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Phosphorus retention and movement through stony soils: Implications of intensive feeding systems and winter forage crops

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Ros Dodd and Richard McDowell

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1. Abstract

Recent evidence suggests that phosphorus (P) enrichment of groundwater is occurring in New Zealand under certain conditions. Enrichment of groundwater with P has large implications for water quality as groundwater inputs to streams and rivers tend to dominate during base flow in the warm summer months when in-stream productivity (e.g. periphyton growth) is at its peak. Factors which are likely to increase the loss of P from soil to groundwater are low anion storage capacity, high permeability and water infiltration rates and, intensive land use. Two winter feeding practices, sited on well drained stony soils, have been identified as possible high risk operations for P loss to groundwater; (1) beef cattle feedlots and; (2) winter grazing of forage crops. This literature review assesses the risks posed by these intensive feeding systems and identifies significant gaps in the current knowledge around P leaching on low ASC, highly permeable soils under these practices.

2. Introduction

Diffuse agricultural pollution is widely recognised as a major cause of water quality degradation in New Zealand rivers and the increasing intensification of farming systems and increasing conversion of dry stock farming to dairying will lead to increased loss of nutrients, in particular nitrogen (N) and phosphorus (P) (McDowell *et al.* 2011). Losses of N and P to surface waters from agricultural sources, while small in agronomic terms, can be environmentally significant and have been linked to the eutrophication of many streams, rivers and lakes (Carpenter *et al.* 1998). Recent evaluation of the dataset from the National Rivers Water Quality Network (NRWQ), which monitors monthly water quality indicators in 35 major river systems spanning the length of New Zealand, showed increasing trends in both N and P concentrations over a 19 year period between 1989 and 2009 (Ballantine & Davies-Colley 2013). Historically, regional councils have focused their attention on reducing N inputs to surface water. However, both N and P can be important factors controlling water quality in New Zealand's rivers and lakes. In fact, in many rivers across New Zealand algal growth is limited by the availability of P or is co-limited by both N and P (McDowell *et al.* 2009). Consequently, quantifying and mitigating P losses is becoming a significant issue as central and regional government move to introduce plans to specify catchment limits for N and P. For example, in Hawke's Bay the proposed Plan Change 6 to the Resource Management plan includes an objective to reduce nutrient losses to waterways and groundwater in the Tukituki catchment and limits for in-stream dissolved reactive phosphorus (DRP) concentrations. Similarly

Environment Southland is developing objectives that translate to nutrient loss limits for inclusion in Plan Change 16.

Due to the perceived high affinity of soil to sorb P, the vertical movement of soil to groundwater through subsurface leaching was historically considered to be negligible (Ryden *et al.* 1974). However, recent evidence suggests that phosphorus enrichment of groundwater is occurring, and furthermore, may be enriching surface waters (McDowell *et al.* 2013). Although, the potential for P to move from land to surface water via shallow groundwater remains a significant gap in the literature, McDowell *et al.* (2013) identified the following factors that increase P loss via subsurface leaching to groundwater; (1) low soil anion storage capacity (ASC); (2) high soil permeability; (3) aquifers of sand and gravel lithology; and (4) intensive land use. A recent stocktake of the distribution and properties of shallow stony soils (soil depth < 45 cm to gravel) in New Zealand was carried out by Carrick *et al.* 2013. This showed that 42 % of these stony soils have an ASC below 30 %, 77 % have moderate to rapid permeability and 58% have a low water storage capacity (30 – 90 mm) all of which are indicators of a high risk of P leaching. Furthermore, stony soils cover 1.68 million ha of easy sloping land (< 15° slope). The intensification of land use on these soils is therefore increasing the potential of these soils to act as hotspots for P leaching to groundwater.

On a catchment scale it is generally considered that the majority of P losses (around 80 %) come from areas which cover a minority of the catchment area (e.g. 20 %) and these areas are termed critical source areas or CSAs (Gburek & Sharpley 1998). Consequently in order to improve surface water quality identification of these CSAs and strategies to reduce P loss in these areas is critical.

