An overview of the cost-effectiveness of nitrogen leaching mitigation strategies based on marginal abatement cost for eighteen dairy farms in Hauraki and Horizons regions

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Abstract

Nitrogen (N) management is crucial for reducing environmental impacts in New Zealand's dairy farming sector, particularly in minimising N leaching into freshwater systems. This study employs Marginal Abatement Cost (MAC) analysis to assess the cost-effectiveness of various N leaching mitigation strategies across 18 dairy farms in the Hauraki and Horizons regions. These farms represent a range of systems, soil types, and management practices. The results show that the MAC varies significantly due to differences in farm characteristics, biophysical conditions, and economic factors. Farms with high purchased N surplus (imported N via fertiliser and supplementary feeds minus exported N in products) generally have lower MAC for early-stage mitigations, such as optimising N inputs and nutrient recycling (optimal use of effluent and manure on crop or pasture). In contrast, farms with low purchased N surplus and already efficient management practices face higher MAC, as further reductions require costly interventions like infrastructure upgrades or stocking rate reductions. Additionally, soil type, climate, existing infrastructure and how the mitigations complement the existing system play key roles in the effectiveness and cost of mitigation strategies. Despite considerable variation in the MAC among farms, overall trends revealed that the most cost-effective strategies often involve nutrient recycling, improved N use efficiency, and the use of plantain. In contrast, de-intensification and off-paddock structures were among the most expensive mitigation options. However, off-paddock structures can become cost-effective when they complement the existing farm system. These findings emphasize the need for farm-specific mitigation strategies to balance environmental sustainability with economic viability.

Keywords: cost-effectiveness, farm system diversity, Marginal Abatement Cost

Introduction

Nitrogen (N) is essential for plant and animal growth, making it a critical factor in agricultural productivity. However, excessive N can lead to leaching into freshwater systems, contributing to environmental issues such as algal blooms and water quality degradation. In response, New Zealand has introduced environmental regulations aimed at improving water quality, reducing greenhouse gas (GHG) emissions, and protecting biodiversity (Ministry for Primary Industries 2020). While these regulations support sustainability, they also pose challenges for dairy farmers, including increased compliance costs and the need for operational adjustments.

To minimise environmental impacts while maintaining farm profitability, dairy farmers must adopt cost-effective N management strategies. Research by Chikazhe et al. (2023) highlights that a well-designed combination of complementary and practical mitigations can significantly reduce N leaching while limiting trade-offs with other emissions and profitability. However, the cost-effectiveness of mitigation strategies varies depending on a farm's economic conditions, biophysical characteristics, and management practices (Chikazhe et al. 2024).

A valuable tool for assessing the financial feasibility of mitigation strategies is Marginal Abatement Cost (MAC) analysis. MAC represents the cost of reducing (or abating) one additional unit of pollution such as N leaching or greenhouse gas emissions typically measured in \$/kg reduced N leached or \$/t $CO_{2\text{-e}}$ reduced (World Bank Group 2023). When multiple mitigation options are evaluated, they can be ranked using a Marginal Abatement Cost Curve (MACC), which visually compares their cost-effectiveness. By plotting mitigation strategies on a MACC, farmers and policymakers can identify measures that offer the greatest environmental benefits at the lowest economic cost.

This study applies MAC analysis to identify broadly applicable cost-effective mitigation strategies in the Hauraki and Horizon regions. Hauraki and Horizon regions were chosen as they are one of the sensitive catchments due to a combination of environmental vulnerability and land use intensity that increases the risk of water quality degradation, particularly from nutrient losses (N and phosphorus) and sediment runoff. The case study farms were selected to reflect diverse farm systems, soil types, climatic conditions, and management practices, ensuring regionally

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relevant insights. The findings will support farm-level decision-making, policy development, and industry recommendations for sustainable dairy production in the Hauraki and Horizon regions.

