From: Matthew McCallum-Clark
To: Felicity Durand
Subject: RE: Further information from 828 Twin Farm Ltd
Date: Wednesday, 12 July 2017 9:40:35 a.m.
Attachments: reference_vibart.pdf

Hi,

In response to the query from Cr Rodway, Roger has sent a copy of the report (attached) and confirmed the reference should be:

Vibart R, Vogeler I, Dennis S, Kaye-Blake W, Monaghan R, Burggraaf V, Beautrais J, Mackay A 2015. A regional assessment of the cost and effectiveness of mitigation measures for reducing nutrient losses to water and greenhouse gas emissions to air from pastoral farms. Journal of Environmental Management 156: 276–289

I will add the correction into the reply report.

Cheers,

Matthew

From: Felicity Durand [mailto:felicity.durand@es.govt.nz]
Sent: Monday, 3 July 2017 10:02 AM
To: Matthew McCallum-Clark <matthew@incite.co.nz>
Subject: FW: Further information from 828 Twin Farm Ltd

Hi Matthew

One for you?

Cheers
F

From: Maurice Rodway [mailto:maurice.rodway@gmail.com]
Sent: Monday, 3 July 2017 10:00 a.m.
To: Felicity Durand
Cc: Rob van Voorthuysen; Edward Ellison; Lloyd McCallum; Eric Roy
Subject: Re: Further information from 828 Twin Farm Ltd

Thanks for all that information Felicity. I am using the "time off" to have another read of the s42A report especially in relation to some of the larger submissions.

I note a reference to Vibart. and others 2015 on pages 37 and 655 of the report but this reference is not in Appendix B18 References. Could you note this for correction and also provide me with a link to this report.

Maurice.

> On 3/07/2017, at 8:35 am, Felicity Durand <felicity.durand@es.govt.nz> wrote:

Please see below and attached.

Felicity Durand
Senior Policy Planner
Environment Southland *Te Taiao Tonga*

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Cnr Price St & North Rd, Private Bag 90116, Invercargill 9840
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From: Andrew Welsh [mailto:snowwelsh@hotmail.com]
Sent: Thursday, 29 June 2017 8:56 p.m.
To: Policy and Planning Team
Subject: Attn: Land & Water Plan Commissioners Panel - From Twin Farm Ltd

Dear Panel,

At our hearing yesterday morning in Gore we were told that the panel had not received a copy of the letter we sent in from Barry Perkins supporting our submission.

You asked that we resend it. Please find the letter attached.

Regards,
Katherine Welsh
Twin Farm Limited

<Letter - Barry Perkins.docx>

Journal of Environmental Management 156 (2015) 276–289

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A regional assessment of the cost and effectiveness of mitigation measures for reducing nutrient losses to water and greenhouse gas emissions to air from pastoral farms

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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 and greenhouse gas (GHG) emissions to air from the predominant mix of pastoral industries in Southland, New Zealand. An evaluation of the cost-effectiveness of several nutrient loss mitigation strategies applied at the farm-scale, set primarily for reducing N and P 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, at no additional cost per kg N-loss mitigated. 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. Only dairy farms were responsive to GHG abatement; greater abatement was achieved by the most intensified dairy farm system simulated. 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 delivered no additional P abatement, and came at a large financial cost to farmers, sheep and beef farmers in particular. The modelling 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 GHG emissions, and the effectiveness of mitigation strategies.

1. Introduction

Concerns about the environmental effects of nutrient enrichment of water bodies by diffuse pollution of surface water and groundwater by nitrogen (N) and phosphorous (P), along with increased greenhouse gas (GHG) emissions from livestock

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operations, continue to rise in New Zealand (Parliamentary Commissioner for the Environment, 2013). Southland, New Zealand's southern-most region with a long tradition of pastoral sheep farming, has undergone a noticeable change in its agricultural landscape in recent years (Beukes et al., 2011; Copland and Stevens, 2012). 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 in the next two decades (Monaghan et al., 2007; 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). Some of the social and economic benefits of this land use change have been reported (Forney and Stock, 2013; Kaye-Blake et al., 2014; Vogeler et al., 2014), but less is understood about the wider, regional sustainability implications associated with this land use change (Monaghan et al., 2007).

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). Setting enforceable water quality and water quantity limits are a key principle of the policy, in an attempt to balance the economic value of water with environmental requirements. Regional Councils in New Zealand have taken different approaches to address the issue of setting nutrient loss limits, N in particular, from agricultural land, including allocating nutrient loss limits based on the natural capital of the soil (Horizons Regional Council, 2014). Enhancing the availability and uptake of science and information, including good management practices and the ongoing improvement of models that can integrate site specific information, will be critical in this process, particularly in the adoption of new mitigation technologies and practices (Ministry for the Environment, 2013).

Farm system and nutrient budget models are increasingly being used to assess current and potential management options to reduce nutrient losses and to evaluate policy options. Field trials (Ledgard et al., 2006; Monaghan et al., 2007, 2009) and farm management surveys (Monaghan and de Klein, 2014) have identified land management strategies that can reduce nutrient losses and GHG emissions. 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 any assessment of the influence of farm practices at a regional scale (Vogeler et al., 2014). Estimates of the cost-effectiveness of adopting on-farm mitigation strategies have also been obtained via integrated modelling and simulation (i.e. integrated at a farm, catchment or regional scale) (Happe et al., 2011; Doole, 2012; Dymond et al., 2013; Kaye-Blake et al., 2014). Regional environmental and economic assessments from varying management practices have been reported using an aggregation approach from individual farms or farm systems to the regional scale (Vatn et al., 2006; Neufeldt and Schafer, 2008) or by using a regional or sectorial modelling approach (Lehtonen et al., 2007; Leip et al., 2008). 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 assess N and P emissions to water and GHG emissions to air from the current predominant mix of pastoral industries in Southland (i.e. sheep and beef, and dairy farming) and to examine the impact of integrated nutrient loss mitigation strategies. The modelling approach used provides a region-wide estimate of the potential for different farming practices to mitigate some of the environmental impacts of pastoral agriculture.

2. Methods

A brief description of the Southland region including geospatial data and land use capability data (2.1) is followed by some of the modelling assumptions related to pasture production (2.2), a brief description of the farm-scale models used (2.3), modelled farm systems (sheep and beef, and dairy) (2.4), the mitigation strategies chosen within groups (2.5), the regional up-scaling method (2.6), and finally, the modelling scenarios tested (2.7).

2.1. Location and land resource data

Southland covers an area of almost 1.7 million hectares (ha), of which 1.1 million ha (65%) was pastorally farmed in 2007 (Statistics New Zealand). According to AgriBase™ (AsureQuality, 2012), a spatial and demographic census of all known New Zealand farms, approximately 0.18 million ha (16%) of the pastoral farming land is currently used for dairy farming, with the balance mainly a combination of sheep and beef (cattle) farming. The 4150 farms that were either under sheep and beef (3396 farms) or dairy (754 farms) were included in the regional scale modelling, accounting for just over 1 million ha. Other land use activities (e.g. arable, horticulture, forestry) were beyond the scope of this study and therefore not considered. By overlaying the geospatially identified individual farms from AgriBase™ 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. Briefly, the LUC system has two fundamental components, the LRI (based on physical factors critical for longstanding land use and management), and the LUC Classification, 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).

To allow for a further characterisation of the land on each farm, the predominant soil order, topography and drainage profiles were identified. Soil orders on each farm were identified using the New Zealand Soil Classification (NZSC) soil orders (Hewitt, 1998). Only the dominant soil orders across the different LUC classes were considered (Brown and Pallic soils; Dystrudepts and Aeric Fragiaqualf in the USDA Soil Taxonomy, respectively) (Vogeler et al., 2014). The predominant topographies on farms were obtained by overlaying AgriBase™ data layers with slope data based on a digital elevation model, as described by Vogeler et al. (2014). Two drainage classes were defined based on the New Zealand Soil Classification (NZSC) drainage classes (Landcare Research): poorly drained soils comprising NZSC drainage classes 1–3 (very poor, poor and imperfectly drained), and well drained soils comprising NZSC drainage classes 4–5 (moderately well and well drained). Southland pastoral LUC classes and their areas, predominant soils orders, topographies and drainage classes are further described in Vogeler et al. (2014).

