Stacking nitrogen leaching mitigations in a Canterbury dairy system whilst minimising profitability losses

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Abstract

The aim of this project was to model combinations ("stacks") of cost-effective nitrogen (N) leaching mitigations within a dairy system that could reduce N leaching by 40-60%, whilst minimising losses in profitability. A FARMAX and OverseerFM combination was used to model a baseline farm representing a typical Canterbury system, and seven sequentially "stacked" mitigated systems. The mitigations were combined and stacked in the following order based on mechanism(s) of action, practicality, and cost-effectiveness: 1) reduced synthetic N fertiliser input (from 190 to 100 kg N/ha/year); 2) including Italian ryegrass in the pasture sward; 3) including plantain in the pasture sward; 4) earlier calving and drying off (by 10 days); 5) wintering on pasture and baleage; 6) standing cows off-pasture; 7) using new-generation nitrification inhibitors. The most cost-effective stack combined mitigations 1 to 5. We estimated that N leaching was reduced by 57% relative to baseline, with an 8% reduction in operating profit. Greenhouse gas emissions were reduced by 8%. The largest single reduction in N leaching was from stack #5, and it coincided with no/little change in milk production pasture eaten and had no capital cost. A careful selection of complementary mitigations could achieve significant reductions in N leaching without compromising greenhouse gas emissions and, to any great extent, profitability.

Keywords: complementarity, mechanisms, cost-effectiveness, practicality

Introduction.

Farming businesses face growing pressures to reduce their environmental footprint, driven by local and international expectations. The challenge is to alter the farm system to reduce negative environmental outcomes whilst maintaining profitability. Over recent decades, the New Zealand agricultural research sector has investigated farm systems designed for a comprehensive whole farm management approach that consider farm productivity, profitability, and environmental outcomes. For example, the Pastoral 21 (P21) research programme (2011-2016) aimed to design industry-accessible, adoptable, systems-level solutions for profitably increasing production while reducing nutrient losses to water (Shepherd et al., 2017). The P21 system design was based on a sound understanding of how nutrients cycle through a dairy system, with the aim of reducing animal urinary nitrogen (N) excretion through feeding low N feeds and reducing urine and dung deposition by standing cows off pasture at times of the year when N leaching risk is greatest. The P21 programme in the Canterbury region achieved a 30% reduction in N leaching from the milking platform but at the expense of production (-24%) and profit (-9%) (Beukes et al., 2019). More recently, the Forages for Reduced Nitrate Leaching (FRNL) programme (2013-2019) had a goal of designing farm systems with forages that reduce N leaching by more than 20% from dairy, arable, sheep and beef and mixed farming systems (DairyNZ, 2020). The FRNL key findings included 1) some pasture species, such as plantain and Italian ryegrass, can reduce N concentration of urine from animals and improve plant N uptake in the cooler months; 2) low N, high quality feed crops, such as fodder beet, maize, and cereals, reduce urinary N excretion by animals; 3) catch crops, such as oats, reduce nitrate leaching when established early in the winter season following a winter crop, through the uptake of water and N. These crops also provide additional feed with lower N concentration than pasture and may increase total annual dry matter (DM) production.

There are opportunities to carefully select multiple mitigations developed by research projects such as FRNL and P21 and integrate them in a complementary and synergistic way into current farm practices to reduce N leaching and minimise profit loss. The aim of this project was to model combinations of N leaching mitigations ("stacks") within a Canterbury farm system to reduce N leaching by 40-60%, whilst minimising losses in profitability. The resulting stacks also aimed

to avoid "pollution swapping" which would occur for example if other contaminants such as greenhouse gases and phosphorus losses were to increase.

Materials and methods

Models

A combination of FARMAX (Bryant et al., 2010) and OverseerFM (Watkins and Selbie, 2015) models were used to predict the economic and environmental impacts of the farm system scenarios. FARMAX is a whole-farm system decision support model that predicts the production and economic outcomes of managerial decisions, whereas OVERSEER predicts nutrient loss to land, water, and air.

The baseline farm

Data from Lincoln University Research Dairy Farm (LURDF) 2021-22 season was used as a baseline farm to represent a Canterbury farming system. The baseline modelling included a support block, and all metrics are presented as per total farmed area unless indicated (Table 1). All animals were grazed on the milking platform and support block.