Two common land use practices have been highlighted by Hawke's Bay Regional Council (HBRC) and Environment Southland Regional Council (ESRC) as potential CSAs. Namely, intensive feeding operations of beef cattle (HBRC) and winter grazing of forage crops (ESRC). These operations are often located on shallow Recent soils over gravels. Such soils are generally well drained hence considered suitable for supporting large stocking densities over the wet winter periods without damaging soil structure and generally have poor pasture production potential. However, under high stocking densities these soils exhibit all the characteristics identified above to indicate that they will be vulnerable to P loss to subsurface flow and ultimately underlying unconfined groundwater, if present. Previous work in Southland has implicated winter forage grazing as a major source of nitrate leaching (Monaghan *et al.* 2013), but the vulnerability to P loss is unclear. Furthermore, the likelihood of contaminated subsurface flow reaching the surface water-body is often increased as these practices commonly occur on river terraces adjacent to streams.

This literature review will assess the potential risk of P loss from these intensive feeding systems and will consider the P sources from each system and the likely transport mechanisms. In addition, research into P losses from intensive feedlot operations from overseas will be reviewed. While these systems differ to those taking place in Hawke's Bay, being much more intensive, largely confined, and with much greater stocking rates, insight into the potential risks of P loss can be gained from reviewing this work.

3. The potential risk of P loss from intensive winter feeding operations

3.1 Intensive feeding operations in the Hawke's Bay

A small number of intensive feeding operations for beef cattle are located in the Tukituki catchment of Hawke's Bay. The mean annual rainfall for this area is around 800 mm with most of the rain falling during winter and early spring.

One such system is located adjacent to the Papanui stream. Historically this stream was part of the much larger Waipawa River before diversion in the 1800's. This has led to a large area of stony river terrace deposits becoming exposed which are now used for finishing beef cattle. The soils are of the Weathered Fluvial Recent Soil Order (Waimakariri Silty Loam over Sandy Loam) (Landcare Research, 2014) and are well drained with moderate to rapid permeability. The cattle are moved onto these soils over the wetter winter months to alleviate damage to soil structure on more vulnerable soils, but due to the high permeability they may be at risk of P leaching. Furthermore the ASC of this soil type has been classified as low with an average of 19 % (Landcare Research 2014) further increasing the risk of P leaching. These intensive feeding areas generally cover 9 – 18 ha and support a stocking density of roughly 70 – 80 SU/ha (Fig. 1a). As the soils do not produce significant pasture growth the cattle are fed a mixture of hay, silage and a small amount of grain located in central feed lots (fig 1b).

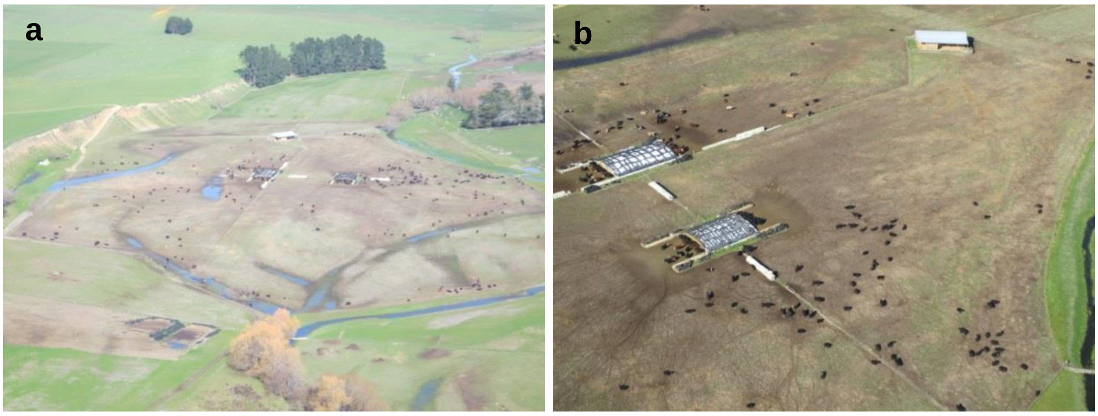

Figure 1: An example of an intensive feeding system for the wintering of beef cattle in the Tukituki catchment of Hawke's Bay (a) shows the entire area of the operation and (b) shows the feedlot areas in more detail (photographs kindly provided by HBRC).

