# CAN I FARM WITHIN A PHOSPHORUS LIMIT?

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**Abstract**
The national policy statement on freshwater management requires Regional Councils to put in place limits to maintain or improve water quality above national bottom lines. One attribute within the policy is periphyton (algal) growth, which is often limited by phosphorus (P) concentrations (McDowell et al., 2009). Given that periphyton growth can respond to small increases in P concentrations, the question is being asked: can I still farm (profitably) within a P limit? Discounting allocation mechanisms (which will vary from Council-to-Council), recent research advocates prohibiting obvious bad practice and then choosing P loss mitigation practices based on their suitability to a farming enterprise. Maximising their cost-effectiveness by applying them to areas of the farm that lose the most P, and at the right time (i.e. a critical source area), will minimise cost and increase the likelihood of meeting a P limit substantially increased over an untargeted and unfocused approach.

**Introduction**
The national policy statement on freshwater management requires Regional Councils to manage or improve water quality above a set of national set of bottom lines for specific objectives. One of these objectives is periphyton (algae) growth in streams and rivers. Periphyton growth is linked to phosphorus concentrations in the water column and other factors (e.g. Snelder et al., 2013; 2014). As such, many Regional Councils are considering or have imposed limits on phosphorus emissions to water. Here I review the policy requirements to manage P, some of the processes and pathways relevant to P emissions, and then ask: what can be done to successfully farm within a P limit?

**Policy**
The National Policy Statement on Freshwater Management (NPS-FM; MfE, 2014) requires all regional councils and unitary authorities to manage water in an 'integrated and sustainable way, while providing for economic growth within set water quantity and quality limits'. The policy stipulates that freshwater quality within a region must be maintained or improved, but allows for some variability at the smaller scale of the freshwater management unit (e.g. a catchment).

The NPS-FM has a number of components. However, for freshwater quality, the bulk of the NPS-FM is dealt with via the National Objectives Framework (NOF). The NOF provides an approach for the setting of freshwater objectives for national values and other values that are nationally consistent, but 'recognises regional and local circumstances'. For every freshwater management unit (FMU; e.g. catchment) in a region, values for 'ecosystem health' and 'human health for secondary contact recreation' must be applied. Other 'optional' values, such as fishing, swimming, irrigation and food production may also be applied. For each value there is a national bottom line (class 'D') for the relevant attribute(s). Councils have to set objectives above, or at, the bottom lines, except where the existing freshwater quality is caused by a natural process (e.g. reference conditions are commensurate with the bottom line;

McDowell et al., 2013), or infrastructure (e.g. impoundments) has indefinitely modified water quality. Where attributes are below national bottom lines, they will have to be improved to at least the bottom lines.

Most regional councils have or are implementing a collaborative process (Berkett et al., 2013) to set community-derived values for freshwater management units. For phosphorus (P), concentrations are managed according to how they influence periphyton in rivers (Snelder et al., 2013) and phytoplankton chlorophyll a concentrations in lakes (Abell et al., 2010). For rivers, no more than 17% of samples taken monthly over a three year period can exceed a chlorophyll-a concentration of 200 mg $m^{-2}$, while in lakes the annual median and maximum concentration cannot exceed 12 and 60 mg chlorophyll-a $m^{-3}$, respectively.

**Sources and pathways of P loss**

The loss of P from land to surface water is a function of the availability of P sources to loss, and a transport pathway to get them from their source to streams and rivers, which may be attenuated en route (Fig. 1). Both the availability of P sources and transport can be influenced by landuse and land management; for instance, switching between dissolved and particulate forms.

Sources of P loss include: the soil, fertiliser, plant residues and animal dung/effluent (McDowell et al., 2007). As P surpluses increase, it is likely that soil P concentrations and P losses increase. Losses of dissolved P are exacerbated in soils with lower anion storage capacity. The erosion of particulate-associated P and loss via surface runoff can be enhanced by soil compaction and pugging following treading by grazing animals. Direct applications of P can also occur via animal dung (not urine) and fertiliser, although the availability of P to loss is inversely proportional to the fertiliser's water solubility (McDowell et al., 2003a). Plant residues can be an important source of P in arable systems (McDowell et al., 2007). This can also be the case for a short time immediately after grazing by ruminants, but is enhanced by dung deposition whose availability decreases rapidly as a crust forms on the dung, thus impairing interaction with rainfall (McDowell, 2006).