2.2. Modelling assumptions – pasture production and LUC classes

Perennial pastures are the main source of nutrients for grazing ruminants in New Zealand, with pastoral agriculture accounting for the largest land use in the country (Valentine and Kemp, 2007). Pasture production was calculated for each farm based on its corresponding area-weighted LUC class. Briefly, 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. Sheep carrying capacity was converted to annual pasture yields assuming the amount of pasture consumed annually by each ewe (and its progeny until weaning) (Woodford and Nicol, 2004) was 600 kg DM on LUC classes 1 to 4, and 550 kg DM on LUC classes 5 to 7, reflecting greater reproductive efficiency for ewes on the more productive land. Further assumptions included: 70% of the pasture grown was able to be consumed (utilised) by the ewes, and estimated pasture production on existing dairy farms was increased by 7% relative to sheep and beef farms to account for improved pasture genetics and grazing management (Copland and Stevens, 2012; Smith, 2012).

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 and Geddes, 2012) and with hill country pastures producing 5–12 t DM/ha (Valentine and Kemp, 2007). Pasture production data was then used to inform the farm systems modelling, livestock carrying capacity for each enterprise in particular.

2.3. 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. Farmax was used to investigate the relationships between feed supply, livestock numbers to obtain key physical production and financial outputs from representative sheep and beef and dairy farms (White et al., 2010).

Modelled livestock policies were exported from Farmax to parameterise Overseer to estimate the nutrient losses and GHG emissions 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.

For the purpose of this study, GHG emissions reported include methane (CH_4) emissions from livestock, soil-mediated nitrous oxide (N_2O) emissions from animal excreta, fertiliser and effluents, and contributions of carbon dioxide (CO_2) emissions from fuel and electricity use, as well as the indirect contribution of lime and fertiliser processing and manufacturing (Wheeler et al., 2008). Of particular interest to this study is the model's predictive ability to estimate on-farm nitrate–N (NO_3–N) leaching losses, P loss risk and GHG emissions (the sum of CH_4, N_2O and CO_2, expressed as CO_2 equivalents, CO_2-e).

2.4. Modelling assumptions – farm systems

2.4.1. Sheep and beef farms

Despite a substantial variation among sheep and beef farming systems in Southland, a representative farm needed to be modelled. A South Island Finishing-Breeding sheep and beef farm (which includes a relatively minor deer component) (Table 1) was modelled for the region (Beef and Lamb New Zealand, 2013). Briefly, these model farm types comprise an extensive type of finishing operation, which accounts for ~58% of the total sheep and beef farm operations in the region (Beef and Lamb New Zealand, 2013). The baseline sheep and beef farm scenario (Base) comprised a hypothetical 450-ha farm, similar to that described by Vibart et al. (2011) (Table 1). A non-irrigated 'South Island' ryegrass/white clover-type pasture was set in Farmax (as with the dairy farms), with an annual rainfall of 1000 mm. Seasonal patterns of pasture growth were scaled to achieve the desired LUC-derived PP class for each farm. Accordingly, adjustments were made to livestock numbers, with cattle, including dairy heifer calves, assumed to use 10% of total DM consumed for PP classes 2 to 4 and 20% of total DM consumed for PP classes 5 and 6 (D. Stevens, AgResearch, pers. comm.) (Table 1). Breeding ewe, cow (on PP classes 5 and 6) and hind replacement rates were set at approximately 28, 18 and 18%, respectively. Ewe pregnancy, lambing and weaning percentages were set at 166, 130 and 126%, respectively.

For both farm types, farm profitability (farm profit before tax) was calculated as:

$$\text{Farm profitability before tax} = \text{total gross income} - \text{total farm expenditure},$$

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 in Southland.

PP class	2	3	4	5	6
Stocking rate (SU ha^{-1})[a]	16.1	13.8	12.6	9.0	5.4
Pasture yield (t DM ha^{-1})	13.6	10.4	8.1	7.1	3.7
Number of livestock carried through winter (1 July)					
Breeding ewes	4058	3430	3135	1976	1186
Total sheep	5360	4532	4142	2606	1565
Breeding cows	–	–	–	51	31
Dairy heifers	72	68	62	40	24
Total cattle	129	120	110	149	90
Hinds	80	68	62	40	24
Total deer	143	122	111	71	43
Animal production (kg ha^{-1})					
Meat	240	205	188	131	79
Wool	68	58	53	33	20
Total	308	263	241	164	99
Feed conversion efficiency[b]	28.9	28.8	28.8	30.1	30.0
Animal reproduction					
Ewe efficiency index (%)[c]	60.8	60.8	60.8	60.8	60.8
Cow efficiency index (%)[d]	–	–	–	37.8	37.8
Financial indicators ($ ha^{-1})					
Gross margin	687	576	519	372	208
Operating profit[e]	450	339	281	134	–32
Fertiliser inputs (kg ha^{-1})					
N	10	10	10	9	7
P	21	17	13	11	9
Soil Olsen P (mg L^{-1})	16	16	16	16	16

[a] SU = Stock units; see text for definition.
[b] FCE = Feed DM required per unit animal product.
[c] Ewe efficiency index = total standardised lamb weaning weight (at 90 days, in kg) per kg ewe mated, expressed as a percentage.
[d] Cow efficiency index = total standardised calf weaning weight (at 200 days, in kg) per kg cow mated, expressed as a percentage.
[e] Farm profit before tax; see text for definition.

where total farm expenditure = total cash expenditure + depreciation; and total cash expenditure = total working expenses + total standing charges, including mitigation expenses. Specifically for sheep and beef farms, financial data were sourced from Farmax Pro and Beef and Lamb New Zealand (2013), including mitigation costs (described further in Section 2.5). 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) (Vibart et al., 2011). These fertilisation rates did not vary across mitigation groups. Maintenance amounts of phosphate (P) fertiliser were applied according to soil order requirements based on Overseer recommendations (Table 1).

2.4.2. Dairy farms

Representative System 3 (D3) and System 4 (D4) dairy farms (DairyNZ, 2010) were modelled. Briefly, a System 3 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 System 4 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. System 3 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) production per cow (380 and 420 kg MS/cow for systems 3 and 4, respectively) and livestock numbers in each system were scaled to achieve maximum pasture utilisation. Milking cow replacement rates were set at 22%. Both dairy systems (within each PP class) were assumed to produce the same amount (and growth patterns) of annual pasture DM, but were supplemented with different amounts of imported feed. 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, but without specific adjustments for Southland or for the systems involved. The milk price was set at NZ$6.05 per kg MS, slightly lower than the price reported by New Zealand Dairy Statistics (2012) for the season.

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 in Southland.

PP class	2	3	4	2	3	4
System	3	3	3	4	4	4
No. cows (at peak lactation)	628	488	381	644	504	393
Stocking rate (SR; cows ha^{-1})	3.37	2.62	2.04	3.46	2.70	2.11
Comparative SR[a]	88	88	88	86	86	86
Pasture yield (t DM ha^{-1})	15.7	12.4	9.8	15.7	12.4	9.8
Pasture consumed (t DM ha^{-1})	12.5	9.7	7.6	12.1	9.5	7.4
Total feed consumed (t DM ha^{-1})	13.9	10.8	8.4	15.1	11.8	9.2
Imported feed/total feed (%)	8	8	8	19	19	19
Annual milksolids (MS) production						
MS (kg cow^{-1})	392	391	391	421	421	421
MS (kg ha^{-1})	1321	1024	799	1455	1139	888
MS (as a % of liveweight; LW)	98	98	98	102	102	102
Feed conversion efficiency[b]	11.6	11.6	11.6	11.4	11.4	11.4
Financial indicators ($ ha^{-1})						
Gross margin	5085	3935	3058	4927	3839	2996
Operating profit[c]	2466	1409	601	2341	1335	558
Area receiving effluent (% of total)	28	28	28	30	30	30
Fertiliser inputs (kg ha^{-1})						
N	136	136	136	135	135	135
P	35	31	29	29	27	24
Soil Olsen P (mg L^{-1})	35	35	35	35	35	35

[a] Comparative stocking rate (CSR) = Liveweight (kg) per t available DM.
[b] FCE = Feed DM required per unit animal product.
[c] Farm profit before tax; see text for definition.