The main P sources in this system are dung excreted by the cattle, including unutilised P from the imported feed, and the soil itself. At a farm scale, these sources generally dominate annual P loss from grazed pastures and typically 40 % of P losses are likely to come from soil and 30 % from dung, with the remaining 10 and 20 % attributed to incidental fertiliser P loss and pasture P lost following grazing (McDowell *et al.* 2007).

Dung - Fresh dung can represent a significant P source to surface runoff if a storm event occurs soon after deposition (McDowell *et al.* 2006). However, while the potential for P loss from fresh dung can be large, this declines rapidly over time as forms of water soluble P are transformed to more recalcitrant forms following drying and dung-P is sorbed by soil and incorporated by earthworm activity into the soil (McDowell & Stewart 2005). A hard crust forms on the dung surface as it dries decreasing the interaction with subsequent rainfall events and the dung is incorporated into the soil via treading by the cattle or dissolution and leaching of P down the soil profile (McDowell *et al.* 2006). Chardon *et al.* (2007) investigated the leaching of P from a dung pad over 234 days using shallow (10 cm deep) lysimeters filled with acid washed silica sand (zero P sorption capacity) or a free draining sandy soil. Leachate collected from the sand filled lysimeters simulated the solution entering the soil from underneath a dung pad and the leachate collected from the sandy soil cores simulated the soil solution leaving the root zone. The total dissolved P (TDP) concentration in the leachate from the sand lysimeters peaked at 25 mg P/L during the first 4 weeks of the trial and remained above 10 mg P/L for the remaining 206 days. TDP concentrations in the leachate collected from the sandy soil cores were lower (peak 4 mg P/L), but still eight times greater than concentrations in leachate collected from soil cores without dung pads, and similarly to the sand filled lysimeters, TDP concentrations remained elevated for the length of the trial. This indicates that manure can act as a long term P source to the soil surface resulting in prolonged leaching of P through the root zone. Other studies have also documented enriched soil P concentrations directly beneath dung pads. Woodard *et al.* (2013) investigated the potential for P leaching from cattle excreta on cattle pastures in Florida. Plant available P concentrations in the soil, as measured by Mechlich-3 extraction, were increased by 35 % in the top 0-10 cm immediately beneath a dung pad. Repeated applications of dung further increased the Mechlich-3 P concentration by 136 % following three dung depositions and increased the degree of P saturation, but there was no change in soil P concentrations below 10 cm. This is in agreement with Aarons *et al.* (2004) who saw a 72 % increase in Olsen P in the 0 – 5 cm layer, but no significant change in the 5 – 10 cm depth. However, both of these studies were carried out on soils with a high P sorption capacity. On soils with a low P retention or where the P loading effectively blocks available P sorption sites (i.e. P saturated soils), leaching of P down the soil profile may be significant.

Soil – Continued deposition of dung to the soil surface will increase the soil P concentration in that area. A wide range of agronomic soil tests (e.g. Olsen P), broadly termed soil test P (STP) are used across different countries to assess the amount of plant available P in the soil. Enriched soil test P (STP) concentrations have been measured in feedlot soils in the US (Vaillant *et al.* 2009), Canada (Olson *et al.* 2005) and Argentina (Wyngard *et al.* 2011). A large volume of research has demonstrated the link between increased STP concentration in soil and the increased potential for P loss to both surface run-off and subsurface leaching (e.g. Heckrath *et al.* 1995; McDowell & Sharpley, 2001). However, these overseas systems are more intensive, generally consisting of small pens stocked at a density ranging from one head of cattle to 18 m^2 (Olson *et al.* 2005) to 50 m^2 (Wyngard *et al.* 1995), which translates to around 200 - 600 SU/ha. In Sweden, soil P concentrations were measured over a five year period in an outdoor feedlot used by dairy cattle over the winter (7 – 8 months of the year) at a stocking density of 62 – 92 SU/ha (Uusi-Kämppä, 2002), which is more comparable to a typical stocking rate of 70 SU/ha used for a feedlot in the Hawkes Bay region. P_{AAAC}, a measure of labile soil P concentrations (comparable to Olsen P) were significantly greater than an adjacent forested control across the whole of the feedlot, and were nearly eight times greater in the top soil layer (0 – 20 cm) at the front of the feedlots where the cows congregated around feed and bedding materials than in the rear of the plots. This is in agreement with work investigating CSA on pasture-based dairy farms where soil P has been shown to accumulate in areas around water troughs (Lucci *et al.* 2010*)* and stock camps (Haynes & Williams 1993). This would suggest that for the Hawke's Bay feedlots, areas around the feed pads may represent hotspots of soil P with an increased potential for loss.

