COST AND EFECTIVENESS OF MITIGATION MEASURES FOR REDUCING NUTRIENT LOSSES TO WATER FROM PASTORAL FARMS IN SOUTHLAND, NEW ZEALAND

Ronaldo Vibart[a,*], Iris Vogeler[a], Samuel Dennis[b], William Kaye-Blake[c], Ross Monaghan[d], Vicki Burggraaf[e], Josef Beautrais[a], Alec Mackay[a]

[a]AgResearch, Grasslands Research Centre, Palmerston North, New Zealand
[b]AgResearch, Lincoln Research Centre, Lincoln, New Zealand
[c]PwC, Wellington, New Zealand
[d]AgResearch, Invermay Research Centre, Mosgiel, New Zealand
[e]AgResearch, Ruakura Research Centre, Hamilton, New Zealand
[*]Corresponding author. E-mail address: Ronaldo.Vibart@agresearch.co.nz

Abstract
Using a novel approach that links geospatial land resource information with individual farm-scale simulation, we conducted a regional assessment of nitrogen (N) and phosphorous (P) losses to water from the predominant mix of pastoral industries in Southland, New Zealand. An evaluation of the cost and effectiveness of several nutrient loss mitigation strategies applied at the farm-scale, set primarily for reducing N losses and grouped by capital cost and potential ease of adoption, followed an initial baseline assessment. Grouped nutrient loss mitigation strategies were applied on an additive basis on the assumption of full adoption, and were broadly identified as 'improved nutrient management' (M1), 'improved animal productivity' (M2), and 'restricted grazing' (M3). Estimated annual nitrate-N leaching losses occurring under representative baseline sheep and beef (cattle) farms, and representative baseline dairy farms for the region were 10 ± 2 and 32 ± 6 kg N/ha (mean ± standard deviation), respectively. Both sheep and beef and dairy farms were responsive to N leaching loss mitigation strategies in M1, at a low cost per kg N-loss mitigated. Only dairy farms were responsive to N leaching loss abatement from adopting M2. Dairy farms were also responsive to N leaching loss abatement from adopting M3, but this reduction came at a greater cost per kg N-loss mitigated. Only dairy farms were responsive to P-loss mitigation strategies, in particular by adopting M1. Overall, M1 provided for high levels of regional scale N- and P-loss abatement at a low cost per farm without affecting overall farm production, M2 provided additional N-loss abatement but only marginal P-loss abatement, whereas M3 provided the greatest N-loss abatement, but came at a large financial cost to farmers, sheep and beef farmers in particular. The modeling approach provides a farm-scale framework that can be extended to other regions, capturing the interactions between farm types, land use capabilities and production levels, as these influence nutrient losses and the effectiveness of mitigation measures.

Keywords: Nitrogen leaching, phosphorous losses, mitigation strategies, pastoral agriculture.

Introduction
Southland, New Zealand's southern-most region, has undergone a noticeable change in its agricultural landscape in recent years. Although sheep enterprises remain the predominant land-use in the region, dairy cow numbers have increased from 200,000 in the 2000/01 milking season to over 500,000 in 2011/12 (New Zealand Dairy Statistics 2012). To a large

extent, the regional land use change in Southland has occurred at the expense of sheep and beef farming, on gentle slopes with relatively reliable summer rainfall (Monaghan *et al.* 2007). The greater profitability of dairy relative to sheep and beef farming has prompted the large number of dairy conversions over the last two decades (Beukes *et al.* 2011), with the potential for current farm conversion rates to continue (Vogeler *et al.* 2014). The conversion usually involves changing from a low-input sheep and beef farming system to a more intensive and high-input dairy farming system. Associated emissions of N and P to water usually also increase, raising community concerns about the impacts on regional water bodies (Environment Southland and Te Ao Marama Inc. 2010).