Stacking mitigations

Selection of the mitigations included in the stacks was based on mechanism of action, cost-effectiveness, and practicality. The stacking order started with low-cost strategies with the more expensive and higher risk mitigations added later in the stacking process (Figure 1).

The order of stacking included:

#1) Reducing synthetic N fertiliser from 190 to 100 kg N/ha/year and altered application rate and timing whilst maintaining stocking rate, allowing for increased legume content in the pastures, and improved N response from pasture (Harris et al., 1995). Synthetic fertiliser application timing was reduced from 5 (September, October, December, February, and March) to 4 (September, November, February, and March). The N response rate was increased in spring from 15 to 20 kg DM/kg N, in February from 14 to 17 kg DM/kg N and in March from 14 to 15 kg DM/kg N. These assumptions were based on response rates achieved under rapid growth conditions (DairyNZ, 2017). An equivalent of 0.7 t DM/ha pasture baleage was imported to fill the feed deficit, as N fertiliser reduction, reduced pasture yield by 0.7tDM/ha.

#2) Including Italian ryegrass in the pasture sward for a stronger N response and pasture performance in winter with potentially more soil N taken up by plants during the high-drainage months, similar to the effects of a catch-crop (Woods et al., 2018). Italian ryegrass increased annual pasture yield by 0.8 t DM/ha because of increased winter growth rates and better N response rates (Martin, 2018). Nitrogen fertiliser response rate increased to 22 kg DM/kg N in spring, 18 kg DM/kg N in February and 16 kg DM/kg N in March (Martin, 2018). We assumed a steady state farm with all pastures already including Italian ryegrass. However, the Italian ryegrass would need renewal every four years; therefore, Italian ryegrass was under-sown annually on a quarter of the farm. The transitioning from permanent ryegrass to Italian ryegrass could be done over for years. The Italian ryegrass seed was assumed to cost $6/kg, with an under-sowing seed rate of 12 kg/ha, and an operational cost of under-sowing of $600/ha, bringing it to a total cost of $672/ha for the re-established area. The under sowing will be done in autumn when the grazing rotation is 42 days, minimising the delay from planting to grazing. However, we assumed a 15-day delay for grazing due to under-sowing and as a result more baleage was imported.

#3) Including plantain (30% of annual DM yield) in the pasture sward to increase urine volume and urination frequency and reduce urinary N concentration. These combined effects reduce urinary N load in the urine patches and increase chances of pasture uptake of urine N (Al-Marashdeh et al., 2021, Mangwe et al., 2019). Plantain will be under-sown at 4 kg/ha, together with Italian ryegrass, every four years, costing $25/kg with an estimated cost of $100/ha to be added to $672/ha of Italian ryegrass under-sowing giving a total re-grassing cost of $772/ha per year. We assumed plantain winter growth would be 3% lower than the Italian ryegrass due to lower base temperature (Powell et al., 2007) reducing annual pasture yield by 0.3 t DM/ha.

#4) Earlier calving (by 10 days), allowing for earlier dry-off to reduce feed demand, N intake and autumn urinary N deposition (Shepherd et al., 2010b). Calving and dry-off dates were brought forward by 10 days to maintain similar days in milk and feed eaten. This mitigation also allows more time for building average pasture covers for the next mitigation where crops are removed, and cows are wintered on pasture. It also captures the feed built up over winter (with our more winter active Italian ryegrass). This implies drying cows off earlier but holding cows longer on the milking platform.

#5) Wintering on pasture and baleage instead of the kale crop to reduce N leaching from crop grazing, reduce soil compaction and maintain plant N uptake from the permanent pasture (Chrystal et al., 2012). Removing winter cropping also reduces cultivation and soil mineralisation of organic N (McNally et al., 2018). The winter kale crop is removed, and baleage is harvested from the former winter crop area. Cows are fed pasture and baleage.

#6) Standing cows off-pasture in winter (16 hours) and autumn (8 hours) to reduce urinary N deposition onto paddocks at the time of year when urinary N is

Table 1 Baseline farm system physical and financial description.

