CHALLENGES AND OPPORTUNITIES TO DECREASE PHOSPHORUS LOSSES FROM LAND TO WATER

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Abstract
Phosphorus (P) loss from land can impair water quality. However, there is concern that we may not be able to decrease current losses, let alone mitigate greater losses due to intensification. Research over the past three decades has revealed the soil and climatic factors and management practices that affect P loss. Put simply, the quantity of P lost is a function of surface runoff or sub-surface drainage and availability, which is affected by inputs and the ability of the soil to retain P. Losses are exacerbated if surface runoff or drainage occurs soon after P inputs (e.g. fertiliser and/or manure and dung).

Strategies to decrease P losses depend on the farm. Providing a range of fully costed options gives flexibility when matching strategies to a farm system. Furthermore, to maximise their effectiveness, mitigation strategies are best used in areas that lose the most P, but occupy little of the farm or catchment's area. Focusing on these areas, termed critical source areas, is more cost-effective than farm- or catchment-wide strategies.

Although strategies may be effective at decreasing P loss, there is a lot of uncertainty over whether or not this will result in the desired (or required) improvement in water quality. Some of this uncertainty surrounds what background and human-influenced losses are. Not all anthropogenic losses will be mitigated. Hence, the concept of a manageable loss is introduced as the maximum quantity of P loss mitigated with current knowledge. The question is: will this be enough?

Introduction
Much work has shown that the efficiency of phosphorus (P) use needs to increase to sustain or improve pasture or crop yields, but also to prevent the deterioration of surface water bodies via eutrophication (Carpenter et al., 1998). Elsner and Bennet (2011) point out that about half of the P applied to land (80% of the P mined) is lost to waterways via soil erosion and leaching. This is an expensive waste of P, especially if another price rise, similar to that in 2007-8, occurs (Vaccari, 2009). However, potentially outweighing the cost of P are the effects of eutrophication both monetary (e.g. fish death, effects on tourism and treatment costs if used as potable water) and social or cultural (e.g. loss of waterways for recreation).

The causes of P loss are simple: anthropogenic inputs and management. Natural losses of P tend to be low and can vary widely geographically, but not usually temporally. The difference between current losses and those produced naturally (i.e. reference conditions) represents the anthropogenic loss, a portion of which will be manageable (Fig. 1). Research over the past three decades has revealed soil and climatic factors together with management practices (e.g. the placement and timing of P inputs) result in P loss. Monitoring and measurement of these processes over time has also shown that, in general, P losses increase as the portion of the catchment under agriculture (especially intensive agriculture) increases (Omernik, 1977; Rast and Lee, 1978).