Materials and Methods

Case study farm selection

To ensure a comprehensive analysis of N leaching mitigations, 18 representative case study farms were selected from the DairyNZ DairyBase database (DairyNZ n.d.). DairyBase is a voluntary data analysis service provided by DairyNZ, allowing farmers to benchmark their farm performance within their milk production region or nationwide. The farms were chosen to represent a diverse range of farm systems and typologies within the Hauraki and Horizons regions. New Zealand dairy farm systems are typically defined by the level of imported feed used to support the herd, particularly during times when pasture growth is limited. These systems range from low-input, pasture-based models to high-input systems that rely more heavily on purchased supplement feeds, such as palm kernel, silage, or grain. DairyNZ farm typologies are defined based on key environmental and management factors, including soil wetness, slope, drainage, and anion storage capacity (ASC), which influence nutrient dynamics and mitigation effectiveness (Monaghan et al. 2018). The selected farmers agreed to participate under the condition that their data would remain anonymous.

Modelling approach

A staged approach was used to stack mitigation strategies, starting with low-cost, practical interventions (Stage 1) before incorporating more complex and expensive measures (Stages 2-4). The initial mitigations aimed to minimise disruption to farm operations, while later stages involved system-level modifications requiring greater investment. However, the MAC was not calculated based on cumulative (stacked) mitigations, but rather on the difference between the stacks. This approach is intended to highlight the marginal abatement potential and cost of each individual mitigation strategy.

Stage 1: Nutrient recycling

This stage aimed to optimise nutrient use efficiency and reduce reliance on synthetic fertilisers. Effluent was captured and applied purposefully as a nutrient source, reducing the need for synthetic N fertilisers. When existing stand-off structures were available (adding no extra capital cost), they were used more frequently to capture urine and dung, particularly in autumn and winter when N leaching risk is highest and redistribute as fertiliser.

Stage 2: Efficient use of N inputs

The goal of this stage was to optimise fertiliser application and feed management by eliminating N fertiliser applications during high drainage and low N response periods (May-July). Individual fertiliser applications were limited to a maximum of 40 kg N/ha, with the annual total kept below the legislated limit of 190 kg N/ha. Where protein intake exceeded animal requirements, high-protein feeds (e.g., soymeal) were substituted with low-protein alternatives (e.g., barley grain or maize silage) provided the farm had the necessary infrastructure to accommodate the feed shift. Where appropriate, minimum tillage was used for cropping to reduce the mineralisation of organic N, and catch crops were established to minimise bare ground and take up residual N in the soil. Minimum tillage works best for robust, fast establishing crops like cereals and brassicas in well managed soils with low weed pressure, but less suitable for fodder beet, swedes and lucerne (Foundation for Arable Research, n.d.)

Stage 3: System changes

This stage introduced more complex, system-altering mitigations designed to further reduce N leaching. These included altering the pasture composition to reduce urinary N concentration and reducing inputs and stocking rates (de-intensification).

Altering pasture composition to reduce urinary N concentration.

Plantain was incorporated into the pasture sward, comprising approximately 20% of both the sward composition and the cows' diet. One-third of the farm (excluding steep hills) was over-sown annually with plantain at a cost of $120/over-sown hectare. Pasture production and growth curves were assumed to remain unchanged. Incorporating plantain was considered a system change, despite assuming unchanged pasture production and growth curves, because plantain requires different agronomic management compared to a traditional ryegrass–clover sward. Plantain's establishment, persistence, and grazing management differ significantly from ryegrass–clover pastures, requiring adjusted management practices even when productivity is similar. (DairyNZ and AgResearch 2021) Research has shown that plantain increases water intake and urination frequency, leading to lower urine N concentration and lower N load in urine patches, which reduces leaching risk (Pinxterhuis et al. 2024).

De-intensification

De-intensification refers to the reduction of farm inputs and forage crops followed by adjustment of stock numbers to better match feed supply to demand. Cropping areas were removed to minimise organic matter mineralisation and prevent bare ground exposure after grazing. To compensate for reduced feed availability, either the stocking rate was lowered, or supplementary feed was imported. N fertiliser application was initially halved, then in a further step completely removed, with stocking rates adjusted accordingly. As cow numbers were reduced, per-cow production was maintained, resulting in both stock numbers and inputs being lowered. This enabled a less intensive system overall. In contrast, maintaining total milk production with fewer cows would require sustaining or even increasing input levels, meaning only cow numbers would reduce while system intensity remains largely unchanged.