Another potential source of P loss on dairy farms is farm dairy effluent (FDE). In the 1970s a two-pond system was introduced that combined an anaerobic pond with a facultative pond (Sukias et al., 2001). This decreased the biological oxygen demand of raw effluent before discharging "treated" effluent to streams, but was inefficient at removing P. Such systems are now uncommon with application of effluent to land being preferred. Land application systems allow the soil to filter out much of the P (and other contaminants) in effluent, but can be inefficient if too much is applied, especially to wet soils, increasing the availability of contaminants to transport via preferential subsurface and surface flow pathways (Houlbrooke et al., 2008; Monaghan and Smith, 2004).

For surface runoff, P losses can occur via infiltration-excess and saturation-excess mechanisms. Under infiltration-excess conditions the infiltration capacity of the soil is exceeded resulting in runoff. In New Zealand, this usually occurs under high-intensity rainfall (or hydrophobic soil conditions; Bretherton et al., 2011) year-round, whereas saturation-excess surface runoff only occurs when soils are saturated (largely in winter and spring) resulting in any excess rainfall running-off. Due to topography, the areas affected by saturation-excess surface runoff are generally located near the stream channel and expand and contract in response to rainfall events and evapotranspiration. Due to the energy of high-intensity rainfall events, infiltration-excess surface runoff can contain more particles (and particulate P) than saturation-excess surface runoff (Buda et al., 2009). However, while most runoff and P loss occurs in winter and spring, small events occurring in summer and autumn can have greater impact on algal growth. For instance, McDowell and Srinivasan (2009) found P losses in winter and spring accounted for 75% of annual losses, but of the remaining storms more P was in a dissolved form and therefore available to periphyton at a time when the seasonal risk of nuisance growths was highest (low flows and higher temperatures).

Sub-surface transport (viz. interflow) of P can also be significant especially when intercepted by artificial drainage. In these circumstances, macropores can provide a rapid conduit between surface sources of P and transport them via subsurface drains to open drains or directly into streams. In pastoral systems where surface runoff has been identified as a significant pathway of P loss, evidence exists to show that losses may simply be transferred in subsurface flow when artificial drainage is installed, although often exported in a dissolved rather than particulate form (Monaghan et al., 2000). Over time, artificial drainage networks may also serve as a source of P where, for instance, the banks of surface drains collapse and erode or mole channels linked to pipe drains collapse.

The confined pore size of soils, the vadose zone and aquifers imparts a much greater filtration effect in transport through groundwater to surface water than likely in direct transport via runoff. Nevertheless, McDowell et al. (2015) found that dissolved groundwater P concentrations were enriched where there was a landuse regularly supplying P, a soil type of low P sorption capacity and sufficient drainage (rainfall- or irrigation-induced) to transport P to groundwater. Furthermore, in aquifers of low P sorption capacity (e.g. sand and gravel), good connectivity to surface waters meant that in some cases P concentrations were also enriched in baseflow.

**Methods to manage to a P-limit**

Linking farm scale emissions to impacts at catchment and regional scales has been the focus of a series of recent modelling studies (e.g. Daigneault et al., 2013; Elliott et al., 2014; Kaye-Blake et al., 2013). These assume that loads, which are used to allocate P losses among contributing sources (e.g. farms), can be measured accurately and translated into concentrations relevant to impacts (e.g. periphyton growth), and that the method of allocation is fair. The issue of uncertainty associated with P measurement, load estimation and translation into concentrations (usually medians) is a technical challenge that has received some attention guiding recommendations on minimum sampling techniques and method to minimise such uncertainty (e.g. Defew et al., 2013; Cassidy and Jordan, 2011). Models linking loads to concentrations and to periphyton growth have also received some recent attention. However, it is recognised that much additional data is required to make more robust predictions of periphyton growth – especially in smaller streams (Snelder et al., 2014). Allocation mechanisms vary, but include: 1) the trading of discharge allowances, 2) an equal allocation to land owners across a catchment, 3) grand-parenting, 4) allocating according to land use capability, and 5) benchmarking according to past performance (Marsh et al., 2014). Different approaches are likely to be taken among Regional Councils likely tailored to local conditions and values.

Irrespective of mechanisms to allocate loading reductions within a FMU, New Zealand studies have shown two general principles apply that can maintain or improve agricultural production and water quality (as impacted by P losses). The first is the application of good management practices (GMPs) to decrease P losses from land to water on the basis of cost-effectiveness. This involves choosing a suite of practices based on their suitability to a farming enterprise and applying the most cost-effective first. For P loss the preferred metric of cost-effectiveness is the annual cost per unit of P retained on land (McDowell, 2014). To date there are around 18 widely tested such practices that can be used on different farming enterprises (McDowell and Nash, 2012; McDowell, 2014). There are more practices suited to dairy farming compared to other land uses, which may reflect a perception (backed up by some evidence; Ledgard, 2014) of excessive P losses, but also investment on behalf of the industry to mitigate losses.