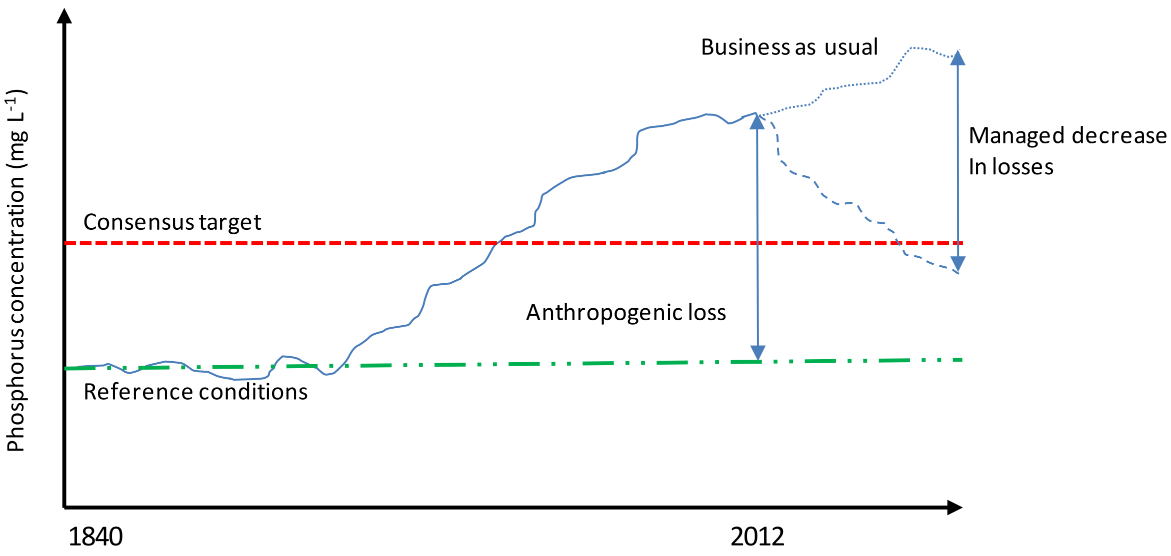

Fig. 1. Conceptual diagram of P concentrations in New Zealand streams and rivers over time and as agricultural intensification increased. Losses would continue to increase, relative to reference conditions, should intensification occur under current management (business as usual) while better management may enable losses to be decreased below a target reached as part of consultation to set values for the catchment's streams and rivers (consensus target).

While the setting of limits to improve surface water quality will often take into account economic and social constraints, it is the role of process-based research that defines how achievable a target is (e.g. without harsh financial penalties), or whether or not that target will result in improved water quality (Woolsey et al., 2007). This paper outlines the processes involved in P loss, examines some of the technologies devised to mitigate P loss, and provides a commentary on the setting of targets relative to natural losses.

Processes controlling the availability of P for loss

Most P loss originates as diffuse sources from agricultural production systems due, in part, to the general ease of identifying and mitigating point sources (Withers et al., 2011). Losses can occur via surface runoff or sub-surface flow (*viz*. sub-surface runoff). Runoff from forests, pastures and other non-cultivated soils carries little sediment, so P losses are generally dominated by dissolved P, which is immediately algal-available (Ryden et al., 1973; Sharpley, 1993). The cultivation of agricultural land greatly increases erosion, and with it, the loss of particulate-bound P (60 to 90% of total P; Sharpley et al., 1995). Some of the particle-bound P is not readily available, but can be a long-term source of P for aquatic biota (Ekholm, 1994).

In acidic soils, P is largely sorbed to Al- and Fe-oxides, whereas in neutral to alkaline soils, P occurs primarily as Ca- and Mg-phosphates often precipitated, or sorbed, onto Ca and Mg carbonates. Organic P can form a significant part of soil P, especially in acidic soils and soils that contain much organic matter and nitrogen. The first factor involved in dissolved P loss is soil P solubility. This is a reflection of how much P is added to the soil and the soils' ability to retain P. Heckrath et al. (1995) was one of the first to show a relationship between P losses in tile drainage and soil test P (STP) concentration (i.e. agronomic tests such as Mehlich, or

Olsen). The potential for dissolved P loss in surface runoff or sub-surface flow was later approximated by a water or 0.01*M* $CaCl_2$ solution (McDowell and Sharpley, 2001). Generally, the relationship between soil test P and runoff P is curvilinear, with P losses increasing as STP, and the capacity of the soil to retain added P via sorption, decreases. This relationship can also be split into two straight lines, either side of a STP concentration, touted by Hesketh and Brookes (2000) as an environmental threshold. Unfortunately, this threshold differed according to the concentration of sorbing materials such as Al- and Fe-oxides or soil pH (Koopmans et al., 2002). Nevertheless, the environmental threshold is often greater than the agronomic optimum, which identified an obvious agronomic inefficiency and unnecessary environmental risk (Fig. 2).