The Central New Zealand Government's 'National Policy Statement for Freshwater Management' (NPS-FM) directs Regional Councils (Authorities) to set water quality standards and limits for freshwater objectives (NPS 2011). To achieve this objective, the inclusion of diffuse losses from agricultural land is required. Regional Councils in New Zealand have taken different approaches to address the issue of setting nutrient loss limits from agricultural land (N losses in particular), including allocating nutrient loss limits based on the natural capital of the soil (Horizons Regional Council 2014). An adequate representation of farming systems within a region and the ability to link farm models to land resource information were identified as critical elements in the assessment of the influence of farm practices at a regional scale (Vogeler *et al.* 2014). Using a novel approach that links geospatial land resource information with individual farm-scale simulation and nutrient budgets, the objectives of this study were to i) assess N and P emissions to water from the current predominant mix of pastoral industries in Southland (i.e. sheep and beef, and dairy) and to ii) examine the impact of integrated nutrient loss mitigation strategies.

Methods

Location and Land Resource Data

By overlaying the geospatially identified individual farms from AgriBase™ (AsureQuality 2012) with additional geospatial information from the Land Resource Information (LRI) system (Landcare Research), land area, land use capability (LUC), topography, predominant soil order and drainage class were obtained for each pastoral farm in the Southland region. The LUC system (Lynn *et al.* 2009) was conceived to provide a reliable basis on which to promote sustainable land management throughout New Zealand. Land is grouped into classes reflecting potential sustainable use. Capability herein refers to the suitability for productive use, with Class 1 to 7 being potentially suitable for pastoral use (Class 1 with the highest productive potential and Class 7 with the most limitations to pastoral use). Southland pastoral LUC classes and their areas, predominant soils orders, topographies and drainage classes are further described in Vogeler *et al*. (2014).

Modelling Assumptions – Pasture Production and LUC classes

Pasture production was calculated for each farm based on its corresponding area-weighted LUC class. Briefly, the extended legend of the LUC system provides an estimate of the sheep carrying capacity (ewes/ha) for each LUC class present on a farm. These provided a basis for calculating potential pasture dry matter (DM) production classes (PP classes; kg DM/ha) across a landscape, irrespective of current land use. Estimates of LUC-derived PP classes were in agreement with previous reports of well managed Southland dairy pastures on flat-to-rolling land producing 11 to 15 t DM/ha (Dalley & Geddes 2012) and with hill country pastures producing 5-12 t DM/ha (Valentine & Kemp 2007). Pasture production data was then used to inform the farm systems modelling.

Farm-Scale Models and Model Setup

To examine the financial and environmental performance of representative sheep and beef and dairy farms in Southland, the farm-scale models Farmax® Pro (version 6.5.3.03; herein Farmax) and Farmax® Dairy Pro (Version 6.6.0.04) were linked with the OVERSEER® (version 6.1.1; herein Overseer) nutrient budget model. Modelled livestock policies were exported from Farmax to parameterise Overseer to estimate the nutrient losses from the two farm enterprises considered in the analysis. In Overseer, the proportion of N and P excreted by livestock is derived from a balance between animal intake, maintenance needs and removal in animal products from the farm (Wheeler *et al.* 2006). The P model is a calibrated risk model for P losses to second-order streams from pastoral blocks, as outlined by McDowell *et al.* (2005). It is important to note that, in addition to sediment losses not being captured, P losses in sediment due to mass erosion are not considered in the model.

Modelling Assumptions – Farm Systems

Sheep and Beef Farms

A South Island Finishing-Breeding sheep and beef farm (which includes a relatively minor deer component) was modelled for the region (Beef and Lamb New Zealand 2013). The baseline sheep and beef farm scenario (Baseline) comprised a hypothetical 450-ha farm (Table 1). Financial data were sourced from Farmax Pro and Beef and Lamb New Zealand (2013), including mitigation costs. All feed was assumed to be produced on-farm, and small amounts of N fertiliser were annually applied (9.3 and 7.3 kg N/ha for PP classes 2 - 4 and 5 - 6, respectively). Maintenance amounts of P fertiliser were applied according to soil order requirements based on Overseer recommendations.