Transport pathways – Due to the high permeability of the feedlot soils, infiltration rates are high and surface run-off minimal – unless soils become saturated or topsoil becomes pugged or compacted. However, many overseas authors have noted that in the intensive cattle feedlot the continued deposition of excreta over a small area leads to a change in soil structure and the generation of an organic stratum on the soil surface consisting of unconsolidated excreta and the presence of a thin, almost black interface layer (Mielke *et al.* 1974; Garcia *et al.* 2011; Miller *et al.* 2008; Olson *et al.* 2005; Vaillant *et al.* 2009). The interface layer has been shown to impede infiltration even on excessively well-drained sandy soils (Garcia *et al.* 2011; Miller *et al.* 2008), effectively sealing the feedlot floor. This effect has been attributed to physical processes such as cattle treading pushing manure into soil pores, chemical dispersion of clay materials and biological mechanisms e.g. gleying, where soil pores become blocked by slime or gums from anaerobic decomposition (Mielke *et al.* 1974). However, while the presence of this interface layer has been used to explain the lack of soil P enrichment to depth under intensive feedlots in some studies (e.g. Vaillant *et al.* 2009), enriched soil P concentrations to depths of 60 cm have been found (Wyngard *et al* 2011). Similarly, in a study by Olson *et al.* (2005) chloride enrichment to 1.2 m depth was presented as evidence of contaminant movement through the interface layer to deeper soil following three years of feedlot use, given manure was the only source of chloride. Furthermore, Mauke & Fonstad (2000) found evidence of manure contamination in shallow groundwater immediately beneath and adjacent to feedlot pens used for 20 – 35 years for finishing beef cattle, but unfortunately no information on stocking densities was available.

The source of P may affect the movement of P through the soil profile. Various studies have shown that P from manure sources is transported further down the soil profile than inorganic P from mineral fertiliser application (Sims *et al.* 1998). This has been attributed to the greater mobility of dissolved organic P forms and the preferential sorption of orthophosphate to soil over many phosphate monoesters or diesters (Leytem *et al.* 2002). In a study comparing the extent of P movement through a fine sandy loam soil (USDA soil taxonomy: Typic Haplustoll) receiving long-term applications of either cattle manure or mineral P fertiliser, Eghball *et al.* (1996) found that while a high P sorbing calcium carbonate layer was effective at limiting the movement of P from a mineral fertiliser source, enriched P concentrations were found below this layer in the plots receiving manure. These findings suggest that the large deposition of excreta during winter feeding has a greater potential to transport P through the soil profile than the application of mineral fertiliser, hence a greater risk of P leaching to groundwater.

Due to the difference in stocking densities between overseas feedlots and the feedlots in the Hawkes Bay region, it is unclear whether the formation of a similar manure interface layer would occur. However, in areas where the cattle tend to congregate, e.g. around feed areas, there is a potential for the build-up of a manure pack. If infiltration is impeded, leaching losses of P may be reduced but surface run-off may become a significant pathway of P transport. The potential for both surface runoff and subsurface flow generation appears to be high in the example feedlot shown in Fig 1a. due to the presence of standing water, and the stream running adjacent to the feedlot suggests increased risk of connectivity between the source and receiving water body. However, detailed studies investigating the soil structure, soil P concentration to depth, infiltration rate, and run-off generation processes (both surface and sub-surface) in addition to connectivity to nearby watercourses are required to fully assess the risk of these areas as CSA for P loss.