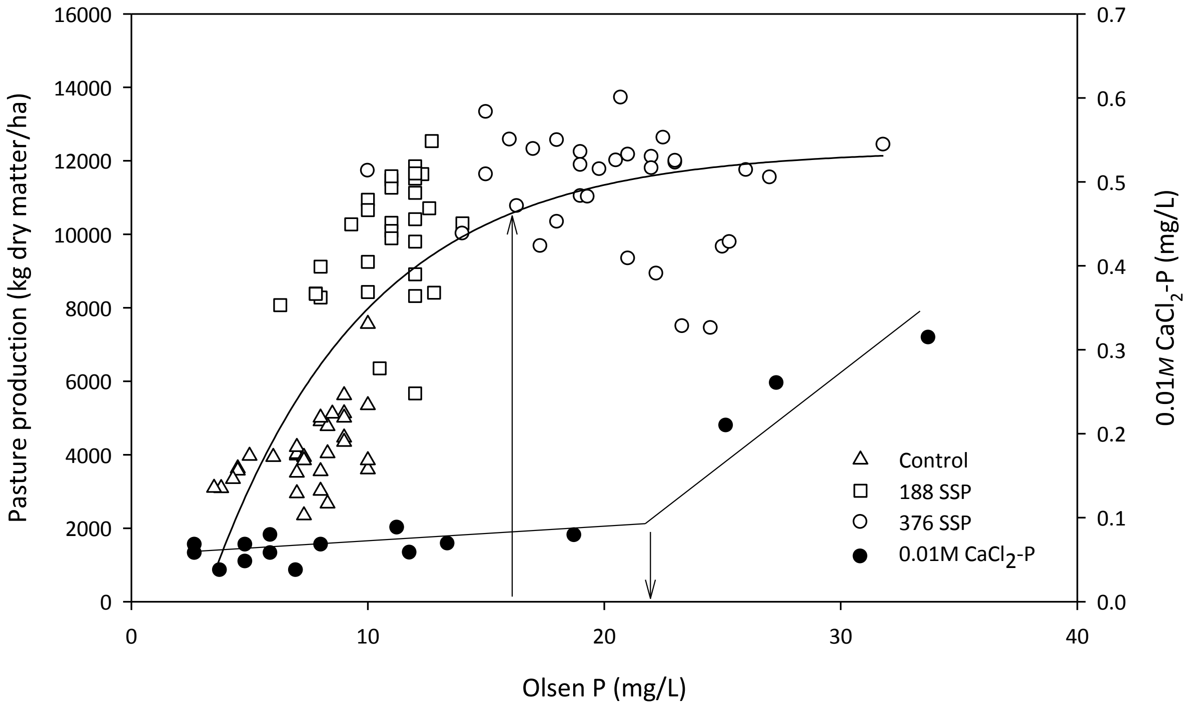

Fig 2. The gap between the agronomic optimum in Olsen P for annual pasture production (up arrow) and a potential threshold (down arrow) in Olsen P for P loss in subsurface drainage (as estimated by 0.01M $CaCl_2$-P) shows there is little justification in exceeding the agronomic optimum. Data are from plots receiving different rates of superphosphate (SSP; kg ha^{-1} yr^{-1}) at Winchmore, Canterbury (McDowell et al., 2012).

Inputs that determine STP concentration include fertilisers and manure or dung (if grazed). The potential for loss from the fertiliser or manure/dung is greatest soon after application, and declines exponentially with time as fertiliser-P is sorbed to the soil, and slurry or manure infiltrates into the soil or crusts-over preventing the interaction of manure with runoff, and invertebrate action buries P into the soil (Vadas et al., 2007). Overall, the magnitude of loss will depend on the rate of application, but also the form and solubility of P. For instance, a low soluble P fertiliser like reactive phosphate rock has been shown to decrease P loss at a catchment scale by about a third compared to highly water soluble superphosphate (McDowell et al., 2010). Another example is that due a lack of the phytase enzyme, monogastric animals such as pigs and poultry produce manure that contains more P as phytate than manure-P from ruminants. With six phosphate moieties, phytate binds strongly to soil and is thought to be less plant (and possibly algal) available (Turner et al., 2002).