Table 1. Physical and management characteristics including livestock policies and financial performance of the baseline sheep and beef farms on pasture production (PP) classes 2 to 6.

PP class	2	3	4	5	6
Stocking rate (SU/ha)	16.1	13.8	12.6	9.0	5.4
Pasture yield (t DM/ha)	13.6	10.4	8.1	7.1	3.7
Breeding ewes	4058	3430	3135	1976	1186
Breeding cows	-	-	-	51	31
Dairy heifers	72	68	62	40	24
Animal production (kg/ha)					
Meat	240	205	188	131	79
Wool	68	58	53	33	20
Operating profit ($/ha)	450	339	281	134	-32

Dairy Farms

Representative System 3 (D3) and System 4 (D4) dairy farms (DairyNZ 2010) were modelled. Briefly, a D3 dairy farm imports 10-20% of total feed consumed, which is offered primarily to milking cows to extend lactation and to dry cows (usually sent off-farm). A D4 dairy farm imports 20-30% of the total feed offered to dry cows and to milking cows during early and late lactation. These systems often have young replacement stock (calves and heifers) and dry cows grazing off the effective milking platform. D3 dairy farms are predominant in Southland, accounting for over 40% of the dairy farms during the 2007/08 milking-season (Vogeler *et al.* 2014).

Modelled dairy farms comprised a milking platform (205 ha for lactating cows exclusively) without a support area for replacement heifers and dry cows (Table 2). Targeted milksolids

(MS; milk fat + milk protein) productions per cow and livestock numbers in each system were scaled to achieve maximum pasture utilisation. All dairy farms were seasonal, spring-calving systems on relatively flat topography. Dairy farm expenditure and gross income were sourced from Farmax for 2011-12 for dairying in the South Island. The milk price was set at NZ$6.05 per kg MS.

To accommodate young dairy livestock categories in the region, replacement heifers were sent to sheep and beef farms by mid-December and returned pregnant to the dairy farms (Table 1). Corresponding nutrient losses from this livestock category were allotted to sheep and beef farms, whereas the financial costs of wintering were included in the assessments of profitability of each enterprise. Wintering cows (dry cows during the winter period) were not accounted for in the current modelling exercise. Both dairy systems received 150 kg N/ha on the non-effluent blocks (in 3 applications of 50 kg N each) and 100 kg N/ha on the effluent blocks, irrespective of farm dairy effluent (FDE) N applied. Maintenance levels of P were applied to sustain production, following Overseer recommendations.

Table 2. Physical and management characteristics including livestock policies and financial performance of the baseline System 3 and System 4 dairy farms on pasture production (PP) classes 2 to 4.

PP class	2	3	4	2	3	4
System (DairyNZ, 2010)	3	3	3	4	4	4
No. cows (at peak lactation)	628	488	381	644	504	393
Stocking rate (SR; cows/ha)	3.37	2.62	2.04	3.46	2.70	2.11
Pasture yield (t DM/ha)	15.7	12.4	9.8	15.7	12.4	9.8
Pasture consumed (t DM/ha)	12.5	9.7	7.6	12.1	9.5	7.4
Total feed consumed (t DM/ha)	13.9	10.8	8.4	15.1	11.8	9.2
Milksolids (MS) (kg/cow)	392	391	391	421	421	421
MS (kg/ha)	1,321	1,024	799	1,455	1,139	888
Operating profit ($/ha)	2466	1409	601	2341	1335	558

Modelling Assumptions – Mitigation Groups

Three groups of mitigation strategies (M1, M2, M3) primarily for reducing N and P losses from the different farm types were considered, based on expert knowledge of the region. The mitigation strategies were grouped by capital cost and potential ease of adoption (Kaye-Blake *et al.* 2014). Capital cost was the primary criterion for grouping and prioritising mitigation strategies. Grouped nutrient loss mitigation strategies were applied on an additive basis on the assumption of full adoption, and were broadly identified as ‘improved nutrient management’ (M1), ‘improved animal productivity’ (M2), and ‘restricted grazing’ (M3). The cost of individual mitigation strategies was calculated and expressed on an annualised basis; the projected cost-effectiveness of each mitigation group was calculated by dividing the annualised net cost of each by the quantity of N and P conserved.

