

Simulating farm system implications of incorporating plantain (*Plantago lanceolata* L.) into dairy pastures across four regions

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Abstract

Understanding the farm system impacts of narrow-leaved plantain (*Plantago lanceolata* L.) is important for supporting farmer adoption to reduce nitrogen (N) leaching from pastoral farming. This modelling used observed herbage accumulation rates and nutritional composition data from pastures across New Zealand comprised of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) without plantain or with plantain at 11% to 32% (averaging 25%) of sward DM. Regional dairy farm systems were simulated using the Whole Farm Model and Urine Patch Framework to investigate the implications of plantain mixed pastures for pasture yield, milk production, profitability, N leaching, and greenhouse gas emissions. Inclusion of plantain did not impact milk production and maintained or slightly increased pasture yield. Operating profit averaged \$11/ha (1%) lower with plantain due to changes in the seasonal pasture supply curve, requiring additional conservation of surplus pasture and additional supplementary feeding during feed deficits. Inclusion of plantain reduced N leaching by 11% to 19%. The reductions in N leaching without significant negative trade-offs make plantain an attractive option for wide-scale adoption. Farmers should consider the potential for changes in seasonal pasture supply and the need for regular re-sowing of plantain due to low persistence in most perennial ryegrass-white clover swards.

Keywords: bio-economic modelling, nitrogen leaching, operating profit, pasture supply

Introduction

Narrow-leaved plantain (*Plantago lanceolata* L.), and specifically the cultivars certified Tonic and Agritonic, have been shown to offer a low-cost, high-impact option for reducing nitrogen (N) leaching (Pinxterhuis et al. 2024; Egan et al. 2025). In the Manawatu over four years, measured N leaching was on average 26% lower from perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) pastures with plantain constituting 25%

of the sward DM and 17% of diet DM, compared with perennial ryegrass-white clover alone (Nguyen 2023). Under irrigation in Canterbury, similar pastures containing on average 17% of sward DM as plantain reduced N leaching on average by 33% over three years compared with perennial ryegrass-white clover alone (DairyNZ 2026a). Reduced leaching is driven by reduced urinary N concentration due to greater urine volume (Eme and Roche 2025) and partitioning of more consumed N away from urine and into faeces and milk (Minnée et al. 2020). Research is showing that further reductions (yet to be fully quantified) from plantain-augmented pastures are possible via nitrification inhibition and reduced drainage in the soil (Carlton et al. 2019). However, at present only the first two “animal mechanisms” are included in farm system models that predict N leaching losses.

Inclusion of plantain in grass-clover pastures can only be effectively promoted for adoption as an N leaching mitigation if there is good understanding of the implications for the farm system. Important considerations for farmer decision making include potential impacts on pasture growth rates and yield, milk production, profitability, and greenhouse gas emissions. Previous work on incorporating plantain-augmented pastures into the farm system either assumed no difference in growth rates and yield compared to standard ryegrass-clover pastures (Beukes et al. 2020; Chikazhe et al. 2023) or relied on limited data sets from one or two dairy regions (Beukes et al. 2014; Romera et al. 2017a). Although Doole et al. (2021) suggest positive effects of plantain-augmented pastures for dairy profitability, they do acknowledge additional establishment costs and that plantain will alter the seasonal pasture supply profile, with higher summer production and lower winter production relative to standard ryegrass-clover pastures. These implications need to be evaluated across different regions, soils, farm systems, climates, and economic parameters before conclusions can be drawn and messages developed to support on farm adoption.

The objective of this farm systems modelling

study was to estimate impacts of plantain inclusion on production, profitability, and environmental outcomes across different soils and climates representing four New Zealand dairy regions.

Materials and Methods

Observed monthly pasture herbage accumulation rates and nutritional composition data from grazed and/or cut agronomic trials across four regions: Waikato, Manawātū, Canterbury, and Southland, were input to scenarios in the Whole Farm Model (v 8.2.y; Beukes et al. 2008) representing regionally relevant farm systems.

Pasture herbage accumulation rates and nutritional composition data

Observed monthly pasture herbage accumulation rates and nutritional composition data from multiple sources in each of the four regions were used. The data were from comparisons of pastures comprised of either perennial ryegrass (STD-R) versus equivalent pasture with the addition of plantain (PLA-R) or perennial ryegrass and white clover (STD-RC) versus equivalent pasture with the addition of plantain (PLA-RC). Nutritional composition data required as model inputs included contents of: DM, crude protein (CP), fat, starch, water soluble carbohydrates (WSC), neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin, ash, soluble crude protein (CPS), and rumen undegradable protein (RUP). Where possible, nutritional composition data from the same source as the pasture herbage accumulation rate data were used and this is specified in the following regional data sections. In cases where some or all the required nutritional composition data were not available, two alternative sources were used. Firstly, values for DM, CP, fat, starch, WSC, NDF, ADF, lignin, and ash content were sourced from existing default values in the WFM database (Beukes et al. 2014), with perennial ryegrass and white clover pasture data used for STD and pasture also containing herbs used for PLA. The existing default values in the WFM database had been derived from measurements in two multi-year (2010 to 2013) grazed plot trials in the Waikato and Canterbury with plantain growing in a mixed sward (Nobilly et al. 2013; Woodward et al. 2013). These previous studies did not provide CPS and RUP values; therefore, these CPS and RUP values were obtained from a second alternative source: cut perennial ryegrass and plantain monoculture plots. A weighted average of region-specific 2023 data from these plots was used (N. Hammond unpubl. data), with weighting in accordance with the plantain content of the source of the pasture herbage accumulation rate data.