Stage 4: Reduce urinary and dung N deposition on paddocks

A stand-off or feed pad was introduced based on the farm's feeding system to reduce urinary N deposition on paddocks. As this required a capital expenditure, and potential system changes it was considered both complex and expensive. A stand-off pad was chosen for farms with minimal supplementary feeding. Cows were moved off pasture during winter (16 hours/day for non-lactating cows) and autumn (8 hours/day for lactating cows) to reduce urinary N deposition onto paddocks when urinary N is most at risk of leaching due to low pasture growth rates and/or likelihood of drainage events. An uncovered stand-off pad was assumed, costing \$2500/cow to construct including associated costs, e.g., effluent upgrade (Reynish 2023). The annual cost included depreciation as a non-cash expense assuming a 25-year lifespan, interest repayment assuming a 7% interest rate per annum, and bedding costs of \$90/cow for adding and removing woodchip.

The cows' diet remained unchanged during stand-off periods. However, for farms feeding significant amounts of supplementary feeds, (e.g., home grown maize and palm kernel) a feed pad was introduced, designed to complement existing systems by improving feed utilisation and recycling effluent for maize production. Cows were moved off pasture for four hours per day during June–August and March–May. An uncovered feed pad was assumed, costing \$1500/cow to construct including associated costs, e.g., effluent upgrade (Reynish 2023). The annual cost included depreciation as a non-cash expense assuming a 25-year life, interest repayment assuming a 7% interest rate per annum.

For farms with more than 400 cows, only the required structure for half their cows was modelled, with cows alternating use to reduce costs. However, farms with fewer than 400 cows, full infrastructure costs were applied, as these smaller herds typically function as a single unit, making cost reduction impractical.

Models used

Environmental and economic impacts were analysed using FARMAX (Bryant et al. 2010) and OverseerFM (Watkins and Selbie 2015) models. FARMAX is a whole-farm system decision support model used to predict the production and economic impacts of farm management decisions. It was used to assess the financial implications of mitigation strategies and ensure their biological feasibility. OverseerFM is a nutrient budgeting model that estimates nutrient use, transfers and losses based on farm management practices. It was used to predict nutrient loss to land, water, and air for each mitigation scenario. The 2022–23 case study farm systems, along with the associated milk price and cost structures, were employed for financial and environmental comparisons, with the season's milk price and cost parameters considered representative of long-term averages. The Overseer and FARMAX outputs were then used to calculate MAC to compare the cost-effectiveness of mitigation strategies. The formula for calculating the MAC is (Vogt-Schilb et al. 2018):

$$MAC = \Delta C / \Delta E$$

Where:

- MAC = Marginal Abatement Cost (\$ per kg N reduced or \$ per ton $CO_{2\text{-}e}$ reduced)
- ΔE = Change in Emissions or nutrient loss (reduction in nitrogen leaching or GHG emissions because of adopting a mitigation strategy).
- ΔC = Change in Cost (cost of implementing the mitigation). In this study, cost is defined as the change in operating profit due to mitigation adoption. Operating profit (also called operating income or earnings before interest and taxes, EBIT) is the profit a business makes from its core activities, before deducting interest and taxes.

Cost-beneficial strategies will generate a negative or low MAC meaning the measures save money or have minimal costs per unit of N reduction. Expensive strategies will generate a positive or high MAC meaning the measures reduce operating profit but might be necessary for compliance or sustainability goals.

To identify cost-effective mitigation strategies that balance environmental benefits with financial viability, modelling data from 18 farms were aggregated (Tables 1 and 2). Farms were modelled individually, and the results were then aggregated to identify broadly applicable mitigations that were cost-effective. Farms were classified into two groups based on purchased N surplus and operating profit. Purchased N surplus was calculated as imported N via fertiliser and supplementary feeds minus exported N (milk, meat, crops and effluent). Farms with purchased N surplus below 70 kg N/ha were classified as low, while those exceeding this threshold were classified as high. Similarly, farms with an operating profit below \$2,500/ha were considered low-profit, and those above this level were considered high-profit. These thresholds were based on the mid-point values of the selected case study farms.