Across all enterprises, the cost-effectiveness of practices tends to decrease the farther away from the source a practice is implemented (McDowell and Nash, 2012). For example, the cost to mitigate P lost from runoff events soon after the application of P-fertiliser can be better minimised by swapping from a highly water soluble (and mobile) P fertiliser to a low water soluble P fertiliser (e.g. reactive phosphate rock) than installing edge-of-field capture systems such as sediment traps and constructed wetlands (Monaghan et al., 2008). This does not negate the use of, for example, a constructed wetland for other purposes such as decreasing sediment, nitrogen and potentially faecal bacteria losses to surface waters (Tanner and Sukias, 2011).

The second general principle is that when applying GMPs, cost-effectiveness can be increased if they are applied in the 'right place' and at the 'right time'. The 'right place' has been hypothesized to be critical source areas, i.e. areas of a catchment, farm or field that account for the majority of P losses, but originate from the minority of the area (Sharpley et al., 2011). The 'right time' refers to coinciding practices with times of year when P losses from CSAs are most likely or the impact of loss is greatest. McDowell (2014) examined the targeting of GMPs to CSAs and was able to show that the impact on the earnings before interest and tax of the average farm within a catchment was far less, but the decrease in P losses similar to, if GMPs were applied across the whole farm or catchment (where applicable). Similarly, timing the use of practices such as the deferred irrigation of dairy shed effluent to land has helped dairy farmers avoid times of year when soils are wet and P losses to surface waters more likely (Houlbrooke et al., 2008).

The implementation of these two principles can, in some circumstances, even result in increased profitability. Figure 1 shows the implementation of GMPs in catchments across a dairy farm in South Otago, New Zealand. Regional policy has dictated that end-of-pipe emissions for farming operations should not result in median DRP concentrations in baseflow greater than 0.026 mg DPP $L^{-1}$ (Otago Regional Council, 2014). In 2007, median concentrations in catchments draining the farm were 0.080 mg DRP $L^{-1}$. Part of the farm (10-15%) received dairy shed effluent using a travelling irrigator at instantaneous application rates of up to 127 mm $hr^{-1}$. This was resulting in periodic losses of effluent to nearby streams via the artificial drainage network. By increasing the size of the effluent storage pond and adopting a low rate effluent application (4 mm $hr^{-1}$), P losses due to effluent were quickly mitigated, but cost the operation NZD \$30 $ha^{-1}$ $yr^{-1}$ (expressed as a whole farm average and depreciated over 20 years). Examining the list of suitable strategies for a dairy farm (Table 1) indicated that another cost-effective strategy was the use of a low P farming system. This system, implemented at a catchment scale, cultivated the near stream area, thereby decreasing Olsen P at the soil surface from > 30 to 12-15 mg $L^{-1}$. Ryegrass was sown in this area, while a monoculture of white clover was sown in higher Olsen P areas in the rest of the catchment. The decrease in Olsen P and breaking of macropores in the plough layer caused a 40-45% decrease in DRP losses, while sowing white clover as a monoculture removed the detrimental shading effect of ryegrass, improving pasture production and quality that was modelled to improve the yield of milk solids and profitability by NZD \$414 $ha^{-1}$ $yr^{-1}$ (McDowell et al 2014). However, due to increased weed pressure and a small increase in N losses, the strategy was not implemented across the whole farm. Nevertheless, much of the remaining farm had been maintaining an Olsen P in excess of the agronomic optimum. Decreasing this by applying a half maintenance application of P fertiliser resulted in less P loss due to decreasing soil Olsen P concentrations, but maintained pasture production (ceasing P fertiliser altogether may have resulted in decreased pasture production; Dodd et al., 2014).