3.2 Winter forage grazing in Southland

In Southland the cool climate limits grass growth during the winter months and pasture yields are insufficient to match the livestock feed requirements. Consequently, it is common practice to provide forage crops, mainly brassica crops such as swede (*Brassica napus*) or kale (*Brassica oleracea*) for winter grazing on roughly 10-15% of the farm area. These crops are grazed intensively for roughly 10 weeks at stocking rates which range between 1000 and 1400 SU/ha, although this will depend on the feed available (Monaghan *et al.* 2013). Similar to the feedlots in Hawkes Bay, paddocks for forage crops are often situated on well drained stony soils, (Fig 2). This minimises compaction and/or pugging issues associated with high stocking densities on vulnerable soils over the wet winter period.

Figure 2. An example of winter forage grazing on stony soils in Southland (photograph kindly provided by ESRC)

As for the intensive winter feedlot scenario in Hawkes Bay, the main P sources in paddocks with winter grazing of forage crops are dung and soil (see section 3.1). Additionally there may be a small contribution from the forage crop itself, but no data is available to confirm this component. Winter grazing at high stocking rates has been shown to lead to compaction, pugging and reduced infiltration rates on poorly drained Pallic soils (Drewry & Paton 2005), which has the potential to increase the risk of nutrient loss to surface run-off. A number of studies have shown increased loss of P in surface run-off following winter grazing of forage crops compared to grazed and ungrazed pastures (McDowell 2006; McDowell & Houlbrooke 2009; McDowell *et al.* 2003). The majority of this P loss was in the particulate form and associated with increased sediment losses associated with erosion enhanced by treading damage and the lack of vegetative cover. McDowell & Houlbrooke (2009) also found an increased loss of dissolved organic P forms, as a result of increased deposition of excreta following grazing on Pallic soils. There has been less investigation of the effect of winter forage grazing on P leaching. In the study by McDowell & Houlbrooke (2009) surface run-off of P was found to be the dominant loss pathway. Specifically, at this site shallow lysimeters (18 cm diameter and 24 cm deep) were taken of the grazed forage crop and grazed pasture soils following three years of grazing. No significant difference in P loss to drainage was seen between treatments over one year and the TDP and total P loads in drainage waters were < 25% and < 10% of that in surface runoff, respectively.

The studies outlined above suggest that winter grazing of forage crops increases the potential for P loss to surface run-off, especially in the particulate form, and that the contribution of leaching to total P loss is small. However, all of these trials were carried out on Mottled Fragic Pallic soils which are characterised by imperfect drainage and moderate to slow permeability (Hewitt, 2010). Furthermore, the trials were carried out on hill slopes where the potential for surface run-off generation is enhanced due to topography. On flat, well drained soils with rapid permeability, e.g. the stony Gore soils (Acidic Orthic Brown soils), the potential for leaching is enhanced and subsurface P losses may be significant. In addition, in the study of McDowell and Houlbrooke (2009) no dung was applied to the surface of the lysimeters during the leaching trial. The only P sources were residual manure P from past grazing and soil P. The addition of fresh dung will have likely increased P leaching losses. Recent research has shown N leaching losses from paddocks used for the winter grazing of forage crops make a disproportionately large contribution to the total N losses of dairy systems (Monaghan *et al.* 2013; Smith *et al.* 2012). A similar scenario is likely for P if surface runoff is likely. Due to the deposition of large amounts of excreta to bare soil during winter when plant uptake is minimal and drainage is likely, it therefore seems likely that on free draining stony soils the loss of P to subsurface flow could also be significant. However, this has not been investigated experimentally and is a distinct gap in the literature.

Roughly 159,500 ha of Southland soils on land with < 15° slope have been classified as stony (Carrick *et al.* 2013) with the potential for intensive land use, and roughly 19,000 to 25,000 ha are thought to be utilised for winter forage crops each year (ESRC Little, A. Pers. comm.). Therefore, due to their widespread use, P leaching from these soils may have important implications for water quality but needs to be assessed.