The mitigation group M1 included the following mitigation strategies and assumptions:

✓ Maintenance fertiliser applications of single superphosphate were replaced by the slow P release reactive phosphate rock (RPR).

✓ A fenced wetland area (5 ha; 1% of farm area) was established in sheep and beef farms. Livestock numbers were adjusted to compensate for reduced effective grazing area.

✓ Dairy cattle were excluded from streams. Dairy soil Olsen P values were reduced from 35 to 30 µg/ml, closer to the economically optimum soil Olsen P levels for pasture growth in the region (Monaghan *et al.* 2007). The amounts of N fertiliser applied on dairy effluent blocks varied according to the amounts of N captured and applied as effluent, resulting in diminishing amounts of N fertiliser applied as the groups progressed from baseline to M3. An uncovered, concrete feed pad was added to D4 dairies.

The mitigation group M2 included the following mitigation strategies and assumptions:

✓ Livestock from sheep and beef farms were excluded from streams. Animal productivity on sheep and beef farms was enhanced by increasing reproductive performance. Lambing, calving and fawning % were increased from 130%, 85% and 80% to 145%, 90% and 85%, respectively. Livestock numbers were adjusted accordingly.

✓ Fewer, more efficient dairy cows with greater genetic merit and greater individual liveweights (LW; 480 and 500 kg/cow from the corresponding baseline LW of 440 and 460 kg/cow) resulted in greater MS production per cow (423 and 459 kg MS/cow) with similar MS production per ha. Stocking rates were adjusted accordingly.

✓ A low-rate effluent application method replaced the previous system (baseline application depth = 12-24 mm). The effluent system evolved from a holding pond, with liquid effluent stirred and spayed regularly by a travelling irrigator, to a low application rate method (K-Line irrigators, RX Plastics, Ashburton, New Zealand).

✓ A fenced wetland area (2 ha; 1% of farm area) was established on dairy farms. Livestock numbers were adjusted to compensate for reduced total pasture availability.

The mitigation group M3 included the following mitigation strategies and assumptions:

✓ The effective grazing area of sheep and beef farms was further reduced by adding a riparian block (grassy buffer strips running next to streams; 2% of farm area). Similarly, a riparian block was added to the dairy farms (2% of farm area). For both enterprises, livestock numbers were adjusted to compensate for reduced effective grazing area.

✓ A covered loafing and feeding pad were added to the sheep and beef model farms for over-wintering beef cows. This was assumed to accommodate 50% of the beef cow herd. Supplemental hay for this category was offered on the sheltered wintering pad.

✓ A covered loafing pad (and feeding pad for D3 dairies) was added to the dairy model farms. The dairy effluent blocks were doubled in size (at the expense of non-effluent blocks) to manage the additional nutrients captured. The amounts of N fertiliser applied were also adjusted accordingly.

Modelling Scenarios Tested

Eight different regional scenarios were examined, consisting of the previously described sheep and beef farm system, with each of the two dairy farm systems and four mitigation groups (Baseline, M1, M2, M3). For simplicity and ease of interpretation, scenarios 1 - 4 included a D3 dairy farm, and scenarios 5 - 8 included a D4 dairy farm, all scenarios with the same sheep and beef farm system. By comparing these scenario results, the modelling estimated potential reductions in N and P via grouped mitigation practices.