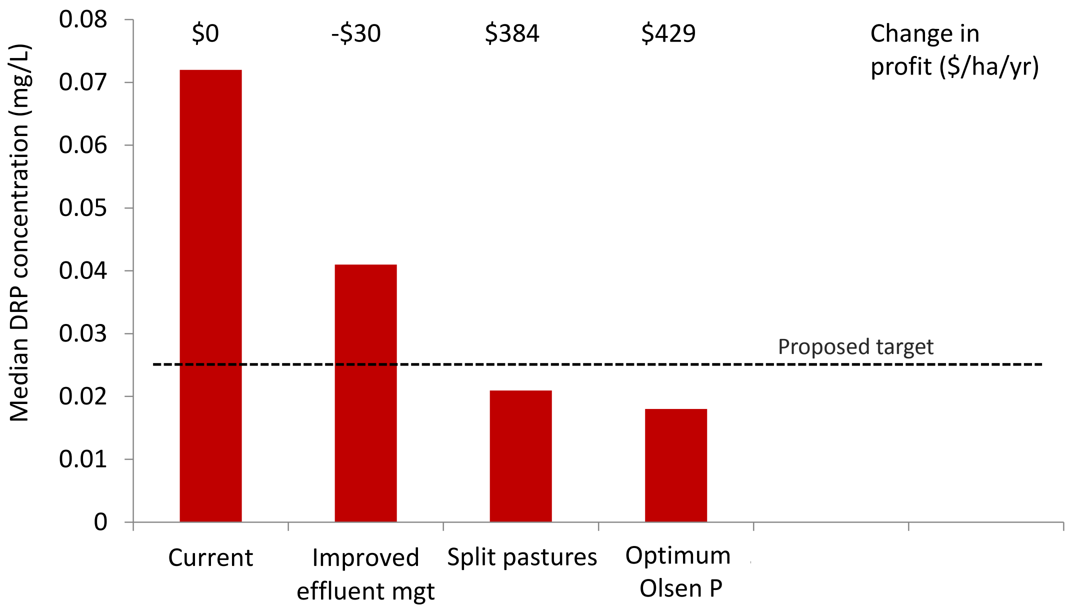


**Figure 1.** Change in median dissolved reactive P concentration and profitability (NZD) five years after the implementation of a mixed model (i.e. removing prohibited practice followed by good management practices used in order of cost-effectiveness) in a catchment draining a dairy farm in Southern New Zealand.

While this strategy enabled the operation to meet regional rules for P loss and improve profitability, two lessons were learnt. The first was that the strategy required a five year period to implement. This may be too long and therefore necessitate the implementation of GMPs based on their effectiveness and speed, with little emphasis on cost. The second lesson was that poor practice, such as the excessive application of effluent at the wrong time of year, results in significant P losses can that can and should be prohibited - often without much impact on the bottom line.

The preferred model for management of P losses might be to have a mixture of legislation prohibiting obvious bad practice, combined with a mix of voluntary measures that are utilised and championed by industry-leading farmers. This is set against the legislative backstop of the National Policy Statement for Freshwater Management (see policy section) that provides a mandatory policy framework for maintaining or improving freshwater quality, i.e. a check that measures are effective. The 'mixed' model focuses on impact and implements management measures according to outputs and an appropriate allocation mechanism to translate catchment scale loads and concentrations (e.g. for periphyton) to the farm scale. By avoiding excessive regulation of inputs or practices, innovative management practices are fostered and flexibility is maintained to change farm management (within defined limits) according to immediate (e.g. climatic) or long-term (e.g. market) demands.

**Table 1.** Range of cost and effectiveness of good management practices to mitigate plot scale P losses on New Zealand dairy farms (McDowell and Nash, 2012; McDowell, 2014).

| Good management practice | | Main targeted P form(s) | Cost - Range (USD $/kg P conserved)[1] | Effectiveness (% total P decrease) |
|---|---|---|---|---|
| Optimum soil test P | Management | Dissolved and Particulate | (highly cost-effective)[2] | 5-20 |
| Low P farming system (split pastures) | Management | Dissolved and Particulate | (330) | 25-30 |
| Low solubility P fertilizer | Management | Dissolved and Particulate | 0-20 | 0-20 |
| Stream fencing | Management | Dissolved and Particulate | 2 - 45 | 10-30 |
| Restricted grazing of cropland | Management | Particulate | 30 - 200 | 30-50 |
| Greater effluent pond storage / application area | Management | Dissolved and Particulate | 2 - 30 | 10-30 |
| Flood irrigation management[3] | Management | Dissolved and Particulate | 2 - 200 | 40-60 |
| Low rate effluent application to land | Management | Dissolved and Particulate | 5 - 35 | 10-30 |
| Tile drain amendments | Amendment | Dissolved and Particulate | 20 - 75 | 50 |
| Red mud (bauxite residue) | Amendment | Dissolved | 75 - 150 | 20-98 |
| Alum to pasture | Amendment | Dissolved | 110 - >400 | 5-30 |
| Alum to grazed cropland | Amendment | Dissolved | 120 - 220 | 30 |
| Grass buffer strips | Edge of field | Dissolved | 20 - >200 | 0-20 |
| Sorbents in and near streams | Edge of field | Dissolved and Particulate | 275 | 20 |
| Sediment traps | Edge of field | Particulate | >400 | 10-20 |
| Dams and water recycling | Edge of field | Dissolved and Particulate | (200) - 400[4] | 50-95 |
| Constructed wetlands | Edge of field | Particulate | 100 - >400[5] | -426-77 |
| Natural seepage wetlands | Edge of field | Particulate | 100 - >400[5] | <10% |