Results

Farm Characteristics

The Horizon and Hauraki regions case study farms displayed variation in farm size, stocking rate, N fertiliser use, and overall farm system intensity. The Horizon region case study farms milking platform area ranged from 87 ha to 546 ha, with stocking rates varying from 1.2 to 3.0 cows/ha (Table 1). N fertiliser application ranged from 0 kg N/ha to 132 kg N/ha, with N leaching values ranging from 18 kg N/ha to 50 kg N/ha. Purchased N surplus varied widely from -29 kg N/ha to 158 kg N/ha. Operating profit per hectare ranged from $607/ha to $3,515/ha.

The Hauraki region case study farms milking platform sizes ranged from 46 ha to 275 ha, with stocking rates between 2.5 to 3.5 cows/ha (Table 2). N fertiliser use was higher than Horizons (27 to 144 kg N/ha), with N leaching values between 12 kg N/ha to 39 kg N/ha. Purchased N surplus varied from -27 kg N/ha to 137kg N/ha.

Operating profit varied from $1,307/ha to $8,345/ha. The Hauraki farms tended to have higher stocking rates, higher N fertiliser application, and greater milk production per hectare than Horizons farms. However, N leaching was highly variable across both regions, influenced by factors such as soil drainage, cropping practices, and farm system intensity.

Mitigation abatement curves

The FARMAX and OverseerFM modelling indicate that N leaching reductions of approximately 10–15% can be achieved with an average minimal profit loss (0–10%). However, further reductions beyond this threshold become increasingly costly (Figure 1).

Farms with low purchased N surplus and no existing off-paddock structures faced higher initial costs compared to those with higher purchased N surplus or existing infrastructure. These farms required expensive mitigation measures from the outset. Consequently, even achieving a 11% reduction in N leaching led to a substantial 20% decline in operating profit, whereas farms with higher purchased N surplus and existing off-paddock structures experienced less than a 10% decline in profit.

For farms with off-paddock infrastructure, nutrient recycling incurs no additional cost. However, for farms without such infrastructure, enabling nutrient recycling resulted in a 5–10% reduction in operating profit.

Farms with low initial profitability experienced the largest percentage reduction in profit, indicating that mitigation costs represent a larger proportion of their total operating profit (Figure 2). The high starting operating profit farms could reduce N leaching by about 35% with about 25% reduction in operating profit. In contrast for a 39% N leaching reduction, the low starting farms operating profit was reduced by 60%.

Cost-effectiveness of the mitigations

Figures 3 and 4 illustrate the aggregated mitigation

Table 1 Characteristics of selected farms in the Horizons region.

Farm	1	2	3	4	5	6	7	8	9
Milking platform area (ha)	133	175	90	161	252	546	150	177	87
Stocking rate (cows/ha)	2.8	2.8	2.8	2.2	2.2	2	1.94	1.2	3
Farm system	4	3	3	5	2	4	3	5	3
N fertiliser (kg N/ha)	72	84	74	56	0	104	132	22	131
% imported supplements	24.6	16.9	13.1	57.2	0.2	26.9	7.3	36	10.2
Purchased N surplus (kg/ha)	61	79	39	158	-29	121	94	1	92
Existing off-paddock structure	Feed pad	-	Standoff pad	Feed pad	-	-	-	-	-
Crops grown	Bulb turnips	Bulb turnips	Bulb turnips	Forage barley & chicory	-	Maize, turnips & kale	Forage rape & kale	Lucerne & maize	Bulb turnips
N leaching 2022/23 (kg N/ha)	25	27	37	20	29	50	27	18	27
Milk production (kg MS/ha)	1100	1055	1145	1183	545	880	915	510	1145
Operating profit ($/ha)	3238	2153	3515	987	2043	755	2311	607	2957
Rainfall (mm)	997	1310	1112	1150	1687	983	1036	956	1025
Drainage/Typology	40% well, 60% imperfect	29% poor, 71% moderate	50% imperfect, 50% poor	100% poor	20% poor, 80% well	50% poor, 50% well	Poor	67% poor, 37% well	100% poor

Table 2 Characteristics of selected farms in the Hauraki region.

