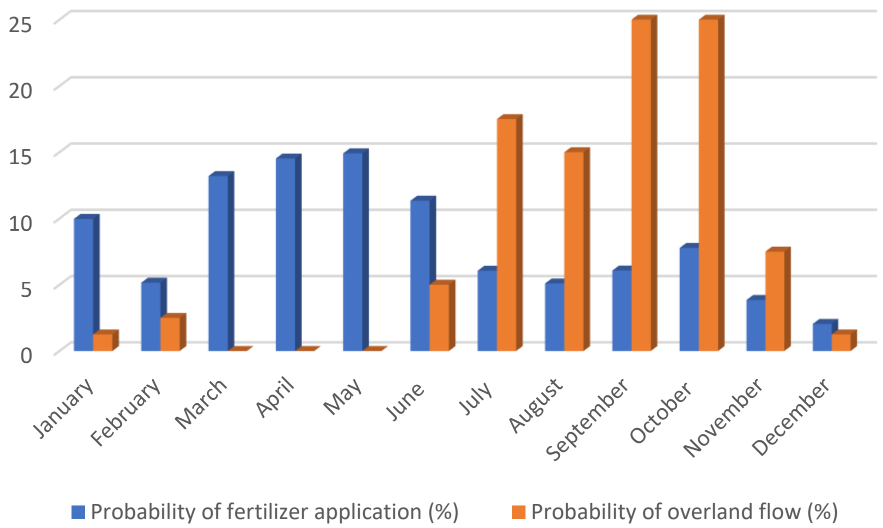
Yes. Appropriate timing of fertilizer applications in relation to overland flow or drainage that could export P offsite is key plank of the 4R Nutrient Stewardship Concept ("Right Time"). Generally, the longer the interval between fertilizer application the smaller its contribution to P exports.

Can you use the information we have regarding fertilizer application to quantify the "likely" contribution of recently applied phosphorus fertilizers to catchment scale phosphorus exports?

Mathematical models derived from field data (Figure 2) have been used, along with fertilizer distribution, grazing and regional overland flow data, to quantitatively estimate P exports attributable to recently applied fertilizer (Nash and Hannah 2011). The study demonstrated that for systems like those for which the equations were derived, P exports directly attributable to fertilizer application (i.e., short-term effects of recently applied fertilizer) are unlikely to have a major impact (i.e., <10%) on annual P exports. A graph showing when fertilizers were applied and when overland flow was likely is presented in Figure 3.

In this study it was assumed that fertilizer application and overland flow occurred at random within a given month. In many regions, conditions conducive to overland flow, such as high antecedent soil moisture (i.e., wet soils), preclude fertilizer application. Moreover, as a result of extension activities farmers are now less inclined to apply fertilizer immediately before overland flow inducing irrigation or rainfall (Department of Primary Industries 2006). It follows that improved management of fertilizer application on a regional basis would of itself probably result in only a small (i.e., <<10%) decline in total P exports.

Figure 3 Probability fertiliser application and grazing probability by month for a rainfed catchment in the West Gippsland Region of south-eastern Australia.



A New Zealand study (McDowell and Catto 2005) used simulated rainfall on intact soil turfs (1050 mm long by 200 mm wide) to investigate the effects of different fertilizer formulations on P exports in overland flow 1, 7, 14, 28, 112 and 192 days after fertilizer application. Decay curves were used in conjunction with monthly overland flow data to show that the risk of direct fertilizer P exports was greatest in June when most overland flow occurs. The decay curves were then used with two years of field monitoring data to simulate P exports from fertilizer applications occurring on June 1 and December 1. From this semi-empirical approach it was concluded that if applied in December, soluble P fertilizers would account for <10% of total P exports for the year (McDowell and Catto 2005; McDowell *et al.* 2009). While outcomes of the study have been questioned (Quin *et al.* 2004), they are consistent with other modelling (Vadas *et al.* 2015).

If fertilizer application is relatively unimportant what is?