Results and Discussion

Farm Systems Modelling – Baseline Farms

Greater farm economic profitability and animal performance (kg meat, wool, MS produced per ha) were obtained on the most productive LUC classes, which in turn was associated with greater PP and thus greater livestock carrying capacity (Table 1 and 2). The calculated regional value ($328 ± $106/ha) (mean ± SD) was in close agreement with the farm profit ($326/ha) reported for South Island Finishing-Breeding farms in 2011-12 (Beef and Lamb New Zealand 2013). Mean stocking rates of the baseline dairy farms were 2.72 and 2.80 cows/ha for D3 and D4 farms (data not shown), respectively, which was in close agreement with the overall regional stocking rate (2.73 cows/ha) reported for the milking season of interest (2011-12) (New Zealand Dairy Statistics, 2012). Heifer replacement rearing in our modelling exercise was undertaken by sheep and beef farms and most of the required heifers were assumed to be raised within the region. At a 22% dairy replacement rate, and assuming all sheep and beef farms carried replacement heifers (Table 1) as an integral component of their operation, sheep and beef farms within the region were able to account for 88 and 86% of the replacement heifers needed for D3 and D4 farms, respectively.

Environmental Outcomes – Baseline Modelling

Estimates of N leaching losses

Mean estimates (± SD) of annual nitrate-N leaching losses occurring under the baseline sheep and beef and baseline D3 and D4 farms were 10.3 (± 2.3), 30.6 (± 5.7) and 32.6 (± 6.2) kg N/ha, respectively (scenarios 1 and 5; Table 3). Estimates of annual N leaching from both sheep and beef and dairy were likely higher from farms with greater PP potential, due to the greater amount of N cycling in the system and the increased number of urine patches from the greater numbers of livestock carried. Mean estimates of annual N leaching losses occurring under the baseline sheep and beef farm were 10.6 and 9.8 kg N/ha for well- (Brown) and poorly-drained (Pallic) soils, respectively (data not shown). These values are in accordance with reported annual N leaching losses from sheep-grazed pastures in New Zealand (Heng *et al.* 1991; Magesan *et al.* 1996; Ruz-Jerez *et al.* 1995). Mean estimates of annual N leaching losses occurring under the baseline D3 farm were 33 and 28 kg N/ha for well- and poorly-drained soils, respectively, and corresponding losses occurring under the baseline D4 farm increased to 34 and 31kg N/ha (data not shown). These values are in overall agreement with those measured by Monaghan *et al*. (2005) from mole- and tile-drained soil plots grazed by dairy heifers and dry cows in eastern Southland (29 to 42 kg N/ha; 100 kg fertiliser N applied/ha).

We did not account for wintering cows (dry cows during the winter period) in the current modelling exercise, which understates the environmental impact of dairy farming in the region. The results could be viewed as a ‘lower bound’ of N leaching associated with dairying. For a similar set of dairy farm systems modelled (Kaye-Blake *et al.* 2013), the wintering period accounted for an additional 13% of regional N leaching losses, without affecting mitigation adoption and production outcomes. Assuming the same incremental level of regional winter losses were included in our calculations, annual N leaching losses at the regional scale would result in a collective loss of 16,570 t and 16,970 t N from a mix of pastoral industries that included either a D3 or a D4 farm, respectively. Our estimates of regional-scale N leaching losses are in agreement with those reported by Ledgard (2014) (16,900 t N/year including wintering support areas) for similar total land areas modelled in the region. Calculations and methodology, however, differed; a single N leaching loss value was assigned to areas grazed exclusively by lactating dairy cows (30 kg N/ha) and to wintering support areas (50,000 ha; 55 kg N/ha), whereas N leaching losses from pastures grazed under intensive or extensive sheep and beef farm systems were assigned either 12 or 6 kg N/ha, respectively (Ledgard, 2014).