A common practice in Southland is to winter young replacement heifers and dry cows off the milking platform (Beukes et al., 2011). To accommodate young dairy livestock categories in the region in this exercise, replacement heifers were sent to sheep and beef farms by mid-December (6 months old; 108 kg liveweight LW) and returned pregnant to the dairy farms by late May (almost 2 years later; 23 months old; 440 kg LW) (Table 1). Corresponding nutrient losses and GHG emissions 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.

The spatial database (AgriBase™) from which the predominant enterprise for each land parcel was obtained, contains two enterprise categories which align to dairy farms: “Dairy cattle farming” and “Dairy dry stock”. When scaling to the regional level, the two enterprise categories were amalgamated into the modelled farm type “Dairy”, for both model simplicity and the impossibility to differentiate areas of distinct use.

In Overseer, the dairy effluent system in the baseline farms included a holding pond, with no solids separation before the effluent enters the pond. Effluent blocks (i.e. areas receiving liquid effluent) for the baseline farm simulations were 28% (57.0 ha) and 30% (60.4 ha) for systems 3 and 4, respectively. For nutrient and GHG emissions modelling purposes, these areas were treated as distinct land areas. Poorly-drained soils had an artificial drainage system in place; the capital cost and derived annualised cost for the mole/tile system was not considered. 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. Similar to sheep and beef enterprises, maintenance levels of P were applied to sustain production, following Overseer recommendations.

2.5. 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. Any abatement in GHG emissions were merely a consequence of adopting these mitigation groups, and no specific GHG mitigation strategies were considered. The mitigation strategies were grouped by capital cost and potential ease of adoption; capital cost was the primary criterion for grouping and prioritising mitigation strategies (Fig. 1). The potential impact of each mitigation group on the economic and environmental performance of the farms was assessed by re-running the farm models using appropriate assumptions. The environmental implications of the more engineering-type options (e.g. introduction of a low rate FDE application system) were assessed in Overseer, whereas mitigation options that required altering livestock numbers and feed input (i.e. greater genetic merit and livestock numbers with feed adjusted accordingly) required the sequential re-running of both farm-scale models to account for whole-system changes.

The mitigation groups were examined on an additive basis i.e. M3 assumes M1 and M2 mitigation options have been previously adopted. The mitigation strategies within groups varied by farm type (sheep and beef vs. dairy), and were broadly identified as ‘improved nutrient management’ (M1), ‘improved animal productivity’ (M2), and ‘restricted grazing’ (M3) (Kaye-Blake et al., 2013). The original mitigation groups of Kaye-Blake et al. (2013) were

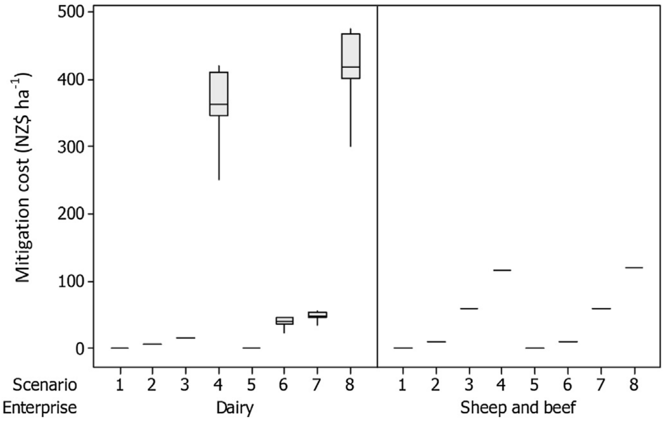

Fig. 1. Box plot of mitigation costs (NZ$ ha^{-1}) for the different scenarios tested (Scenarios 1 to 4 = dairy system 3 with mitigation groups Base, M1, M2, M3; Scenarios 5 to 8 = dairy system 4 with mitigation groups Base, M1, M2, M3; see text for detail) and enterprises in Southland. Top, middle, and bottom lines of interquartile range boxes represent the third quartile (Q3), the median, and the first quartile (Q1), respectively.

modified by the addition of a feed pad to the System 4 dairy farms as part of M1 and extending the life expectancy of herd shelters from 10 to 15 years. The cost of individual mitigation strategies was calculated and expressed on an annualised basis, and included depreciation, operational and maintenance costs. The projected cost-effectiveness of each mitigation group was calculated by dividing the annualised net cost of each by the quantity of N, P or GHG 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). Fertilisation costs of soluble and low solubility P sources were assumed to be similar (Monaghan et al., 2008).
- A fenced wetland area (5 ha; ~1% of farm area) was established in sheep and beef farms. A planting plus fencing cost of NZ$44,680 was assumed (Financial Budget Manual, 2012). Livestock numbers were adjusted to compensate for reduced effective grazing area.
- Dairy cattle were excluded from streams. A fencing cost of NZ$4440/km was assumed (electric fence, 2 wires, Canterbury contractor) (Financial Budget Manual, 2012).
- 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 System 4 dairies, at a cost of NZ$200/cow (E. Dominatti, AgResearch, pers. comm.). Feed pads were used for 2 h every day, with solid manure scraped, separated from the liquid portion, covered from rain and spread on selected blocks of land.

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

- Livestock from sheep and beef farms were excluded from streams. A fencing cost of NZ$13,790/km was assumed (standard 8-wire fence, full contract rate, Canterbury contractor) (Financial Budget Manual, 2012).
- 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 to compensate for greater feed demand from young livestock.
- Animal productivity on dairy farms was enhanced by introducing greater genetic merit cows and increasing individual LW of cows on farm. Fewer, more efficient dairy cows with greater genetic merit (breeding worth; BW increased to 106 and 112 from the baseline BW of 88 and 93 for D3 and D4 dairies, respectively) 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 relative to previous scenarios. 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). An upgrading annual cost of NZ$612 was assumed (20 irrigation pods, 400 m of pipe, labour and miscellaneous setup costs (Financial Budget Manual, 2012).
- A fenced wetland area (2 ha; ~1% of farm area) was established in dairy farms. A planting plus fencing cost of NZ$16,480 was assumed (Financial Budget Manual, 2012). 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; length = 12,860 m, width = 7 m, 9 ha, 2% of farm area). A fencing cost of NZ$13,790/km was assumed (Financial Budget Manual, 2012). Similarly, a riparian block was added to the dairy farms (length = 5400 m, width = 7 m, 3.8 ha, 2% of farm area). A fencing cost of NZ$4440/km was assumed (Financial Budget Manual, 2012). 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. The concrete pad was cleaned by scraping; the effluent system included a holding pond, with infrequent spraying using a slurry tanker on selected blocks of land (flat and rolling areas exclusively). Liquid effluent was applied in September, October and November, at an application depth of 12–24 cm. A cost of NZ$1500/wintered cow (5.5 SU-equivalent) was assumed (effluent system included) (Financial Budget Manual, 2012).
- A covered loafing pad (and feeding pad for D3 dairies) was added to the dairy model farms. It was constructed to feed all supplements indoors and to withhold cows from grazing during wet periods to minimise damage to pastures (Beukes et al., 2013). Effluent solids captured were separated before the regular treatment, and spread on selected blocks of land. The liquid portion of effluent was treated in the same way as the FDE. The covered pad was primarily used during the shoulders of the season (i.e. early and late lactation), and time spent grazing was adjusted accordingly. In addition to the cost of the structure, a

cost of NZ\$60/cow was assumed for purchasing sawdust flooring material and NZ\$30/cow for extra labour cost.
- 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.