[1] numbers in parentheses represent net benefit, not cost.
[2] depends on existing soil test P concentration.
[3] includes adjusting clock timings to decrease outwash < 10% of inflow, installation of bunds to prevent outwash, and re-levelling of old irrigation borders.
[4] upper bound only applicable to retention dams combined with water recycling.
[5] potential for wetlands to act as a source of P renders upper estimates for cost infinite.

While we have the ability to meet the demands of water quality policy at the farm scale, there are several reasons why the mixed model may fail. For instance, farmers may not have sufficient information or capability to make the day-to-day or strategic management decisions to mitigate P losses. There is also the possibility that poor operators or performing enterprises are not being picked up by compliance regimes, diluting the efforts of good operators at a catchment scale. Furthermore, the link between cause and effect, and hence a satisfactory and fair allocation mechanism, may be poor. For instance, our ability to monitor at sufficient spatial and temporal scales may be disconnected to management decisions and P losses on a catchment scale. Modelling is used to make that connection. However, estimates of P loss, and the models that are derived from them, contain uncertainties (accuracy and precision). Clear and effective policy needs to account for these uncertainties and often does so using statistically-defined limits that accommodate short-term perturbations that may cause spikes in annual loads, but favours a focus on measuring, modelling and limiting long-term trends of increasing of P losses (Smith et al., 1997).

An additional uncertainty is the potential that processes may not be correctly represented in models of P loss. For instance, it is generally thought that P losses can be quickly mitigated due to the dominance of surface runoff pathways (McDowell and Nash, 2012). However, recent research in New Zealand is showing that where soils are enriched with P, have poor sorption capacity (indicated by a low anion storage capacity) and receive either rainfall or irrigation to move P beyond topsoil, groundwater P concentrations may be enriched (McDowell et al., 2015). Furthermore, if aquifers have poor P sorption capacity (usually of sand or gravel lithology) and have good connection to surface water, baseflow in streams will reflect groundwater P concentrations. This may result in a continual legacy of P inputs even if inputs via surface process are stopped. Of concern is the fact that among the 18 GMPs to decrease P losses, only 8 of these would be effective at substantially decreasing P losses to groundwater. This is clearly an area in need of further research.

Finally, New Zealand is not immune to social and cultural impediments in implementing GMPs and limits to P loss. It is often noted that New Zealand's lack of subsidies has resulted in farming operations that are efficient and able to respond quickly to market demands (MacLeod and Moller, 2006). However, it is also clear that many farming enterprises are subject to an increased level of risk compared to many other countries – being more vulnerable to spikes in market prices. Coupled to this is added risk associated with losing market access, especially given that the vast majority of New Zealand agricultural produce is exported. Such risk can make farming as an enterprise, and kept within a family more difficult than if the enterprise is run simply as a corporate entity. Constitutionally, New Zealand also has vast areas that are held by Māori. Distinct from Western concepts of land ownership, Māori tend to farm on the basis that the land will be held and passed down the tribal entity in perpetuity. However, such long-term planning can result in farming operations that are run with a different set of values (e.g. environmental) prevailing over other non-Māori operations that are run as a function of the bottom line.

**Conclusions**

Our ability to farm within a P-limit requires good knowledge of the sources and pathways of P loss, but also of how emissions are measured across appropriate spatial and temporal scales and linked to impacts. Current and potential policy looks to ensure P losses are allocated fairly and that these allocations are complied with. A method of decreasing P losses is to focus on prohibiting obvious bad practice while allowing farming to take place on the understanding that outputs (i.e. losses) would be mitigated. Recent advances in the isolation of pathways and critical source areas for P loss has allowed us to increase the cost-effectiveness of mitigation strategies by targeting certain pathways and focusing them to when CSAs are actively losing P. Doing so has been demonstrated to allow farming to remain profitable (sometimes increasing profitability) while also meeting the requirements of a P-limit.

**Acknowledgements**

Much of the underpinning work reviewed in this document was funded by the Ministry for Business, Innovation and Employment's contract 'Clean Water, Productive Land' (C10X1006)

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