Estimates of P losses

Phosphorous loss risk was estimated as the total amounts of P lost annually (McDowell *et al.* 2005). Mean estimates (± SD) of annual P losses occurring under baseline sheep and beef farms, and baseline D3 and D4 farms were 0.2 (± 0.1), 1.0 (± 0.3) and 1.2 (± 0.4) kg P/ha, respectively (scenarios 1 and 5; Table 3). Mean annual P losses occurring from the baseline D3 farms were 0.7 and 1.4 kg P/ha for well- and poorly-drained soils; corresponding losses occurring from the baseline D4 farms increased to 0.8 and 1.6 kg P/ha. These values are greater than those measured from mole- and tile-drained soils grazed by dairy heifers and dry cows in eastern Southland (152 g P/ha) (Monaghan *et al.* 2005; Smith & Monaghan 2003), but in agreement with estimates from dairy milking platforms located in a poorly-drained but intensively-farmed catchment in central Southland (1.3 kg P/ha) (Monaghan *et al*., 2007). The relatively low P loss values reported for the study site in eastern Southland were attributed to a low Olsen P status of the soil, presumably below the biological optimum for pasture growth, and the procedure opted to measure drainage flow rates, representing a minimum estimate of annual P loss from the site (Smith & Monaghan 2003).

Compared with N leaching losses, a greater degree of uncertainty (and caution) applies to regional estimates of P losses. Scaling up on-farm P loss data from the baseline scenarios resulted in an annual collective loss of 371 t and 406 t of P at the regional scale from baseline sheep and beef and D3 farms and baseline sheep and beef and D4 farms, respectively. Fewer modelling studies have attempted to estimate regional P losses from Southland using similar methodologies. Our annual estimates are lower than those reported by Ledgard (2014) (636 t P including wintering support areas) for similar regional land areas modelled. Calculations and methodology, however, differed between studies: Ledgard (2014) assigned single P loss risk values to areas grazed by lactating dairy cows (0.8 kg P/ha), wintering dairy support areas (1.2 kg P/ha), and intensive (0.6 kg P/ha) and extensive (0.3 kg P/ha) sheep and beef farm systems.

Table 3. Mean estimates of annual N leaching losses (kg/ha), P losses (kg/ha), and farm profit ($/ha) for different scenarios tested in Southland [scenarios 1 to 4 = sheep and beef (S&B) + dairy System 3 (D3); scenarios 5 to 8 = S&B + dairy system 4 (D4), each with mitigation groups Base, M1, M2, M3; see text for detail].

Scenario	1	2	3	4	5	6	7	8
Mitigation group	Base	M1	M2	M3	Base	M1	M2	M3
N leaching losses (kg/ha)								
D3	30.6	28.0	25.2	20.2				
D4					32.6	24.7	21.9	17.6
S&B	10.3	7.2	7.2	6.9	10.3	7.2	7.2	6.9
P losses (kg/ha)								
D3	1.0	0.7	0.6	0.6				
D4					1.2	0.7	0.7	0.7
S&B	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Profit before tax ($/ha)								
D3	1546	1561	1622	1329				
D4					1463	1492	1511	1208
S&B	328	316	323	262	328	316	323	262

Cost-effectiveness of mitigation practices
Both dairy farms (D3 and D4) and sheep and beef farms were responsive to N loss mitigation strategies in M1, with a reduction of 2.6, 7.9, and 3.1 kg N/ha, respectively (Table 3). In contrast, only dairy farms were responsive to P loss abatement using M1 mitigation, and no further abatement was achieved by sheep and beef farms adopting incremental P mitigation. At the regional scale, mitigation strategies in M1 (most likely to be adopted) applied to sheep and beef + D3 farms (scenario 2) delivered a 22% reduction in N leaching losses and a 21% reduction in P losses (Table 4). Similarly, M1 applied to sheep and beef + D4 farms (scenario 6) delivered a 28% reduction in N leaching losses and a 24% reduction in P losses (Table 4).