The direct economic costs of mitigation for sheep and beef farms (and M1 and M2 mitigation groups for D3 farms) remained unaffected by livestock numbers; whereas these costs varied with livestock numbers carried by D4 farms (Fig. 1).

2.6. Regional up-scaling

To account for the various land units with differing pasture production and drainage characteristics on individual farms, linear regression analyses was performed on farm-scale model outputs. Regression relationships were established between nutrient losses, GHG emissions and profit (dependent or response variables), and PP classes (independent or predictor variable), similar to those reported by Vogeler et al. (2014). Estimates of environmental and financial outcomes from each mitigation group (Baseline, M1, M2, M3) were then associated with their corresponding PP class. Separate regression analyses were conducted for well- and poorly-drained soils and all of the resulting equations are listed in the Appendix.

To extend current estimates of nutrient losses, GHG emissions and profits beyond farm boundaries, individual farm-scale outputs were aggregated at the regional scale. Model outputs from the farm-scale Farmax and Overseer models were linked with farm data (e.g. LUC land units) obtained from the land resource database. Estimates of regional nutrient losses, GHG emissions and farm profitability (Y) were calculated in a similar way to Vogeler et al. (2014) as:

$$Y = \sum (E_{S\&B} {*} A_{S\&B}) + \sum (E_D {*} A_D)$$

where $E_{S\&B}$ and E_D are estimates of farm nutrient losses, GHG emissions and profitability on a per-ha basis for sheep and beef and dairy farms, and $A_{S\&B}$ and A_D are the corresponding farm areas (ha) under these farm types.

2.7. 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 (also described above), and four mitigation groups (Baseline with no mitigation, M1, M2, M3). For simplicity and ease of interpretation, scenarios 1 to 4 included a D3 dairy farm, and scenarios 5 to 8 included a D4 dairy farm. The aim of the research was to estimate the potential impacts of mitigation practices on N and P losses, and GHG emissions in Southland, from LUC-derived annual pasture production (kg DM ha^{-1}) and livestock carrying capacity (stock units ha^{-1} for sheep and beef farms and dairy cows ha^{-1} for dairy farms). The modelling started with a baseline scenario that simulates current practices in Southland, and therefore, provided estimates of the current environmental outcomes. Next, scenarios were modelled that estimated the impact of full adoption of each group of mitigation practices across farms in the region. By comparing these scenario results, the modelling estimated potential reductions in N, P, and CO$_2$-e emissions via grouped mitigation practices.

3. Results and discussion

3.1. Farm system modelling – baseline farms

Stocking rates for both types of farm modelled, along with animal performance (meat and fibre and MS production), were widely represented across the region (Tables 1 and 2). Greater farm economic profitability and animal performance (kg meat, wool, MS produced ha^{-1}) were obtained on the most productive LUC classes, which in turn was associated with greater PP and thus greater livestock carrying capacity (Tables 1 and 2). Stocking rates on sheep and beef farms ranged from 16.1 SU ha^{-1} on PP class 2 (producing 13.6 t pasture DM ha^{-1}) to 5.4 SU ha^{-1} on PP class 6 (producing 3.7 t pasture DM ha^{-1}) (Table 1). Corresponding farm profits ranged from NZ\$450 ha^{-1} to −NZ\$32 ha^{-1} (Table 1). The calculated regional value (NZ\$328 ± NZ\$106 ha^{-1}) (mean ± SD) was in close agreement with the farm profit (NZ\$326/ha) reported for South Island Finishing-Breeding farms in 2011–12 (Beef and Lamb New Zealand, 2013).

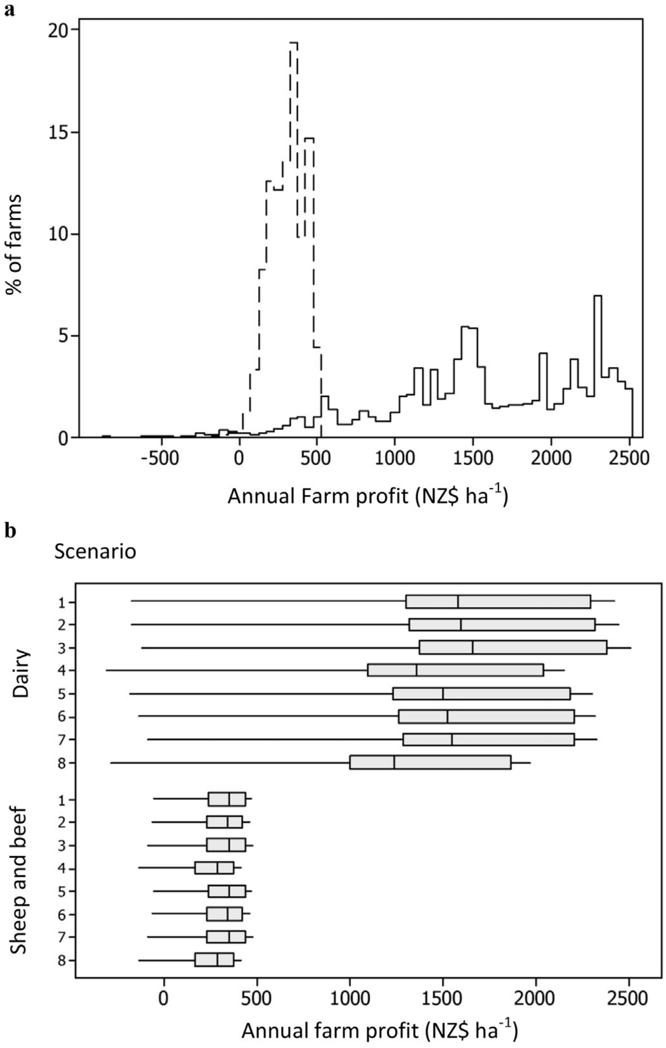

Fig. 2. a. Histogram of farm profitability (profitability before tax, NZ\$ ha^{-1}) for sheep and beef (-) and dairy (–) farms in Southland. All scenarios tested are included. b. Box plot of farm profit (profit before tax, \$ ha^{-1}) for the different scenarios tested (1–4 = dairy system 3 with mitigation groups Base, M1, M2, M3; 5 to 8 = dairy system 4 with mitigation groups Base, M1, M2, M3; see text for detail) in Southland.

Mean stocking rates of the baseline dairy farms were 2.72 and 2.80 cows ha^{-1} for D3 and D4 farms (data not shown), respectively, which was in close agreement with the overall regional stocking rate (2.73 cows ha^{-1}) reported for the milking season of interest (2011–12) (New Zealand Dairy Statistics, 2012). Modelled dairy cow production targets (390 and 420 kg MS cow^{-1} yr^{-1} for systems 3 and 4, respectively) were slightly greater than the regional mean value (382 kg MS cow^{-1} yr^{-1}) reported for the season (New Zealand Dairy Statistics, 2012). The modelled D3 and D4 farms produced 170,200 and 188,260 t MS yr^{-1}, respectively, slightly lower than the number reported for the 2011–12 season in Southland (193,250 t MS yr^{-1}) (New Zealand Dairy Statistics, 2012). The baseline dairy farms, when scaled up to a regional level, accounted for approximately 478,000 and 492,000 dairy cows, slightly lower than the total numbers reported to be present for the 2011–12 season (505,700 dairy cows) (New Zealand Dairy Statistics, 2012). Although System 3 farms continue to be the most predominant dairy systems in Southland, the number of cows that were accounted for in the modelling exercise (and resultant MS production) suggests that D3 farms, as they continue to intensify, are potentially and gradually evolving into D4 farms. These later farms tend to carry a greater number of cows of greater individual animal performance, and have a greater reliance on imported feed (Table 2). The wider implications of greater reliance on imported feed for the region remain to be fully explored.