Parameter	Units	Value for 2021-22 season
Milking platform area	ha	12
Support block area	ha	5
Stocking rate (Milking platform)	cows/ha	3.33
Comparative stocking rate (CSR)	kg Lwt/t DM	84.2
Cows wintered on support block kale crop	%	100
Young stock grazed on support block	%	100
Pasture production	t DM/ha	16.7
N leaching	kg N/ha	41
Synthetic N fertiliser	kg N/ha	190
Purchased supplements	% feed offered	5.2
Planned start of calving	Date	1-Aug
Days in milk	Days	255
Milksolids (MS) production per cow	kg MS/cow	470
MS production per hectare (milking platform)	kg MS/ha	1593
Farm working expenses (2019-20)	$/kg MS	3.63
Operating profit @ $6.35/kg MS milk price (long-term milk price)	$/ha	2,725

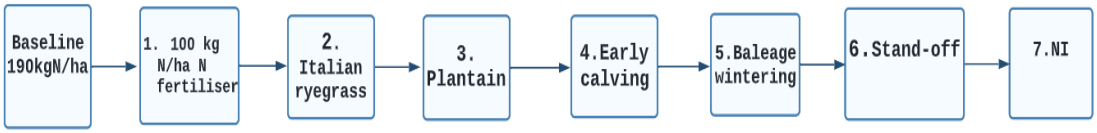

Figure 1 The mitigation stacking order. Each box gets added to the previous as the stacking of mitigations progresses from left to right in this diagram. N refers to synthetic fertiliser-N and NI is nitrification inhibitor.

most at risk of leaching due to low pasture growth rates and/or likelihood of drainage events (Chikazhe et al., 2022). The cows diet remained the same as in stack #5. An uncovered stand-off pad was assumed, costing $1500/cow to construct including associated costs, e.g., effluent upgrade (Askin and Askin, 2016). The annual cost included depreciation as a non-cash expense assuming a 25-year life, interest repayment assuming a 7% interest rate per annum, and bedding costs of $90/cow for adding and removing woodchip (Beukes et al., 2013).

#7) Using new-generation nitrification inhibitors (NI) to slow the nitrification of ammonium-N to the highly leachable nitrate-N form (Romera et al., 2017). This is achieved through inhibitors that restrict microbial conversion of ammonium to nitrate. Although the nitrification inhibitor dicyandiamide (DCD) is no longer on the market, its mode of action is still represented in the OverseerFM model. The mode of action of new-generation inhibitors is essentially the same as DCD, via temporarily inhibiting nitrification by deactivating the enzyme ammonia monooxygenase (AMO) in ammonia-oxidizing microbes (Di et al., 2011). The nitrification inhibitor was applied three times a year, in August, April, and May. The estimated cost of the product and application was $150/ha/application (Romera et al., 2017).

Results and discussion

The most cost-effective stacked system that achieved our targeted 40-60% N leaching reduction combined mitigations 1 to 5 (stack #5). For this stack OverseerFM predicted a 57% reduction in N leaching, with an operating profit reduction of 8% relative to the baseline (Table 2). Each kg reduction in N leached cost $14/ha (Table 2). In addition, P loss was unchanged whilst total greenhouses gas (GHG) emissions were reduced by 8%. Previous modelling has generally shown a greater rate of decline in operating profit once N leaching is reduced beyond 20% (Muller, 2017). Complementarity of the mitigation mechanisms has likely assisted with reducing the profit reduction, while achieving the large 57% leaching reduction.

In stack #1, reducing N fertiliser from 190 to 100 kg N/ha resulted in an 11% N leaching reduction, a 4% reduction in operating profit and a 5% reduction in GHGs (primarily due to nitrous oxide (N_2O) and carbon dioxide (CO_2) reduction with a smaller reduction in methane (CH4); results not shown). Reducing N fertiliser reduced modelled pasture production by 0.7 t DM/ha, moderated by predicted increases in clover content and N response rate. An equivalent of 0.7tDM was imported to fill the deficit. As a result, operating profit was only reduced by 4%. Stocking rate and milk production were maintained through importing supplements.