4. Conclusions

The literature review highlighted the following risk factors which may increase the potential for P loss to subsurface flow, groundwater and ultimately surface waters; (1) low ASC; (2) high permeability and infiltration rate; (3) large amounts of excretal P return to bare soil (a function of high stocking rate) and; (4) proximity to the receiving surface water body. This suggests that the use of stony river terrace soils for intensive winter feeding operations, such as the feedlot scenario in the Hawke's Bay and the winter grazing of forage crops in Southland are likely CSA for P loss by this pathway. Additionally, within the feedlot scenario, congregation areas around feed pads may act as additional hotspots of P loss. However, there is little data available to quantify the potential risk or the likely partitioning of P loss to surface runoff or subsurface flow.

Overseas work has shown enrichment of groundwater under confined intensive feeding operations. However, due to large differences in these systems to the winter feeding operations in New Zealand there is uncertainty around the comparability of these studies.

Additional work is required to; (1) develop a qualitative risk matrix which relates likely soil, climatic and management factors with enhanced P loss and (2) quantify the P loss to both surface runoff and subsurface flow on stony soils under these land use scenarios.

5. References

Aarons, SR, O'Connor, CRO & Gourley, CJP. 2004. Dung decomposition in temperate dairy pastures I. Changes in soil chemical properties. *Australian Journal of Agricultural Research* **42**: 107-114.

Ballantine, DJ & Davies-Colley, RJ. 2013. Water quality trends in New Zealand Rivers: 1989-2009. *Environmental Monitoring and Assessment* (in press).

Carpenter, SR, Caraco, NF, Correll, DL, Howarth, RW, Sharpley, AN & Smith, VH. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* **8**: 559-568.

Carrick, S, Palmer, D, Webb, T, Scott, J & Lilburne, L. 2013.Stony soils are a major challenge for nutrient management under irrigation development. In: Accurate and Efficient Use of Nutrients on Farms (Currie, L.D., Christensen, C.L.) Occasional Report No. 26, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 6 pp http://www.massey.ac.nz/~flrc/workshops/13/Manuscripts/Paper_Carrick_2_2013.pdf

Chardon, WJ, Aalderink, GH & van der Salm, C. 2007. Phosphorus leaching from cow manure patches on soil columns. *Journal of Environmental Quality* 36: 17-22

Drewry, JJ & Paton, RJ. 2005. Soil physical quality under cattle grazing of a winter-fed brassica crop. *Australian Journal of Soil Research* **43**: 525-531.

Eghball, B, Binford, GD & Baltensperger, DD. 1996. Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application. *Journal of Environmental Quality* **25**: 1339-1343.

Garcia, AR, Maisonnave, R, Massobrio, MJ & Fabrizio de Iorio, AR. 2012. Field-scale evaluation of water fluxes and manure solution leaching in feedlot pen soils. *Journal of Environmental Quality* **41**: 1591-1599.

Gburek, WJ & Sharpley, AN. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. *Journal of Environmental Quality* **27**: 267-277.

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

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.

Hewitt, AE. 2010. *New Zealand Soils Classification* Manaaki Whenua Press.

Landcare Research. 2014. S-map Online. Available at http://smap.landcareresearch.co.nz/home (accessed 22/01/14)

Lucci, GM, McDowell, RW & Condron, LM. 2010. Potential phosphorus and sediment loads from sources within a dairy farmed catchment. *Soil Use and Management* **26**: 44-52.

Maulé, CP & Fonstad, TA. 2000. Impacts of cattle penning on groundwater quality beneath feedlots. *Canadian Agricultural Engineering* **42:**87-93

McDowell, RW. 2006. Phosphorus and sediment loss in a catchment with winter forage grazing of cropland by dairy cattle. *Journal of Environmental Quality* **35:** 575-583**.**

McDowell, RW, Dodd, RJ, Cox, N & Wheeler, D. 2013. Assessing and mitigating a potential legacy of phosphorus loss form land to surface waters: A national perspective. 2013 AWRA Spring Speciality Conference – Agriculture Hydrology and Water Quality II, March 25-27, St. Louis, MO.