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 (Hedley and Kolver, 2006) and assuming all sheep and beef farms carried replacement heifers (Table 1) as an integral component of their operation (Vogeler et al., 2014), 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. Fig. 2a and b highlight the differences in farm profit between the two farm types, with a narrower profitability range for sheep and beef farms and a reduced overlap between the two pastoral industries.

3.2. *Environmental outcomes — baseline modelling*

3.2.1. *Estimates of N leaching losses*

Hereafter, farm-scale enterprise results and implications are presented first, followed by regional-scale data and implications. 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^{-1}, respectively (scenarios 1 and 5; Table 3). The differences in distribution of N leaching losses between farm types is highlighted in Fig. 3a and b, with dairy farms showing a broader range and greater N leaching losses compared with sheep and beef farms, and a reduced overlap of N losses between the two main pastoral industries. 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. Urine patches from grazing livestock remain the largest single source of N leaching losses from pastoral agricultural systems (de Klein et al., 2006).

Losses from N leaching were also associated with soil drainage characteristics; these differences have been primarily attributed to varying infiltration rates and denitrification (Monaghan et al., 2008). Mean estimates of annual N leaching losses occurring under the baseline sheep and beef farm were 10.6 and 9.8 kg N ha^{-1} for well- (Brown) and poorly-drained (Pallic) soils, respectively (data not shown). Farm-scale N leaching from sheep and beef farm scenarios ranged from 5 to 20 kg N ha^{-1} for well-drained soils, and from 7 to 14 kg N ha^{-1} for poorly-drained soils (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; Ruz-Jerez et al., 1995; Magesan et al., 1996). Mean

Table 3
Area-weighted mean annual N leaching losses (kg ha^{-1}), P losses (kg ha^{-1}), GHG emissions (kg CO$_2$-e ha^{-1}) and farm profit (NZ$ ha^{-1}) for different scenarios tested in Southland [scenarios 1 to 4 = sheep and beef (S&B) + dairy System 3 (D3) with mitigation groups Base, M1, M2, M3; scenarios 5 to 8 = S&B + dairy system 4 (D4) 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[a] **(kg ha^{-1})**								
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
Region S&B + D3	13.6	10.6	10.2	9.1				
Region S&B + D4					13.9	10.0	9.6	8.6
P losses[a] **(kg ha^{-1})**								
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
Region S&B + D3	0.3	0.3	0.3	0.3				
Region S&B + D4					0.4	0.3	0.3	0.3
GHG emissions[a] **(kg CO$_2$-e ha^{-1})**								
D3	9839	9684	9329	9134				
D4					12,044	10,591	10,523	10,382
S&B	3812	3834	3842	3751	3812	3834	3842	3751
Region S&B + D3	4797	4790	4739	4631				
Region S&B + D4					5157	4939	4935	4835
Profit before tax[a] **(NZ$ ha^{-1})**								
D3	1546	1561	1622	1329				
D4					1463	1492	1511	1208
S&B	328	316	323	262	328	316	323	262
Region S&B + D3	431	426	433	337				
Region S&B + D4					418	415	415	318

[a] Outcomes presented as aggregated across the region (area-weighted means).

estimates of annual N leaching losses occurring under the baseline D3 farm were 33 and 28 kg N ha^{-1} for well- and poorly-drained soils, respectively, and corresponding losses occurring under the baseline D4 farm increased to 34 and 31 kg N ha^{-1} (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 (29–42 kg N ha^{-1}; 100 kg fertiliser N applied ha^{-1}).

Scaling up the on-farm N loss data from the baseline scenarios to a regional scale resulted in an annual collective loss of 14,670 t and 15,014 t of N from baseline sheep and beef and D3 farms and baseline sheep and beef and D4 farms, respectively. Sheep and beef farms (~3400 farms) accounted for 63% of total N leaching losses from 84% of the area considered, and the remaining 37% of N losses attributed to dairy farms on 16% of the landscape.

Areas used for carrying dry cows over winter (typically for 8–12 weeks; 61 d in our modelling exercise) usually contribute significantly to N leaching losses from dairy systems. These contributions are often disproportionately large given the deposition of excreta N from intensively grazed fodder crops (typically on less than 20% of the farm area) at times when plant uptake is minimal, soil mineral N amounts are relatively high and soil moisture is often close to or at field capacity (Smith et al., 2012; Monaghan et al., 2013). 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 by an unknown amount and thus 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.

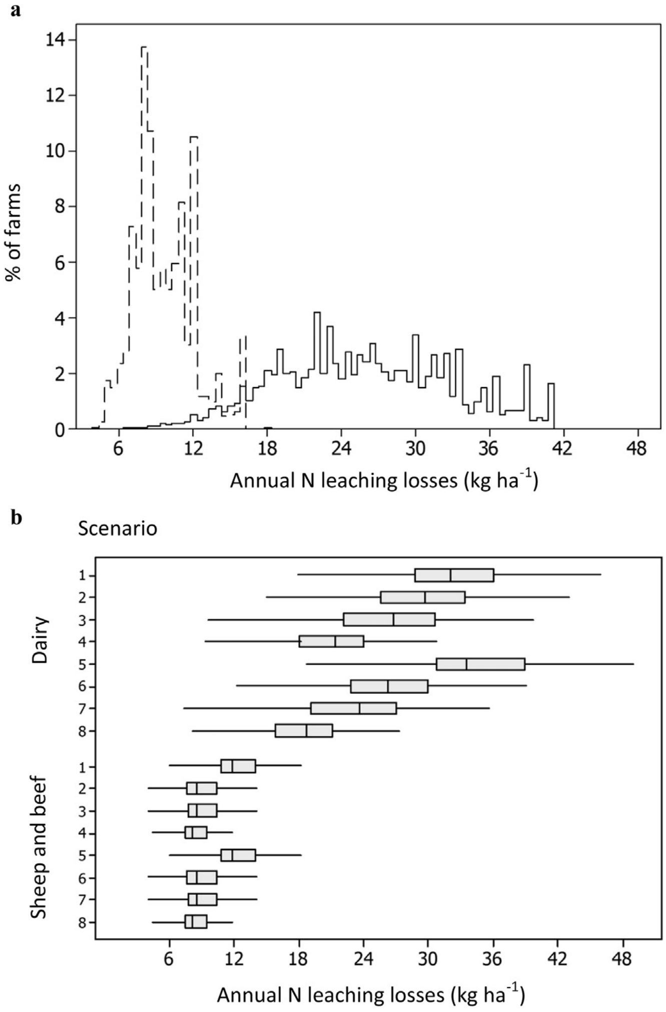

Fig. 3. a. Histogram of nitrogen (N) leaching losses (kg ha^{-1}) from sheep and beef (–) and dairy (—) farms in Southland. All scenarios tested are included (see text for detail). b. Box plot of nitrogen (N) leaching losses (kg ha^{-1}) for the different scenarios tested (1–4 = dairy system 3 with mitigation groups Base, M1, M2, M3; 5 to 8 = dairy system 4 with mitigation groups Base, M1, M2, M3; see text for detail) in Southland.

Our estimates of regional-scale N leaching losses are broadly in agreement with those reported by Ledgard (2014) (16,900 t N year^{-1} including wintering support areas) and with those reported by Kaye-Blake et al. (2013) (16,500 and 18,600 t N year^{-1} without and with wintering support areas, respectively) for similar total land areas modelled in the region. Although relatively minor, differences can be attributed to calculations and methodology. A single N leaching loss value was assigned to areas grazed exclusively by lactating dairy cows (i.e. dairy platforms; 30 kg N ha^{-1}) and to wintering support areas (50,000 ha; 55 kg N ha^{-1}), 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^{-1}), respectively (Ledgard, 2014). Conversely, a broader representation of farm systems, a total of 121 different farm scenarios including forestry, were included in the analyses performed by Kaye-Blake et al. (2013).