Transport of P from the soil matrix to waterways

Chemical principles describe the availability of P, but hydrologic processes determine whether or not losses occur. As the driver for runoff, rainfall events can be divided into (1) rainfall of low intensity and high frequency that tends to move P in subsurface flow, and, (2) rainfall events of high intensity and low frequency that tends to move P in surface runoff from a thin layer of P-rich topsoil. As high intensity storms have more kinetic energy and erosive power, more P, especially in particulate forms is lost during surface runoff than in storms of low intensity that result in subsurface flow. For example, Sharpley et al. (2008) found that despite only accounting for 32% of total annual flow, surface runoff derived from high intensity storms contributed the vast majority of total P lost annually (80%), much of it as particulate-P. Similarly, surface runoff can be further divided into Hortonian (limited by infiltration rate) and saturation-excess (limited by soil water storage capacity). Infiltration-rate limited surface runoff will have a greater capacity to detach and move soil particles (Kleinman et al., 2006), but is restricted to either large storm events or areas where the infiltration rate has been decreased or is low (e.g. dispersion, cattle treading damage, or tracks and lanes).

Saturation- and infiltration-excess conditions often combine in effect to yield a complex pattern of P loss. Saturation-excess surface runoff can be described by variable source area (VSA) hydrology (Ward, 1984). The size and time that these areas actively produce runoff varies rapidly during a storm as a function of precipitation, soil-type, topography, and moisture status. During a rainfall event, a VSA will expand upslope as the saturated area increases, meaning that surface runoff will be restricted to areas close to the stream in dry summer months compared to wetter winter months when the entire hillslope may contribute surface runoff. In contrast, where infiltration-excess conditions dominate, parts of the catchment can alternate between sources and sinks of runoff as a function of soil properties and rainfall intensity. Srinivasan and McDowell (2009) and McDowell and Srinivasan (2009) examined the role of both runoff processes in generating P losses from a grazed grassland catchment in Otago. They found that the infiltration-excess areas forming part of farm infrastructure (e.g., lanes), or created by animal treading and soil compaction (e.g., stock camps or around watering troughs and gateways), accounted for most of the dissolved P lost in small storms that dominated during summer and autumn (Fig. 3). Importantly, summer-autumn is also when dissolved P would be most detrimental to stream water quality due to warm temperatures and light conditions that help stimulate algal growth. This finding would have been missed if attention was only paid to winter when most P was lost from areas that contributed P via saturation-excess surface runoff.

Although many studies have found that P losses tend to be dominated by surface runoff (Haygarth et al., 2000), subsurface flow losses may be important under certain soil or hydrologic conditions. The loss of P in subsurface flow generally decreases as the degree of soil-water contact increases, due to sorption by P-deficient subsoils. Exceptions occur where organic matter may accelerate P loss together with Al and Fe, or where the soil has a small P sorption capacity (e.g., some sandy soils), where subsurface flow travels from P-rich topsoil in via macropores, or is intercepted by artificial drainage (van Beek et al., 2009; Sims et al., 1998).