The effects of Italian ryegrass (Stack #2) on N uptake were not captured in OverseerFM predictions, as the Italian ryegrass mechanism of action is not currently included in the model. There was a slight increase (1%) in N leaching in stack #2 relative to stack #1 (Table 2), likely due to increased pasture production and more N cycling through the herd, with more urinary N deposited onto pastures. Based on evidence from the field studies measuring N leaching under Italian ryegrass, we expect some N leaching reductions from the Italian ryegrass (Woods et al., 2018, Malcolm et al., 2014). Research has shown that Italian ryegrass has an improved winter and early spring growth and greater N uptake which reduces nitrate concentration in drainage water and drainage volume (Maxwell et al., 2019). Importantly, there was an increase in profitability of 3% due to 0.8 t DM/ha greater pasture production, less imported supplement, and less N fertiliser. The increased pasture production enabled stocking rate and production to be maintained with reduced imported supplements. This generated a buffer in operating profit for subsequent N mitigations in the stacking order.

Including plantain in stack #3 reduced N leaching by 18% compared to stack #2 (or a cumulative 28% compared with baseline) but negated the profitability gains from previous stacks up to this point due to a reduction in winter pasture production (by 0.3 t DM/ha) which required supplements to be imported to fill the feed deficit. The plantain mitigation will result in greater urination frequency and higher daily urine volumes. These effects lead to greater urine patch coverage but a lower urinary N rate/patch (kg N/ha) which reduced N leaching by 18%.

In stack #4, calving and drying off 10 days earlier reduced N leaching by 1% relative to stack #3 and by 29% relative to baseline. This mitigation had no impact on profitability and total GHG. Calving and drying off earlier was included as a mitigation because of its effect on the pattern of feed requirements, N intake and N excretion in high-risk autumn period (Shepherd et al., 2010b). Stocking rate and feed demand is reduced over autumn, which reduces the autumn load of urinary N deposited onto the paddocks. Calving early allows for the utilisation of increased Italian ryegrass pasture growth in winter and early spring. The lack of effect on N leaching in the OverseerFM prediction was likely due to the total N input and farmgate N surplus remaining unchanged (Table 2). OverseerFM's farmgate N surplus is calculated as N inputs (fertiliser, purchased supplementary feed, biological fixation (e.g., by clover), irrigation, atmospheric deposition (via rainfall) minus N in outputs (milk, meat, crops sold; kg N/ha; Ledgard et al., 2004).

In stack #5, changing to pasture and baleage wintering reduced N leaching from the wintering block by 70% compared to a winter kale block (Table 3) and from the whole farm system by 38% relative to stack #4 (Table 2), which resulted in a total of 57% reduction relative to baseline (Table 2). There was a predicted 8% reduction in total GHG emissions relative to baseline due to further N_2O and CO_2 reductions and 3% relative to stack #4. There was little change in CH4 because total DM intake remained the same. Operating profit was 8% lower than baseline. Table 3 shows the crop block having a four to six times higher N leaching compared to the other blocks. As a result, replacing crop with the pasture and baleage wintering mitigation had the highest N loss reduction. This is primarily because compared to the bare ground after grazing a kale crop, the Italian ryegrass in stack #5 is actively growing and utilising the deposited N. Additionally, there is less N released from organic matter mineralisation due to the removal of the need for cultivation. Based on LURDF soils (relatively free draining) and farm management we assumed little damage to pastures during winter grazing. This assumption applied even in the absence of a stand-off structure where cows could be kept for some hours during very wet conditions. The implication of this assumption is that on this farm pasture recovery and growth into spring is good, allowing silage to be made from the former wintering area. If these assumptions do not hold and pasture is damaged, it may not recover in time to produce the necessary silage for the next winter. More importantly, imported silage will be required in this situation, which could influence operating profit.

Stacks #6 and #7 presented large reductions in operating profit (Table 2), driven by the costs of stand-off infrastructure and the nitrification inhibitor (NI). Nitrogen losses were reduced by a further 2% and 7% relative to stack #5, which resulted in a 59% and 64% reduction relative to baseline. Using stand-off during winter to protect wet soils had a larger effect on profitability (up to -25% from baseline) because of the costs of the facility, supported by the findings of Chikazhe et al. (2022). We, therefore, concluded that risking potential pugging damage was an economically more favourable option than investing in a stand-off facility for this modelled LURDF farm scenario. Also, the farm is already incurring more pasture replacement cost with widespread direct drilling of Italian ryegrass and plantain. We speculate that this level of reduced profitability with the stand-off infrastructure would limit adoption. For farms where the stand-off is more expensive and pasture/baleage wintering is likely to result in pasture damage, then combining mitigations 1 to 4 could be the most cost-effective stack (#4 in Table 2), albeit only achieving half the N loss reduction. A new generation nitrification inhibitor (with the same effectiveness as DCD) could increase the N loss reduction to an estimated 64%, but at a cost of a 41%