3.2.2. *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^{-1}, respectively (scenarios 1 and 5; Table 3). The differences in distribution of P losses between pastoral enterprises are highlighted in Fig. 4a and b, with a narrower and lower range of P losses from sheep and beef farms compared with dairy farms, and showing a reduced overlap of P losses between the two main pastoral industries.

Annual P losses also varied with soil drainage characteristics. Mean estimates of annual P losses occurring under baseline sheep and beef farms were 0.1 and 0.3 kg P ha^{-1} for well- and poorly-drained soils, respectively (data not shown). Mean annual P losses occurring from the baseline D3 farms were 0.7 and 1.4 kg P ha^{-1} for well- and poorly-drained soils; corresponding losses occurring from the baseline D4 farms increased to 0.8 and 1.6 kg P ha^{-1}. 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^{-1}) (Smith and Monaghan, 2003; Monaghan et al., 2005), 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^{-1}) (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 adopted to measure drainage flow rates, representing a minimum estimate of annual P loss from the site (Smith and Monaghan, 2003).

Estimates of annual P losses from dairy farms were higher for farms with a greater proportion of more productive LUC classes and associated numbers of livestock carried. This modelled effect is due to the greater amounts of P in the system from greater quantities of fertiliser and feed inputs, as well as greater quantities of animal excreta deposited in the field and at the milking shed. This greater input and recycling of P contributes to greater P loss via overland flow or subsurface drainage pathways of water movement.

The response of P losses to PP classes from sheep and beef farms were best described by a quadratic, rather than a linear, function (refer to Appendix). Soil topography may have played a role; in addition to soil properties affecting infiltration rates and potential for overland flow, topography is one of the core transport drivers of P loss (McDowell et al., 2005). Farms on LUC classes >4 (LUC classes 5 and 6 under sheep and beef, in particular) were modelled on combined slopes (55% flat + 45% rolling and 85% flat + 15% rolling on LUC class 5 well- and poorly-drained soils, respectively; 25% flat + 50% rolling + 25% easy hill and 50% flat + 50% rolling on LUC class 6 well- and poorly-drained soils, respectively) (Vogeler et al., 2014).

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. Sheep and beef farms accounted for 47 and 44% of total P losses (excluding P losses from erosion). Fewer modelling studies have attempted to estimate regional P losses from Southland using similar methodologies. Our estimates are lower than those reported by Ledgard (2014) (636 t P yr^{-1} including wintering support areas) and similar to those reported by Kaye-Blake et al. (2014) (421 and 539 t P/yr^{-1} without and with wintering support areas, respectively) 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^{-1}), wintering dairy support areas (1.2 kg P ha^{-1}), and intensive (0.6 kg P ha^{-1}) and extensive (0.3 kg P ha^{-1}) sheep and beef farm systems. Correspondingly, a greater proportion of P losses were attributed to sheep and beef farming systems (66%) in Ledgard (2014) than in our study.

3.2.3. Estimates of GHG emissions

Mean estimates (±SD) of GHG emissions were 3812 (±1093) kg CO_2-e ha^{-1} from baseline sheep and beef farms, and 9839 (±1648) and 12,044 (±2133) kg CO_2-e ha^{-1} from baseline D3 and D4 farms,

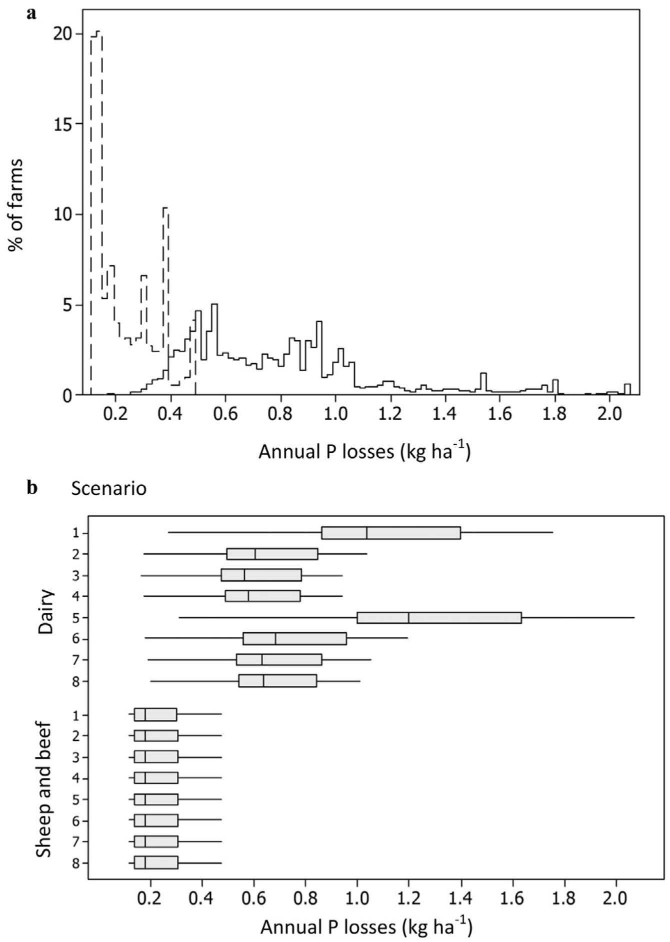

Fig. 4. a. Histogram of phosphorous (P) losses (kg ha^{-1}) from sheep and beef (‐) and dairy (—) farms in Southland. All scenarios tested are included (see text for detail). b. Box plot of phosphorous (P) losses (kg ha^{-1}) for the different scenarios tested (1–4 = dairy system 3 with mitigation groups Base, M1, M2, M3; 5 to 8 = dairy system 4 with mitigation groups Base, M1, M2, M3; see text for detail) in Southland.

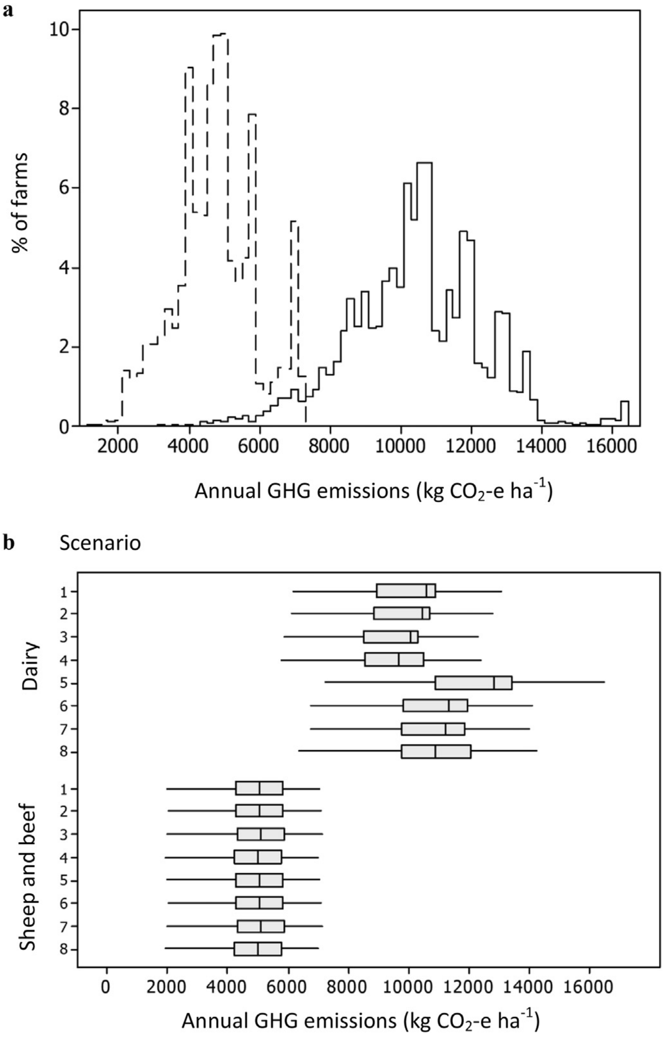

Fig. 5. a. Histogram of greenhouse gas (GHG) emissions (kg CO_2-e ha^{-1}) from sheep and beef (‐) and dairy (—) farms in Southland. b. Box plot of greenhouse gas (GHG) emissions (kg CO_2-e ha^{-1}) for the different scenarios tested (1–4 = dairy system 3 with mitigation groups Base, M1, M2, M3; 5 to 8 = dairy system 4 with mitigation groups Base, M1, M2, M3; see text for detail) in Southland.

respectively (scenarios 1 and 5; Table 3). Fig. 5a and b highlight the differences in distribution of GHG emissions between the two pastoral industries, with dairy farms showing a broader range and greater GHG emissions compared with sheep and beef farms; the latter accounted for 66% of total GHG emissions in the region.