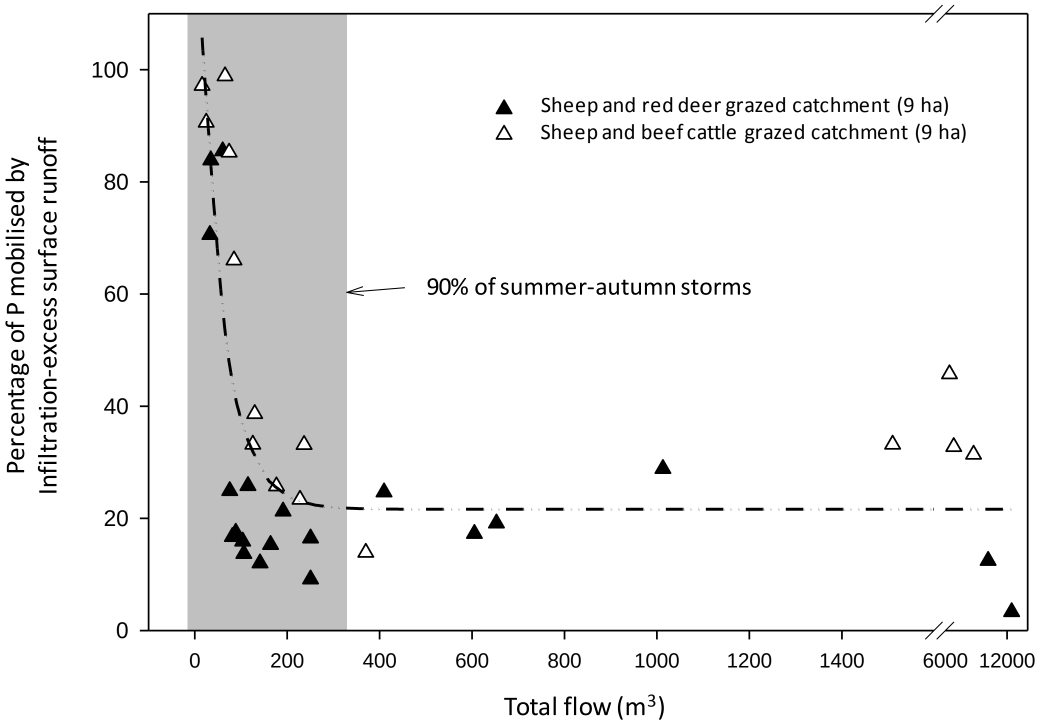

Fig 3. Graph showing the proportion of P contributed by infiltration-excess surface runoff decreases with increasing streamflow as saturation-excess and storm sizes increase. The grey box represents the area where 90% of the summer and fall storms occurred.

Management to decrease P losses from land to water

Management to decrease P losses from grazed pastures focuses on a few key areas. The current version of the dairy Clean Streams Accord accounts for some, but not all, of the "low-hanging fruit". These first steps can be effective. However, unless they are fully assessed, strategies that may appear good at decreasing P loss, may not be cost-effective, therefore leading to decisions that could decrease profit unnecessarily. Recent social and biophysical research suggests that a range of mitigations options are necessary to provide the user with choice based on cost-effectiveness and social considerations and provide flexibility to match the most suitable strategy to the farm type (McDowell and Nash, 2012). Furthermore, the same authors also found that, in general, the further strategies are implemented away from the source, the more expensive, and less cost-effective, they become (Table 1).

Table 1. Summary of efficacy and cost of P mitigation strategies for low, average and high producing dairy farms and for an average farm in the Waikakahi, Canterbury showing the "horses for courses" approach in matching strategies to different farm systems (from McDowell and Nash, 2012).

Strategy		Main targeted P form(s)	Effectiveness (% total P decrease)	Cost - Range (USD $/kg P conserved)[1]	Cost - Waikakahi (USD $/kg P conserved)[1]
Optimum soil test P	Management	Dissolved and Particulate	5-20	(highly cost-effective)[2]	(15)
Low solubility P fertilizer		Dissolved and Particulate	0-20	0-20	0
Stream fencing		Dissolved and Particulate	10-30	2 - 45	14
Restricted grazing of cropland		Particulate	30-50	30 - 200	n.a.
Greater effluent pond storage / application area		Dissolved and Particulate	10-30	2 - 30	13
Flood irrigation management[3]		Dissolved and Particulate	40-60	2 - 200	4
Low rate effluent application to land		Dissolved and Particulate	10-30	5 - 35	27
Tile drain amendments	Amendment	Dissolved and Particulate	50	20 - 75	n.a.
Red mud (bauxite residue)		Dissolved	20-98	75 - 150	n.a.
Alum to pasture		Dissolved	5-30	110 - >400	n.a.
Alum to grazed cropland		Dissolved	30	120 - 220	n.a.
Grass buffer strips	Edge of field	Dissolved	0-20	20 - >200	30
Sorbents in and near streams		Dissolved and Particulate	20	275	n.a.
Sediment traps		Particulate	10-20	>400	>400
Dams and water recycling		Dissolved and Particulate	50-95	(200) - 400[4]	200
Constructed wetlands		Particulate	-426-77	100 - >400[5]	300
Natural seepage wetlands		Particulate	<10%	100 - >400[5]	n.a.