Table 2 Modelling results for the stacked mitigations. All changes (%) are relative to baseline and refer to the whole farm system (i.e., including wintering and young stock areas- all hectares counted). NI = nitrification inhibitor.

	Baseline	1. 100 kg N/ha	2. +Italian ryegrass	3. +Plantain	4. +Early calving	5. +Baleage wintering.	6. +Stand-off	7. +NI
N loss (kg/ha)	41	37	38	30	29	18	17	15
Farmgate N surplus kg N/ha	272	231	230	230	230	214	216	225
Pasture yield tDM/ha	16.7	16	16.7	16.4	16.4	16.4	16.4	16.4
Pasture and crop eaten tDM/ha	13.8	13.1	13.7	13.5	13.5	13.2	13.2	13.2
Bought feed/feed offered %	5.2	10.3	6	8.9	8.9	12.9	12.9	12.9
Total GHG (kg CO2-e/ha)	13615	13007	12991	12897	12869	12524	12588	12375
Operating profit ($/ha)	2725	2623	2813	2663	2657	2506	2047	1597
Cost per kg N loss reduction ($/kg N)		25.5	-	19	6	14	459	225
Cumulative N loss change	0%	-11%	-10%	-28%	-29%	-57%	-57%	-64%
Cumulative GHG change	0%	-4%	-5%	-5%	-5%	-8%	-8%	-9%
Cumulative Operating profit change	0%	-4%	3%	-2%	-2%	-8%	-25%	-41%

Table 3 Block N leaching (kg/ha) for the stacked mitigations.

	Baseline kg N/ha	1. 190-100 ryegrass	2. +Italian calving	3. +Plantain wintering	4. +Early off	5. +Baleage	6. +Stand-	7. +NI
Milking block (11.8 ha)	33	27.3	27.3	19.5	18.8	18.3	18	16
Young stock block (3.2 ha)	32	28.7	28.7	20.8	20.8			
Wintering kale block (1.8 ha)	114	114	114	114	113			
Young stock area plus winter kale block (5 ha)	62	59	59	54	54	16	15.5	13.3

reduction in operating profit. In this case, the cost of the product at three applications over the whole farm was based on historical costs for DCD scaled to current prices using average inflation rate. The cost-benefit ratio appears highly unfavourable, it cost $225/ha loss in profit per 1 kg N leaching reduced.

The modelled results were influenced by the various key assumptions noted earlier. The calculated reductions in N leaching for the single component mitigations reduced N leaching by 11% for N fertiliser reduction, and by 18% for plantain. This aligns with published work on the effects of reduced fertiliser-N and plantain mitigations (Harris et al., 1995, Al-Marashdeh et al., 2021). However, larger percentage N leaching reductions were expected for stand-off and nitrification inhibitor mitigations, although this is influenced by carry-over effects of saved N within the farm system and how effluent from the stand-off is managed. The large benefit from pasture wintering relative to kale is greater than that recorded from two comparisons in the Southland region (Ross Monaghan, pers. comm.) but there is little other research on this practice and more field validation measurements are required.

Conclusion

A careful selection of complementary, practical, and cost-effective mitigation mechanisms is expected to achieve significant reductions in N leaching without compromising other emissions whilst minimising profitability loss. Four key drivers of reducing N leaching whilst minimising profitability losses for this analysis were a) minimising losses in pasture yield and pasture eaten, b) implementing pasture species that reduce urine concentration and promote N uptake, c) reducing N input and recycling more N on the farm, and d) reducing winter crop grazing and replacing with pasture and baleage wintering and using pastures species with greater winter growth. However, due to limitations of the static models used, to provide confidence to modelled results, the stacked system #5 will now be evaluated in a multi-year farmlet experiment at LURDF.

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