Expectedly, emissions varied with soil drainage class; emissions from the baseline sheep and beef farm were 3510 and 4428 kg CO_2-e ha^{-1} for well- and poorly-drained soils, respectively. Mean estimates of annual GHG emissions occurring from the baseline D3 farms were 8321 and 9652 kg CO_2-e ha^{-1} for well- and poorly-drained soils, respectively. Corresponding emissions occurring from the baseline D4 farms increased to 9856 and 12,187 kg CO_2-e ha^{-1} (data not shown). The relative contribution of N_2O to total GHG emissions increased from 17 to 29% for well- and poorly drained soils, respectively. Nitrous oxide emissions are largely driven by the drainage characteristics of soils. Soil water-filled pore space (WFPS) has been accepted as one of the main regulators of N_2O emissions (Smith et al., 1998). As the WFPS increases, diffusion of oxygen into soil aggregates decreases, creating greater and longer anaerobic conditions for N_2O production (Saggar et al., 2004).

Measures of eco-efficiency from the baseline farms, such as N leaching losses per unit of saleable animal product (kg N leached kg^{-1} MS or meat and fibre produced) (Table 4), were in line with those reported by Mackay et al. (2012) and Basset-Mens et al. (2009) for medium intensity sheep and beef and dairy farms, respectively. Similarly, estimates of GHG emissions per unit of saleable animal product (kg CO_2-e kg^{-1} MS or meat and fibre produced) were in line with those reported for medium intensity sheep and beef (Dynes et al., 2011; Vibart et al., 2011; Mackay et al., 2012) and dairy (Basset-Mens et al., 2009) farm systems.

3.3. *Cost-effectiveness of mitigation practices*

Mitigation strategies were grouped by capital cost and ease of adoption into M1, M2, and M3 groups, and modelled based on expert knowledge of the region and on the assumption of full adoption of each group. Because of the expected relatively high contribution from dairy farms to catchment nutrient loads, dairy farms were signalled as the main target for most of the mitigation options chosen within groups (Monaghan et al., 2007).

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^{-1}, respectively (Table 3). In contrast, only dairy farms were responsive to P loss reductions using M1 mitigation strategies, and no further abatement was achieved by sheep and beef farms adopting incremental P mitigation (Table 3).

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, whereas GHG emissions remained unaffected relative to baseline emissions (Tables 3 and 4). Similarly, M1 applied to sheep and beef + D4 farms (scenario 6) delivered a 28% reduction in N leaching losses, a 24% reduction in P losses, and a 4% reduction in GHG emissions (Table 4).

Dairy livestock exclusion from streams (reducing animal-water body connectivity), slight reductions in the rates of N fertiliser applied to dairy farms (annual savings of up to 30 kg N/ha for System 4 dairies), and the inclusion of a feed pad to System 4 dairy farms, contributed to the N abatement achieved by dairy farms on M1. The baseline D4 farms were first modelled with a feed pad, and had slightly lower N leaching losses than System 3 farms, even when carrying greater livestock numbers: 33, 26 and 21 kg N/ha for

Table 4

Impact of mitigation groups on farm nutrient loss abatement, GHG emission 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 (D3) with mitigation groups M1, M2, M3; scenarios 6, 7 and 8 = S&B + dairy System 4 (D4) 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	3285	3702	4919	4200	4632	5721
Kg ha^{-1}	3.0	3.4	4.6	3.9	4.3	5.3
\$ kg^{-1} N mitigated, D3	1.9	3.0	34.4			
\$ kg^{-1} N mitigated, D4				4.9	4.4	27.6
\$ kg^{-1} N mitigated, S&B	3.2	19.2	34.0	3.2	19.2	34.0
\$ kg^{-1} N mitigated, total	3.0	15.1	34.2	3.7	13.2	31.1
Kg N lost t^{-1} MS[a,b]	29	26	21	23	20	16
Kg N lost t^{-1} 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^{-1}	0.1	0.1	0.1	0.1	0.1	0.1
\$ kg^{-1} P mitigated	128	659	2023	163	571	1671
Kg P lost t^{-1} MS[a,b]	0.7	0.6	0.6	0.7	0.6	0.6
Kg P lost t^{-1} M + F[a,c]	1.0	0.9	0.9	1.0	0.9	0.9
Annual GHG emissions abatement						
Total, t CO_2-e	6943	61,929	178,851	235,392	239,813	347,352
Kg ha^{-1}	6	57	166	219	223	322
\$/t CO_2-e mitigated	1414	900	940	67	256	521
T CO_2-e emitted t^{-1} MS[a,b]	10.0	9.7	9.5	9.9	9.5	9.3
T CO_2-e emitted t^{-1} M + F[a,c]	18.5	17.6	17.0	18.5	17.6	17.0
Annual profit before tax						
Regional, \$ ha^{-1}	−6	1	−95	−3	−3	−100
Dairy, \$ ha^{-1}	15	76	−222	29	48	−255
S&B, \$ ha^{-1}	−10	−13	−70	−10	−13	−70

[b] Unit of nutrient loss or GHG emitted per tonne milksolids (MS) produced. Baseline: 32 and 30 kg N t^{-1} MS, 1.1 and 1.2 kg P t^{-1} MS, 10.2 and 11.3 t CO_2-e t^{-1} MS (Scenarios 1 and 5).

[c] Unit of nutrient loss or GHG emitted per tonne of meat (net production) and fibre (M + F) produced. Baseline: 50 kg N t^{-1} M + F, 0.9 kg P t^{-1} M + F, 18.5 t CO_2-e t^{-1} M + F (Scenarios 1 and 5).

System 4 dairy farms vs. 36, 29, and 23 kg N/ha for System 3 dairy farms on PP classes 2, 3 and 4, respectively. 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; Houlbrooke et al., 2009). On sheep and beef farms, the inclusion of a fenced wetland (5 ha) with planted trees (and adjusting livestock numbers accordingly), also contributed to the reduction in N losses. This reduction can be attributed to the combined effects of wetland attenuation processes and a reduction in animal numbers (Mackay et al., 2012).

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 and Nash, 2012; McDowell, 2014). These managements have often proven to be the most cost-effective strategies for mitigating on-farm P losses, with a cost range of NZ$0 to NZ$200 per kg of P conserved (McDowell and Nash, 2012). Our results for M1 fall within this range (Table 4).

Only dairy farms were responsive to N leaching loss abatement from adopting M2 mitigation strategies, 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, a 23% reduction in P losses, and a 1% reduction in GHG emissions, 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, a 26% reduction in P losses, and a 4% reduction in GHG emissions (Table 4). For both scenarios, this represented a slight improvement in N and P abatement relative to M1, with no additional effect on GHG emissions abatement, but with slight regional gains in farm profitability (profitability gains from dairy farms exclusively) (Table 4, Fig. 6).

Reductions in N losses from dairy farms adopting M2 were caused mainly by a reduction in dairy cow stocking rates (a 5–8% reduction) through the farms carrying fewer, slightly heavier cows, each with greater genetic merit (reflected in greater MS production per cow), without increasing MS production per unit of area. 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 and GHG emissions 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 (Mackay et al., 2012). Dairy farms were also responsive to P loss abatement, but minor gains (7–8%) were achieved relative to M1 (Table 4). Low rate effluent application to land has proven effective in reducing P losses, with an effectiveness (as a % of total P reduction) often in the 10–30% range (McDowell and 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 (Ledgard et al., 2006; Christensen et al., 2012). 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 and 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.