Table 4. Impact of grouped mitigation strategies on farm nutrient loss abatement and farm profit in Southland. Negative values represent profit losses. Unless stated otherwise[a], values are relative to baseline scenarios [scenarios 2, 3 and 4 = sheep and beef (S&B) + dairy System 3, scenarios 6, 7 and 8 = S&B + dairy System 4; each with mitigation groups M1, M2, M3 (see text for detail)].

Scenario	2	3	4	6	7	8
Mitigation group	M1	M2	M3	M1	M2	M3
Annual N leaching loss abatement						
Total, t	3,285	3,702	4,919	4,200	4,632	5,721
Kg/ha	3.0	3.4	4.6	3.9	4.3	5.3
$/kg N mitigated, D3	1.9	3.0	34.4			
$/kg N mitigated, D4				4.9	4.4	27.6
$/kg N mitigated, S&B	3.2	19.2	34.0	3.2	19.2	34.0
$/kg N mitigated, total	3.0	15.1	34.2	3.7	13.2	31.1
Kg N lost/t MS[a,b]	29	26	21	23	20	16
Kg N lost /t M+F[a,c]	35	33	31	35	33	31
Annual P loss abatement						
Total, t	76.6	84.6	83.1	96.2	107.2	108.3
Kg/ha	0.1	0.1	0.1	0.1	0.1	0.1
$/kg P mitigated	128	659	2023	163	571	1671
Kg P lost/t MS[a,b]	0.7	0.6	0.6	0.7	0.6	0.6
Kg P lost/t M+F[a,c]	1.0	0.9	0.9	1.0	0.9	0.9
Annual profit before tax						
Regional, $/ha	-6	1	-95	-3	-3	-100
Dairy, $/ha	15	76	-222	29	48	-255
S&B, $/ha	-10	-13	-70	-10	-13	-70

[b]Unit of nutrient loss per tonne milksolids (MS) produced. Baseline: 32 and 30 kg N/t MS, 1.1 and 1.2 kg P/t MS (Scenarios 1 and 5). [c]Unit of nutrient loss per tonne of meat (net production) and fibre (M+F) produced. Baseline: 50 kg N/t M+F, 0.9 kg P/t M+F, (Scenarios 1 and 5).

Dairy livestock exclusion from streams (reducing animal-water body connectivity), slight reductions in the rates of N fertiliser applied to dairy farms, and the inclusion of a feed pad to D4 dairy farms, contributed to the N abatement achieved by dairy farms on M1. The feed pad contributed to greater feed utilisation and a reduction in grazing time, reducing the amount of N in animal excreta (urinary N in particular) deposited elsewhere (i.e. paddocks and lanes) (Monaghan *et al.* 2007). On sheep and beef farms, the inclusion of a fenced wetland with planted trees contributed to the reduction in N losses, most likely attributed to the combined effects of wetland attenuation processes and a reduction in animal numbers.

While the main emphasis of preventing N losses to waterways is to target urinary N, measures for reducing P losses from farms focus on avoiding livestock access to streams, ensuring FDE are applied to land at rates and times when soils can absorb that applied (Monaghan *et al.* 2010), using slow-release P fertilisers on soil types prone to surface runoff, and ensuring that soil test P concentrations do not exceed optimal levels for pasture production (McDowell & Nash 2012). These options have often proven to be the most cost-effective strategies for mitigating on-farm P losses, with a cost range of $0 to $200 per kg of P conserved (McDowell & Nash 2012). Our M1 results fall within this range (Table 4).

Only dairy farms were responsive to N leaching loss abatement from adopting M2, with an additional mean reduction of 2.8 kg N/ha relative to M1 (Table 3). At the regional scale, mitigation options grouped in M2 ('improved animal productivity') applied to sheep and beef + D3 farms (scenario 3) delivered a 25% reduction in N leaching losses and a 23% reduction in P losses, relative to the baseline (Table 4). Similarly, M2 applied to sheep and beef + D4 farms (scenario 7) delivered a 31% reduction in N leaching losses and a 26% reduction in P losses (Table 4). For both scenarios, this represented a slight improvement in N and P abatement relative to M1, but with slight regional gains in farm profitability (profitability gains from dairy farms exclusively) (Table 4).