Farm	10	11	12	13	14	15	16	17	18
Milking platform area (ha)	66	76	46	63	140	85	275	87	56
Stocking rate (cows/ha)	3.3	2.5	3.3	3.5	3	2.5	3.3	3.2	3.2
Farm system	3	2	2	5	4	3	4	5	3
N fertiliser (kg N/ha)	130	45	47	87	144	27	132	27	123
% imported supplements	15.4	0	10	21.3	26	12	26	39	20
Purchased N surplus (kg/ha)	85	-27	8	79	64	-1	71	81	137
Existing off-paddock structure	Feed pad	-	Standoff pad	Feed pad	Feed pad	Covered stand-off pad	-	Feed pad & makeshift stand-off pad	-
Crops grown	Maize	Chicory, swedes & bulb turnips	-	Bulb turnips & maize	Maize	Bulb turnips	Chicory & maize	Chicory	Maize & turnips
N leaching 2022/23 (kg N/ha)	24	22	26	33	26	12	20	39	33
Milk production (kg MS/ha)	1546	1001	1209	1476	1461	998	1440	1468	1189
Operating profit ($/ha)	8345	3575	5041	2242	3105	3579	3876	1307	3317
Rainfall (mm)	1065	1240	1125	1294	1248	1133	1132	1125	1269
Drainage/Typology	44% well, 56% poor	100% well	38% well, 33% poor, 29% imperfect	73% well, 27% poor	100% well	78% poor, 22% imperfect	60% poor, 40% imperfect	95% well, 5% poor	85% well, 15% poor

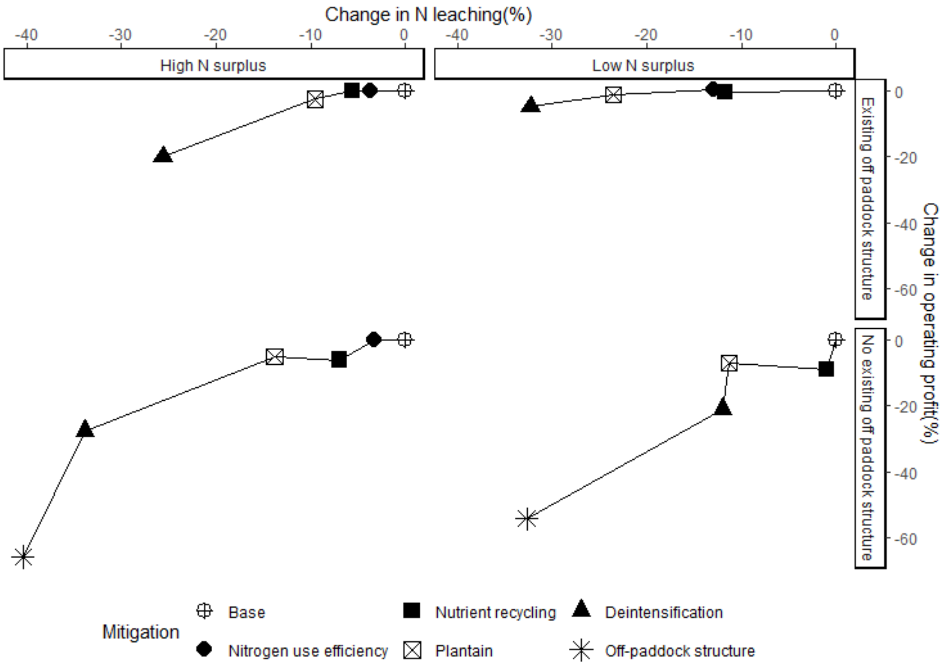

Figure 1 Mitigation abatement curves for aggregated high and low purchased N surplus farms with and without stand-off structures.