By far the biggest factor affecting P exports was the soil fertility (i.e., background component). Interestingly, in the study by Nash and Hannah (2011), grazing appeared to make a bigger contribution to total P exports than fertilizer. While such findings need to be viewed with caution, they are plausible. Grazing increases water available P in the mixing layer at the soil and grazing occurs more often at times of the year when overland flow is more frequent (e.g., during the irrigation season and late winter and early spring in rainfed systems).

So, if I apply my fertilizer in summer that'll be fine?

Not necessarily. In a New Zealand study (*unpublished data*) superphosphate (40 kg P/ha) was applied in summer to a Pumice soil resulting in 8 kg P/ha of fertiliser-P lost in surface runoff from summer storms due to soil hydrophobicity (90% of total P loss). Each farm and each farming system have subtle differences that mean P export processes need to be assessed *in situ*.

Key take home messages:

- *Phosphorus fertilizers can overwhelm other sources of P exported from grazed pastures.*

- *Where the 4R Nutrient Stewardship (i.e., apply the Right Source of nutrients, at the Right Rate, at the Right Time and in the Right Place) concept has been applied fertilizers can make an insignificant (i.e., <10%) contribution to P exports.*

- *The Best Fertilizer Management Practices consider differences between and within individual farms, tailoring fertilizer management to different soil properties and areas.*

Concluding comments

There is little doubt that not following the 4R principles for P fertilizers can result in excessive P exports from grazing systems in Australasia. Numerous studies have shown what is possible soon after fertilizers are applied. But the important question is not "What is possible?", but "What is probable?".

Using conceptually sound empirical models, it is possible to investigate the likely contribution of recently applied fertilizer to overall P exports from these systems. These analyses suggest that with good management practice, recently applied fertilizers make a minor (e.g., <10%) contribution to total P exports. But that is not necessarily the case where, for example, the soil has a poor sorption capacity, there is frequent rainfall or fertilizer applications coincide with drainage events. However, by understanding the processes responsible for P mobilization, and the pathways through which P may be exported, it should be possible to mitigate the short-term risks associated with fertilizer use through prudent selection of compounds and formulations, and optimizing their application in terms of rate, timing and placement (i.e., applying the 4R concept).

Fertilizer good management practices are cost-effective compared to other mitigation strategies that occur at the edge of the field or in-stream (McDowell and Nash 2012). Their catchment-scale efficacy and cost-effectiveness in mitigating P exports are improved if they are targeted at critical source areas (i.e., areas within a farm or farms within a catchment) where surface and/or sub-surface drainage are prevalent. For example, when appropriate P mitigation strategies were applied to 14 catchments in New Zealand, P exports were estimated to be halved with minimal impact on farm profitability (<2% of farm earnings before interest and tax) (McDowell 2014). In New Zealand, semi-quantitative evidence would suggest that despite intensive land use expanding, good management practice combined with increasing awareness of P and critical source areas, and their reinforcement through voluntary processes and regulation, has seen stream water P concentrations decrease in the last ten years (McDowell *et al.* 2019).

Acknowledgements

This contribution to the 2020 FLRC Workshop at Palmerston North, New Zealand, is based on a review funded by the Fertiliser Association of New Zealand entitled "Direct exports of phosphorus from fertilizers applied to grazed pastures" (Nash *et al.* 2019).

References

Bruulsema, T (2018) Managing nutrients to mitigate soil pollution. *Environmental Pollution* **243** 1602-1605.

Cottingham, P, Bennison, G, Robinson, D, Dunn, R, Lidston, J (1995) Algal bloom and nutrient status of Victorian surface waters. State Water Laboratory of Victoria, Victorian State Government, Melbourne, Victoria, Australia. Available

Dairy Australia (2018) Best Management Practices - Fert$mart. Available at http://fertsmart.dairyingfortomorrow.com.au/getting-it-right/best-management-practices/ [Verified May 24, 2018]

Department of Primary Industries (2006) 'Gippsland Nutrient Extension Program Evaluation.' (State of Victoria, Department of Primary Industries: Melbourne, Australia)

Drewry, JJ, Cameron, KC, Buchan, GD (2008) Pasture yield and soil physical property responses to soil compaction from treading and grazing: a review. *Soil Research* **46** (3), 237-256.