Reductions in N losses from dairy farms adopting M2 were caused mainly by a reduction in dairy cow stocking rates (a 5 to 8% reduction). Dairy farm systems that carry fewer, but more efficient cows, have proven effective in reducing N leaching losses (Chapman *et al.* 2012). Increasing the reproductive performance of the breeding livestock categories on sheep and beef farms resulted in an overall slight increase in stocking rate, as measured by feed intake, due to the larger numbers of progeny carried over the summer period. However, the reduction in N leaching losses per unit of animal product (Table 4) is a reflection of a greater allocation of the total amount of feed available to saleable product and proportionally less to the maintenance of capital livestock. Dairy farms were also responsive to P loss abatement, but minor gains (7 to 8%) were achieved relative to M1 (Table 4). Low rate effluent application to land has proven effective in reducing P losses, with a measured effectiveness (as a % of total P reduction) often in the 10 – 30% range (McDowell & Nash 2012).

Dairy farms were responsive to N leaching loss abatement from adopting M3, with an expected mean reduction of 5.0 and 4.3 kg N/ha for scenarios 4 and 8, respectively, relative to M2 (Table 3). These reductions were mainly associated with minimising the amounts of N returned to pastures by withholding cows from grazing pastures for up to 12 h per day during early (August/September) and late lactation (March/April). This type of restricted, duration-controlled grazing strategy has proven effective in reducing N leaching (Christensen *et al.* 2012; Ledgard *et al.* 2006). Because the amount of urine-N excreted by livestock is the primary driving factor of N leaching losses (rather than inefficiencies in N fertiliser use) (Di & Cameron 2002) reductions in N fertiliser use (by adjusting the amounts applied to the expanded block receiving additional FDE) may have played a lesser role in N abatement. The full extent of abatement potential through implementing restricted grazing strategies, however, was not captured in our modelling exercise due to the dairy wintering approach modelled.

The N captured on the sheltered wintering pad used by beef cows on sheep and beef farms contributed only to a slight reduction in N leaching losses. The herd, however, was a relatively minor component of the total number of livestock carried by these systems. The riparian areas added (2% of farm area for both farm types) may have contributed to N abatement, mainly via a reduction in livestock numbers.

Mitigation strategies in M3 applied to sheep and beef + D3 farms (scenario 4), delivered a 33% reduction in N leaching losses and a 23% reduction in P losses, relative to the baseline (Table 4). Similarly, M3 applied to sheep and beef + D4 farms (scenario 8) delivered a 38% reduction in N leaching losses and a 27% reduction in P losses (Table 4). For both scenarios, this represented an improvement in N abatement and no additional P abatement relative to the previous mitigation group. The adoption of these strategies, however, came at a considerable economic cost to farmers (Table 4), particularly for those in sheep and beef farming.

As pastoral farming moves to operating within constraints, understanding how nutrient losses and farm profit change as a consequence of adopting mitigation strategies becomes increasingly important. The cost-effectiveness of non-point source pollution mitigation from pastoral agriculture is complex to assess, as the cost of attaining different levels of abatement varies broadly across individual farms. Farm heterogeneity across the region was captured almost exclusively by pasture production (and corresponding carrying capacity), and not by varying individual management policies and efficiencies. Non-lactating cows were unaccounted for during the critical (from a nutrient loss perspective) winter period, with only nutrient losses from milking platforms and young dairy stock considered.

Conclusions

The modeling approach provides a farm-scale framework that can be extended to other regions to accommodate different farm production systems and performances, capturing the interactions between farm types, land use capabilities and production levels, as these influence nutrient losses and the effectiveness of mitigation strategies.

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