[1] numbers in parentheses represent net benefit, not cost. Data taken as mid-point for average farm in Monaghan et al. (2009).
[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 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.

Often one of the first steps taken in nutrient management is to balance P inputs with outputs at a farm scale. Although essential in determining P losses and the potential for decreasing loses, adhering to this alone will not arrest P loss. Moreover, P losses can still be high if, for example, Olsen P concentrations are enriched and above plant requirements (Woolsey et al., 2007). This requires the use of mitigation technologies, in addition to a negative P balance, to obtain a level of P loss that is acceptable environmentally and agronomically. Obvious strategies include: minimising the direct deposition of dung into waterways with fencing; optimizing stocking rates to suit pasture production; avoiding grazing wet pastures; the use of fertiliser or effluent to maintain soil test P concentrations at the optimum for plant growth; and not grazing areas or at times likely to produce surface runoff.

In a paddock that doesn't receive effluent, McDowell *et al*. (2007) found that approximately 10, 30, 20, and 40%, of P losses in surface runoff during a year were attributable to fertiliser, dung, pasture-plants and soil (including treading) components, respectively. However, there is potential for wide variation of each of these sources. McDowell (2006) also showed that the potential for P loss from dung would have been initially high but decreased exponentially with time. The same relationship is also true for fertiliser, but the initial potential loss depends upon the water solubility of the fertiliser, which is why some studies have shown less P loss in soils with reactive phosphate rock (water solubility < 1%) applied compared to superphosphate (> 90% water solubility) (McDowell et al., 2003a). The pasture component was attributed to P released during the ripping of pasture and the loss of P from denuded material. Mundy *et al*. (2003) also showed that P losses during flood irrigation from ungrazed, but mown pasture, was twice that of ungrazed and unmown pasture. In a grazed pasture, McDowell *et al*. (2003b) showed that the rate of P losses increase if the pasture is been grazed for more than 24 hours due to significantly decreased infiltration rates and potential for surface runoff. Finally, as shown above, the application of excessive P to maintain soil P concentration beyond the plant optimum on the basis that it is "money in the bank" may lead to large P losses. Furthermore, once enriched with P, a soil can take a long time to decrease concentrations below environmentally acceptable concentrations. Johnston and Poulton (1976) showed soils which had received no farmyard manure since 1901 took 73 years to deplete Olsen P concentrations from 63.9 and 69.2 to 12.4 and 11.9 mg kg^{-1} in off-takes. However, due to stratification of P in topsoil, a quicker strategy to decrease P losses is tillage, which in a grazed dairy can occur as part of a farm re-grassing programme, and redistribution of P within the plough layer (Sharpley, 2003).

Failure to exclude cattle from streams can result in a disproportionate impact on water quality due to direct deposition and bank erosion (McDowell and Wilcock, 2007). In a 1,200 km^2 catchment in the U.S.A. facing P-based water quality restrictions, James *et al*. (2007) estimated that 2,800 kg of P was annually defecated directly into pasture streams by dairy cattle, with an additional 5,600 kg P defecated within 10 m of the streams. In-stream defecation was equivalent to 12% of the annual P loadings attributed to all agricultural sources. Elsewhere, McDowell and Wilcock (2007) observed enriched concentrations of total P in stream flow associated with factors including trampling and destabilization of the stream bank by stock. Thus stream exclusions for pastured cattle provide cost-effective reductions in P loadings, but require consideration of drinking water source, laneway layout and fence maintenance.