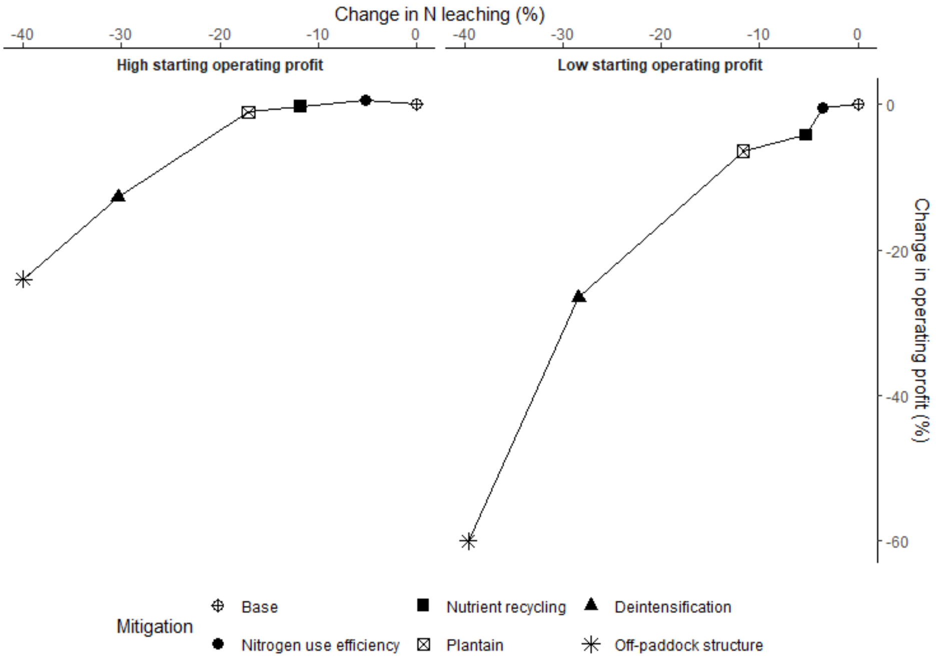

Figure 2 Mitigation abatement curves for aggregated high and low starting operating profit.

potential and the MAC of N leaching reduction strategies for the 18 case study farms. The x-axis (horizontal) represents the percentage reduction in N leaching (abatement potential, % N leaching reduced). The wider the MACC bar, the greater the abatement potential. Y-axis (vertical) shows the MAC; the cost per unit of pollution reduction ($ per kg N reduced). The cost-beneficial strategies have negative or low-cost measures; they save money or have minimal costs per unit of N leaching reduction; the MACC bar sits on or is below the x-axis and is on the left side of the graph. Expensive strategies have high-cost measures. they are less economical but may be necessary for compliance or sustainability goals; the MACC bar is above the x-axis and on the right-hand side of the graph. For both high and low purchased N surplus farms, the MAC for N use efficiency as a strategy was below zero, showing it is a cost-saving approach that reduces N leaching. It was particularly effective in high purchased N surplus farms with a negative MAC, providing an economical way to lower emissions.

Nutrient recycling was also a low-cost strategy across different farm types, especially on farms with existing infrastructure. However, farms without off-paddock structures, and limited effluent infrastructure incurred additional costs to implement nutrient recycling. The aggregated MACC presents the mean range for the MAC (Figure 3 and 4), but there was considerable variation between farms. Nutrient recycling had a MAC ranging from 0 to $27/kg N leaching reduced. Plantain had a moderate MAC ranging from $7.8 to $56/kg N leaching reduced, but a relatively small abatement potential (2-16%). Deintensification was costly for both high and low purchased N surplus farms, though costs were higher for low-N surplus farms. The MAC for deintensification ranged from $23 to $380/kg N leaching reduced. Off-paddock structures were the most expensive strategy in both farm types, but they offered substantial N leaching reductions. The MAC for off-paddock structures ranged from $63 to $380/kg N leaching reduced.

Discussion

The results indicate that mitigation strategies investigated here can significantly reduce N leaching. However, their cost-effectiveness varied depending on farm characteristics, biophysical conditions, and overall profitability. This is consistent with findings from Vibart et al. (2015). The diverse range of case study farms across the two regions provided an evaluation of mitigation strategies under different environmental conditions. Despite considerable variation in the MAC among farms, overall trends revealed that the most cost-effective strategies often involve nutrient recycling, improved N use efficiency, and the use of plantain. In contrast, de-intensification and off-paddock structures were among the most expensive mitigation options. Less profitable farms experience a greater proportional