McDowell, RW, Drewry, JJ, Muirhead, RW & Paton, RJ. 2003. Cattle treading and phosphorus and sediment loss in overland flow from grazed cropland. *Australian Journal of Soil Research* **41**: 1521-1532.

McDowell, RW & Houlbrooke, DJ. 2009. Management options to decrease phosphorus and sediment losses from irrigated cropland grazed by cattle and sheep. *Soil Use and Management* **25**: 224-233.

McDowell, RW, Muirhead, RW & Monaghan, RM. 2006. Nutrient, sediment and bacterial losses in overland flow from pasture and cropping soils following cattle dung deposition. *Communications in Soil Science and Plant Analysis* **37**: 93-108.

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

McDowell, RW, Larned, ST & Houlbrooke, DJ. 2009. Nitrogen and phosphorus in New Zealand streams and rivers: Control and impact of eutrophication and the influence of land management. *New Zealand Journal of Marine and Freshwater Research* **43**: 985-995.

McDowell, RW & Sharpley, AN, 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. *Journal of Environmental Quality* **30:** 508-520.

McDowell, RW & Stewart, I. 2005. Phosphorus in fresh and dry dung of grazing dairy cattle, deer and sheep: Sequential fraction and phosphorus-31 Nuclear Magnetic Resonance Analysis. *Journal of Environmental Quality* **34**: 598-607.

McDowell, RW, van der Weerden, TJ & Campbell, J. 2011. Nutrient losses associated with irrigation, intensification and management of land use: A study of large scale irrigation in North Otago, New Zealand. *Agricultural Water Management* **98**: 877-885.

Mielke, LN, Swanson, NP & McCalla, TM. 1974. Soil profile conditions of cattle feedlots. *Journal of Environmental Quality* **3**: 14-17.

Miller, JJ, Curtis, T, Larney, FJ & McAllister, TA. 2008. Physical and chemical properties of feedlot pen surfaces located on moderately coarse- and moderately fine-textured soils in South Alberta. *Journal of Environmental Quality* **37**: 1589-1598.

Monaghan, RM, Smith, LC & de Klein, CAM. 2013. The effectiveness of the nitrification inhibitor dicyaniamide (DCD) in reducing nitrate leaching and nitrous oxide emissions from a grazed winter forage crop in southern New Zealand. *Agriculture, Ecosystems and Environment* **175**: 20-38.

Olsen, BM, Miller, JJ, Rodvang, SJ & Yanke,LJ. 2005. Soil and groundwater quality under a cattle feedlot in Southern Alberta. *Water Quality Research Journal of Canada* **40**: 131-144

Ryden, JC, Syers, JK & Harris, RF. 1974. Phosphorus in runoff and streams. In: *Advances in Agronomy* (ed. NC Brady), Academic Press. pp. 1-45.

Sims, JT, Simard, RR & Joern, BC. 1998. Phosphorus loss in agricultural drainage: historical perspective and current research. *Journal of Environmental Quality* **27**: 277-293.

Smith, LC, Orchiston, T & Monaghan, RM. 2012. The effectiveness of the nitrification inhibitor dicyandiamide (DCD) for mitigation nitrogen leaching losses from a winter grazed forage crop on a free draining soil in northern Southland. *Proceedings of the New Zealand Grassland Association* **74**: 39-44.

Uusi-Kämppä, J. 2002. Nitrogen and phosphorus losses from a feedlot for suckler cows. *Agricultural and Food Science in Finland* **11**: 355-369.

Vaillant, GC, Pierzynski, GM, Ham, JM & DeRouchey, J. 2009. Nutrient accumulation below cattled feedlot pens in Kansas. *Journal of Environmental Quality* **38**: 909-918.

Woodard, KT, Liu, K., White-Leech, UR & Sollenberger, LE. 2013. Leaching potential of phosphorus from cattle excreta patches in the Central Highlands of Florida. *Journal of Environmental Quality.* **42**: 872-880.

Wyngaard, N, Picone, L, Videla, C, Zamuner, E & Maceira, N. 2011. Impact of feedlot on soil phosphorus concentration. *Journal of Environmental Protection* **2**: 280-286.