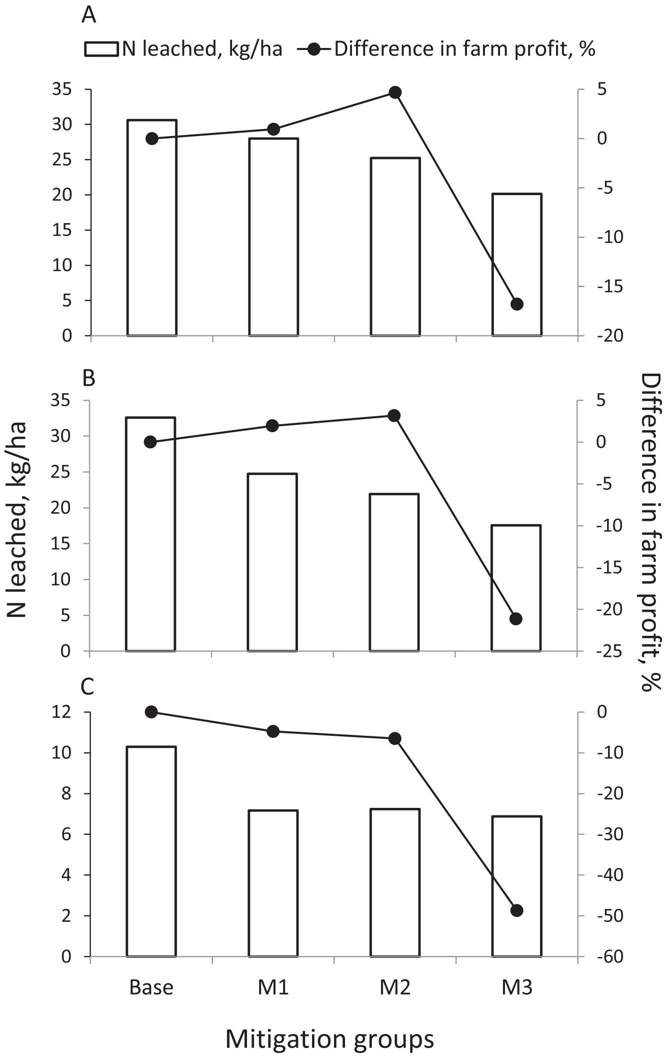

Fig. 6. Annual N losses to water bodies (kg ha^{-1}; bars) by enterprise (A: simulated System 3 dairy farms; B: simulated System 4 dairy farms; C: simulated sheep and beef farms) and projected cost-effectiveness of mitigation groups (Base, M1, M2, M3) relative to baseline (difference in farm profit, %; ●).

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 enterprises) 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, a

23% reduction in P losses, and a 3% reduction in GHG emissions, 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, a 27% reduction in P losses, and a 6% reduction in GHG emissions (Table 4). For both scenarios, this represented an improvement in N and GHG abatement and no additional P abatement relative to the previous 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 (Fig. 6).

As pastoral farming moves to operating within constraints (set emission limits), understanding how nutrient losses, GHG emissions, 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 (Doole, 2012). Therefore, the modelling exercise undertaken in the current study is subject to a considerable number of assumptions, limitations and uncertainty. 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 and GHG emissions from milking platforms and young dairy stock considered.

We also acknowledge that not all mitigation options available were explored. In addition to a partial assessment of the abatement potential of restricted grazing, N abatement options such as the use of nitrification inhibitors (Monaghan et al., 2008; de Klein et al., 2010) and low N feeds (Doole, 2012; Vogeler et al., 2013), and P abatement options such as soil amendments and edge of field options (McDowell and Nash, 2012) were not explored in this study. Notwithstanding these limitations, the current modelling exercise provided an assessment of the impact of integrated mitigation options on potential nutrient losses to water bodies and GHG emissions to the atmosphere in Southland, New Zealand.

4. Conclusions

Farm-scale modelling was integrated with spatially-derived estimates of pasture production to estimate the financial and environmental impacts from current pastoral land uses in Southland, New Zealand. Overall, the mitigation group M1 provided for high levels of regional N and P abatement at a low cost per farm without affecting farm production. Mitigation group M2 provided more N abatement but only marginal P loss abatement in dairy farm systems, and had the added benefit of slight increases in overall dairy farm profitability. Mitigation group M3 provided for the greatest N abatement and no additional P abatement, but had a large economic cost to farmers, sheep and beef farmers in particular. The modelling 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 GHG emissions, and the effectiveness of mitigation strategies.

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Appendix. Relationships ($y = ax + b$) between environmental and financial outcomes, and pasture production classes (x) in Southland. Separate regression analyses were conducted for well-(WD) and poorly-drained (PD) soils (WD/PD regression coefficients).

Scenario	1	2	3	4	5	6	7	8
Mitigation group	Base	M1	M2	M3	Base	M1	M2	M3
N leaching losses (kg/ha)								
Dairy, slope (*a*)	−6.32/−6.07	−5.95/−5.24	−5.44/−4.53	−4.06/−3.52	−6.10/6.32	−5.84/−5.11	−5.17/−4.91	−3.80/−3.39
Dairy, intercept (*b*)	48.1/44.4	45.1/38.9	41.5/33.7	32.0/27.0	44.8/44.9	41.4/36.0	37.6/32.1	28.6/24.5
Dairy, R^2	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99
Sheep and beef, *a*	−2.10/−1.02	−1.86/−0.85	−1.86/−0.85	−1.54/−0.85	−2.10/−1.02	−1.86/−0.85	−1.86/−0.85	−1.54/−0.85
Sheep and beef, *b*	20.2/14.1	15.9/10.3	15.9/10.3	14.0/10.2	20.2/14.1	15.9/10.3	15.9/10.3	14.0/10.2
Sheep and beef, R^2	0.98/0.99	0.95/0.99	0.95/0.99	0.96/0.99	0.98/0.99	0.95/0.99	0.95/0.99	0.96/0.99
P losses (kg/ha) − *Dairy*								
a	−0.14/−0.20	−0.07/−0.09	−0.07/−0.08	−0.07−0.08	−0.15/−0.22	−0.09/−0.12	−0.08/−0.09	−0.08/−0.09
b	1.10/1.99	0.60/1.13	0.57/1.01	0.60/1.01	1.15/2.15	0.68/1.32	0.64/1.14	0.66/1.09
R^2	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99
GHG emissions (kg CO$_2$-e/ha)								
Dairy, *a*	−1758/−2012	−1698/−1930	−1631/−1853	−1707/−1806	−1965/−2202	−1935/−2150	−1906/−2089	−1959/−2028
Dairy, *b*	13,398/15,894	13,103/15,476	12,607/14,892	12,953/14,225	15,088/17,428	14,749/16,824	14,610/16,568	14,894/15,956
Dairy, R^2	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99	0.99/0.99
Sheep and beef, *a*	−882/−1182	−882/−1183	−894/−1196	−889/−1187	−882/−1182	−882/−1183	−894/−1196	−889/−1187
Sheep and beef, *b*	7562/9412	7586/9443	7644/9512	7536/9372	7562/9412	7586/9443	7644/9512	7536/9372
Sheep and beef, R^2	0.99/0.97	0.99/0.97	0.98/0.97	0.99/0.97	0.99/0.97	0.99/0.97	0.98/0.97	0.99/0.97
Profit (NZ$/ha)								
Dairy, *a*	−932	−940	−944	−885	−891	−883	−867	−809
Dairy, *b*	4289	4326	4398	3927	4085	4090	4061	3589
Dairy, R^2	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Sheep and beef, *a*	−117	−115	−126	−121	−117	−115	−126	−121
Sheep and beef, *b*	702	686	727	650	702	686	727	650
Sheep and beef, R^2	0.97	0.97	0.97	0.98	0.97	0.97	0.97	0.98

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