Recently, surface runoff from farm infrastructure such as lanes, tracks and gateways has been highlighted as potentially greater sources of P loss than runoff from pasture (Lucci *et al*., 2009). The importance of farm infrastructure cannot be discounted as losses during summer and autumn are when detrimental effects on surface water quality are most likely (Jarvie et al., 2006). Strategies to mitigate this loss generally involve engineering solutions, such as diverting flow back onto pasture, but the application of steel melter slag rich in Al- and Fe-oxides to the side of a laneway was shown to decrease P losses in runoff by about 95% and losses to a small catchment by about 66% (McDowell, 2007).

Assuming a nutrient budget (and plan) is adhered to, the size of the effluent block is dictated by the amount of potassium present, meaning that the effluent block should comprise at least 10% of the farm. This may mean that some additional P fertiliser is required to maintain soil Olsen P; however, poor effluent application is a common cause of excessive P losses. A recent strategy has been to increase storage so that effluent applications avoid times of year when the soil is wet and loss via surface runoff or drainage is likely. In addition, the use low rate application (< 4 mm hr^{-1}), compared to the traditional “travelling irrigator” (*c*. 120 mm hr^{-1}) allows for effluent and the P entrained therein to interact with and be taken up by the soil, thereby minimising losses. Houlbrooke *et al*. (2006) showed that a low rate strategy decreased P losses by 67%

Individually each of these strategies can mitigate a component of P loss; however, only when used collectively in the right place and at the right time can the greatest effect be achieved. This requires knowledge of the spatial and temporal variation of P losses. Pionke et al. (2000) and others have advocated that the majority of P losses come from areas of high source and transport potential – termed critical source areas (CSAs). These are hypothesized to account for the majority of P losses, although originating from a minority of land area. This hypothesis has been explored further by McDowell and Nash (2012) who concluded that the cost-effectiveness of mitigation strategies can be maximised if applied to CSAs and not across an entire catchment or farm. Furthermore, for New Zealand and Australian dairy farms, which receive no financial subsidies or incentives to decrease P losses, optimal placement and timing of mitigation strategies within CSAs will likely minimise any impact on profitability.

The setting of limits relative to management to decrease P losses

In a programme to prevent eutrophication within a catchment, limits (e.g. Fig. 1) are often set that apply during warmer times of year when algal growth is likely and when freshwater is used for recreation. The setting of limits in terms of concentrations, not loads, can avoid a situation where loads are small due to little rainfall, but concentrations (and effects) in the stream are high. Kleinman et al. (2012) argued that targets should be realistic and cite a case in the Chesapeake Bay where in 1987 a reduction target of 40% in P (and N) was to be achieved by 2000. Catchment programmes that focused on the “low hanging fruit” achieved a 25% decrease. This target was perhaps ambitious given the complexity of political and economic restrictions. However, in other cases, focusing on “low hanging fruit” may be able to achieve significant effects. For instance, McDowell et al. (2011) showed that focusing on better methods to apply dairy shed effluent could significantly decrease P losses and eutrophication in the Pomahaka River, Otago, New Zealand. With additional strategies like optimal Olsen P (as matched after consideration of Table 1 and farm systems), modelled data suggested it was possible for an average dairy farm to decrease P losses to less than the proposed target for the river and close to a natural baseline or reference concentration (Fig. 4).