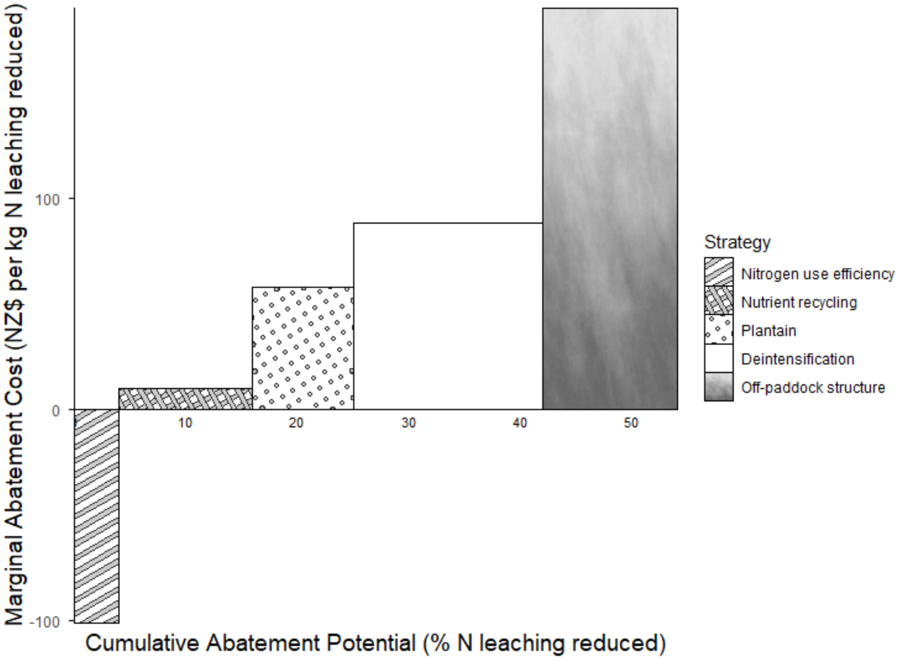

Figure 3 Aggregated marginal abatement cost curve for high purchased N surplus case study farms.

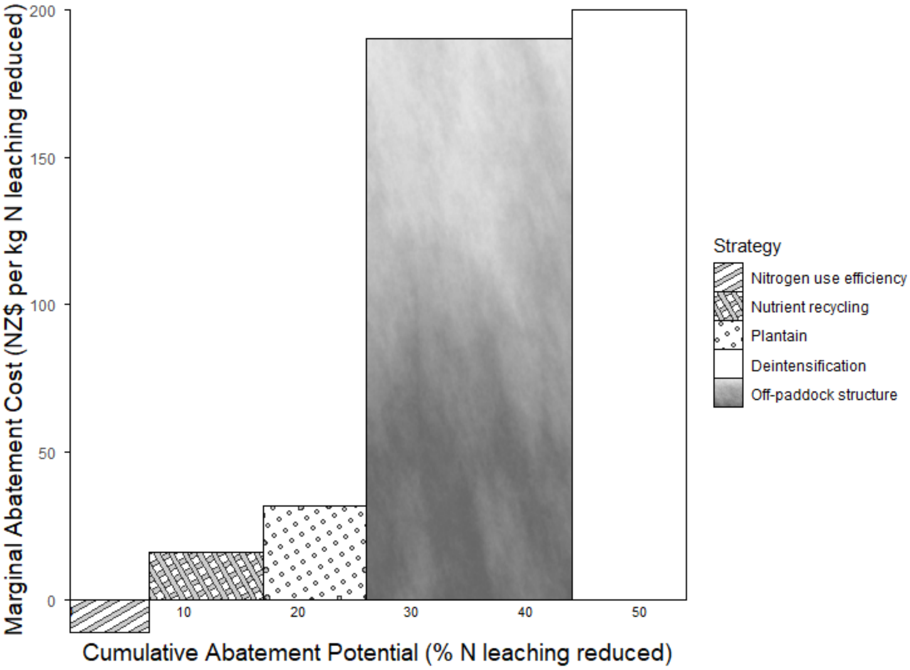

Figure 4 Aggregated marginal abatement curve for low purchased N surplus case study farms.

loss in operating profit, making it more challenging for them to meet financial obligations when adopting mitigation strategies.