Haygarth, PM, Jarvis, SC (1999) Transfer of phosphorus from agricultural soils. *Advances in Agronomy* **66** 195-249.

Larned, ST, Snelder, T, Unwin, MJ, McBride, GB (2016) Water quality in New Zealand rivers: current state and trends. *New Zeal. J. Mar. Fresh.* **50** (3), 389-417.

McDowell, R, Nash, D, George, A, Wang, QJ, Duncan, R (2009) Approaches for quantifying and managing diffuse phosphorus (P) exports at the farm/sub catchment scale. *Journal of Environmental Quality* **38** 1968-1980.

McDowell, RW (2014) Estimating the mitigation of anthropogenic loss of phosphorus in New Zealand grassland catchments. *Sci. Total Env.* **468-469** 1178-1186.

McDowell, RW, Catto, W (2005) Alternative fertilisers and management to decrease incidental phosphorus loss. *Environ. Chem. Lett.* **2** 169-174.

McDowell, RW, Hedley, MJ, Pletnyakov, R, Rissman, C, Catto, W, Patrick, W (2019) Why are median phosphorus concentrations improving in New Zealand streams and rivers? *J. Roy. Soc. New Zeal.* **49**

McDowell, RW, Nash, DM (2012) A review of the cost-effectiveness and suitability of mitigation strategies to prevent phosphorus loss from dairy farms in New Zealand and Australia. . *Journal of Environmental Quality* **41** 1-14.

Nash, D, Hannah, M (2011) Using Monte-Carlo simulations and Bayesian Networks to quantify and demonstrate the impact of fertiliser best management practices. *Environmental Modelling and Software* **26** 1079-1088.

Nash, DM, Halliwell, D (1999) Fertilisers and phosphorus loss from productive grazing systems. *Australian Journal of Soil Research* **37** (3), 403-429.

Nash, DM, Halliwell, D, Cox, J (2002) Hydrological mobilisation of pollutants at the slope/field scale. In 'Agriculture, Hydrology and Water Quality'. Eds PM Haygarth, SC Jarvis.) pp. 225-242. (CABI Publishing: Oxon, UK.)

Nash, DM, McDowell, RW, Condron, LM, McLaughlin, MJ (2019) Direct exports of phosphorus from fertilizers applied to grazed pastures. *Journal of Environmental Quality* **48** (5), 1380-1396. 10.2134/jeq2019.02.0085

NZ Government (2017) National Policy Statement for Freshwater Management 2014 (amended 2017). Available at http://www.mfe.govt.nz/fresh-water/national-policy-statement/about-nps [Verified 17-01-2019]

Pierzynski, GM, McDowell, R, Sims, JT (2005) Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In 'Phosphorus: Agriculture and the environment'. Eds JT Sims, A Sharpley.) pp. 53-86. (ASA-CSSA-SSSA: Madison, WI, USA)

Quin, BF, Hart, MR, Blennerhassett, JD, Wedderburn, L (2004) Phosphorus loss. *New Zeal. J. Agr. Res.* **47** (1), 105-108.

Turral, H, Wood, M, Fitzpatrick, C (2017) Macalister land and water management plan review. West Gippsland Catchment Management Authority Traralgon, Victoria Australia. Available at http://www.wgcma.vic.gov.au/our-region/projects/9132-2

Vadas, PA, Busch, DL, Powell, J, Brink, GE (2015) Monitoring runoff from cattle-grazed pastures for a phosphorus loss quantification tool. *Agr. Ecosyst. Environ.* **199** 124-131.

Wheeler, D, Edmeades, D (1995) Effect of depth and lime or phosphorus-fertilizer applications on the soil solution chemistry of some New Zealand pastoral soils. *Soil Research* **33** (3), 461-476.