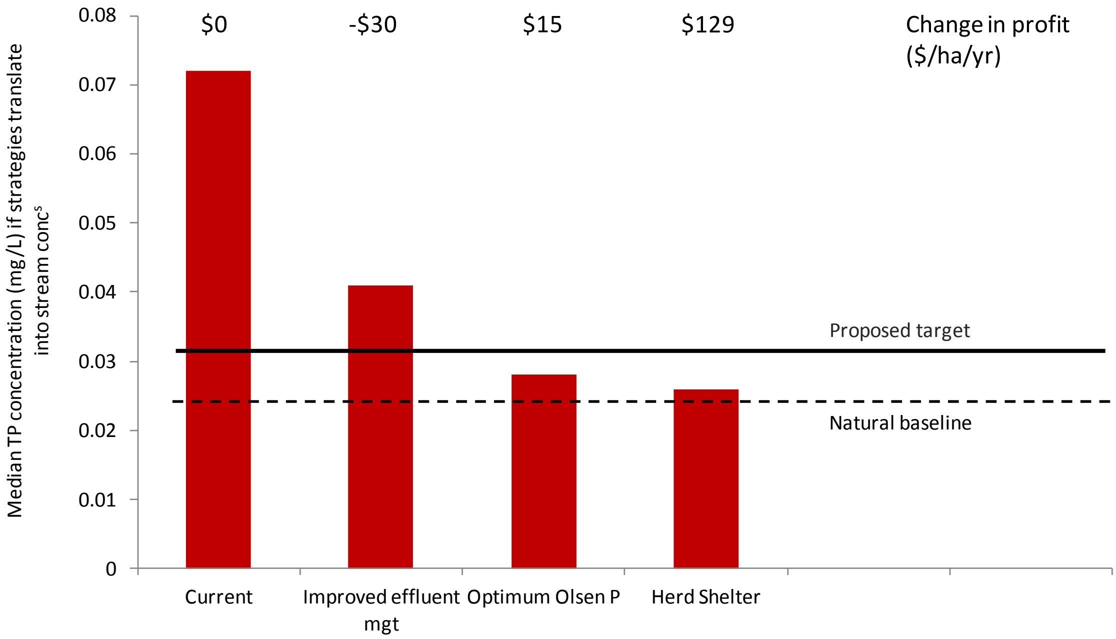

Fig. 4. Estimated median total P concentration lost in runoff from an average dairy farm in the Pomahaka catchment and with mitigation strategies implemented one on top of another. (adapted from McDowell et al. 2011)

The optimisation of mitigation strategies, in combination with furthering our understanding of CSAs, will enable us to achieve better decreases in P loss especially in areas of intensive land use. However, there is probably a limit to what is achievable. This will depend on how "polluted" the waterway is, and what is the natural baseline. It is fortunate that the setting of targets often involves the local community who may recall that a river was naturally polluted, and hence may not be expected to obtain conditions considered acceptable in other areas. Nevertheless, the worry is that our ability to optimise systems to decrease P losses may not keep pace with the rate of intensification and P loss. Furthermore, given that policy can be reactionary, and often requires science to establish the main leakage points before they are managed, the frequency of water quality impairment may increase in the future. I contest that the best approach to solve the problem of P losses, in light of increasing intensification, is to be proactive and identify freshwater systems that are resilient to P inputs, CSAs for mitigation management, and farming systems that lose little P, but still make a profit.

Conclusions

The availability of P for loss by transport mechanisms such as surface runoff and sub-surface flow tends to increase with intensification *viz.* the frequency and quantity of inputs via fertiliser, the saturation of the soil's sorptive matrix with increasing Olsen P or surface applications of dung (via grazing animals) or manure. Many of our strategies focus on mitigating sources and can be effective at reaching targets. However, hydrologic transport mechanisms vary greatly in space and time. The coincidence of soil- or management-specific factors that influence both availability and transport of P loss has been termed a critical source area. Management of these CSAs is seen as the next step beyond balancing farm P balances and simple measures ("low hanging fruit") in mitigating P losses. However, the worry is that even mitigating P loss from CSAs may not enable a farm to reach a target in a sensitive catchment, especially if land use intensification occurs. A proactive approach is therefore needed that identifies streams that are resilient to P inputs and areas unlikely to lose much P, if land use is intensified.

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