Farms with a high purchased N surplus typically had higher N fertiliser use and imported feed (Table 1 and 2). High purchased N surplus did not always correspond with high leaching levels, as outcomes are also influenced by factors such as soil type and rainfall conditions largely beyond the farmer's control. In contrast, N inputs are a key component of the system that farmers can actively manage. These characteristics offer greater opportunities for initial cost-effective N leaching reductions. These farms benefited from improved N use efficiency (i.e. more efficient N management), leading to reduced N input costs for fertiliser and feed, and hence retained their profitability after mitigation. These farms could reduce N leaching by about 10% on average with little or no cost. Nutrient recycling and improved N use efficiency consistently emerged as key cost-effective strategies for reducing N leaching on all the selected case study farms. These strategies complement the reduction of imported synthetic N fertiliser, through better recycling nutrients that are already in the system. On farms with a low purchased N surplus and no off-paddock structures, nutrient recycling and N use efficiency improvements provided minimal benefits since these farms already operate with low N external inputs, and because they needed capital investment in infrastructure to enable greater nutrient recycling.

De-intensification, which involved lowering input use (e.g., fertilisers, feed supplements, crops) then consequently reduce cow numbers and milk production, was generally a costly mitigation strategy. Fewer inputs and animals in most cases resulted in lower total milk production, leading to reduced revenue unless compensated by higher product prices or could maintain same total milk production with fewer animals. However, many farm costs (e.g., infrastructure, equipment, land leases, weed and pest, depreciation, labour) remained fixed, as reducing production does not necessarily lower expenses proportionally. Some farms operate at optimal efficiency for their system. Reducing herd size may lead to inefficiencies in feed utilisation, pasture use and resource allocation. For example, for lowly stocked, low purchased N surplus farms such as Farm 8 (1.2 cows/ha) in the Horizon region and Farm 11 (2.5 cows/ha) in the Hauraki region, further de-intensification and purchased N surplus reduction became economically unviable.

Existing farm infrastructure also influenced the cost-effectiveness of mitigation strategies. If anything, the farms with existing infrastructure could had previously made those investments to address other aspects of their farm system such as improving feed utilisation or minimising pugging damage and can now extend those benefits to reducing N leaching. In contrast, farms without such infrastructure would need to invest in it primarily to meet leaching reduction goals. Farms with infrastructure could optimise their use and recycle more captured nutrients, with little or no added cost. Farms without infrastructure faced higher upfront costs, leading to higher MAC for capital-intensive mitigations. However, for farms already feeding maize in the paddock, introducing infrastructure complemented the existing farm system, and increased feed utilisation, integrated manure as a nutrient source for maize crops, and enhanced the cost-effectiveness of mitigation measures. This aligned with findings from Beukes et al. (2022).

Larger farms (e.g., those with over 400 cows) could benefit from scale by building the required infrastructure for only half their number of cows, then alternate the cows using the feed pad, significantly reducing costs. However, smaller farms with fewer than 400 cows might have to bear the full cost if it is not practical to split the herd. For instance, Farm 18 could halve the feed pad cost, utilise existing maize crops more efficiently, and recycle manure as fertiliser, making this mitigation strategy more cost-effective than deintensification. For low-input farms with little to no supplemental feeding, a feed pad is not practical. As a result, an expensive off-paddock stand-off pad option becomes necessary, with nutrient recycling and reduced pasture damage as the only benefits. The reduction in N fertiliser from captured urine and dung did not offset the running costs of the system on any of the farms.

Conclusion

This analysis highlights that while mitigation strategies analysed here could effectively reduce N leaching, their cost-effectiveness depended on how they complemented the existing farm system. Despite considerable variation in the MAC among farms, overall trends revealed that the most cost-effective strategies often involved nutrient recycling, improved N use efficiency, and the use of plantain. In contrast, deintensification and off-paddock infrastructure were among the most expensive mitigation options. However, off-paddock infrastructure in some cases became cost-effective when it complemented the existing farm system. The results of this study indicate significant reductions in N leaching are possible, but their cost-effectiveness varied considerably depending on farm characteristics, biophysical conditions, and original profitability. Our findings emphasise the need for farm-specific mitigation strategies to balance environmental sustainability with economic viability.

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