Waikato

Herbage accumulation rate data were available from a cutting pasture plot trial near Ngāhinapōuri

(-37.915891S, 175.192994E), for the period 2021-23 (S. Mackenzie unpubl. data). This site included two soil orders, gley and allophanic, and the comparison on each was STD-R vs. PLA-R. The annual pasture yields from these plots were uncharacteristically low for the Waikato region at around 10-11 t DM/ha, for both STD-R and PLA-R pastures. The AgPasture model (v2.0.4.1) was run within the WFM (v8.4.n) using 2021-23 Ruakura weather station data (Earth Sciences New Zealand 2025) to generate a more characteristic pasture growth profile yielding 13.5 t DM/ha/year for the STD-RC pasture. These monthly pasture growth rates from AgPasture were then adjusted to generate a profile representing the PLA-RC pasture by utilising the relative percentage differences in monthly herbage accumulation rate from the Ngāhinapōuri pasture plot data. For these adjustments, differences were explored by comparing STD-R growth with plots targeting 15%, 30%, and 100% of sward DM as plantain. Using both comparisons and the STD-R pasture growth profile from AgPasture, a PLA-RC pasture growth profile representing 25% of sward DM as plantain was generated. Contents of pasture DM, RUP, and CPS were available from the plot trial. The remaining nutritional composition parameters were obtained from the WFM database.

Manawātū

The first dataset of monthly pasture herbage accumulation rates was available for the period 2020-2023, from a grazed plot trial at Massey University Number 4 dairy farm near Palmerston North (40.394068S, 175.609064E, Nguyen 2023, S. Wilson unpubl. data). The comparison was STD-RC vs. PLA-RC, where PLA-RC pasture contained 18% to 32% of sward DM as plantain across the three years. The trial was conducted on a Tokomaru silt-loam with tile drains. The farmlet trial pasture data included NIRS derived pasture contents of DM, CP, fat, starch, WSC, NDF, ADF, lignin, and ash.

A second set of monthly pasture herbage accumulation rate data were available from a cutting plot trial near Cheltenham (40.133532S, 175.655122E) running from 2021 to 2023 on a Pallic moderately well drained soil (S. Mackenzie unpubl. data). The comparison was STD-R vs. PLA-R, where PLA-R pastures targeted three plantain contents (15%, 30%, 50% of sward DM) and the herbage accumulation rates of the PLA pastures differed from STD. However, there were no consistent differences between plantain treatments and thus an average of growth data from the PLA pastures were used and a plantain content of 25% of sward DM assumed to be near the maximum content achievable long term on farm. The dataset included pasture DM, CPS, and RUP contents.

A third monthly pasture herbage accumulation

rate dataset was available from pasture cage cuts on a commercial farm in the Taranaki district, for the period 2020-2021 (Dodd et al. 2022). The farm has a dominant allophanic well-drained soil type. The comparison was STD-RC vs. PLA-RC with the PLA-RC pasture averaging 25% of sward DM as plantain, and DM content data were available.

Canterbury

Monthly pasture herbage accumulation rate data based on pasture mass estimates using the winter rising plate meter calibration formula (DairyNZ 2025a) were available from a farmlet trial at the Lincoln University Research Dairy Farm (43.639424S, 172.461195E) for the period 2021-2024, on a Templeton/Barrhill/Wakanui imperfectly to well-drained silt loam (O. Al Marashdeh unpubl. data). The comparison was STD-RC vs. PLA-RC, with the PLA-RC pasture containing on average 24%, 17% and 11% of sward DM as plantain for the three years, respectively. Nutritional composition data were available for DM, CP, NDF, ADF, and WSC from near infrared spectrometry (NIRS) analysis.

A second monthly pasture herbage accumulation rate dataset was available from a two-year cutting plot trial on a Pallic soil near Lincoln (43.611687S, 172.468924E) for the period 2022-2024 (S. Mackenzie unpubl. data). The comparison was STD-R vs. PLA-R, where the PLA-R pastures averaged 28% and 11% of sward DM as plantain in the first and second years, respectively. The dataset included DM content.

Southland

Monthly pasture herbage accumulation rate data based on pasture mass estimates using the winter rising plate meter calibration formula (DairyNZ 2025a) were available from pastures at the Southern Dairy Hub research farm (46.311524S, 168.309403E) for the 2023-24 production year (Southern Dairy Hub 2026). The site is located on a deep, well-drained orthic brown soil, and compared STD-RC vs. PLA-RC, with PLA-RC pastures averaging 15% of sward DM as plantain. Data were available from the farm pastures for DM content and for CP, ADF, NDF, WSC, starch, and lipid from NIRS analyses.

A second dataset of monthly pasture herbage accumulation rates was available from a two-year, 2022-2024, cut plot trial in Edendale (-46.341624S, 168.781121E) on a brown, well-drained soil (S. Anderson unpubl. data). The comparison was STD-R vs. PLA-R and the plantain content of the PLA-R pasture was 26% and 12% of sward DM in the first and second year, respectively. The dataset included pasture DM content.

Whole Farm Model scenarios

The WFM was used to compare differences between

STD and PLA pastures for key farm performance metrics: pasture yield, milksolids (MS) production, N leaching, greenhouse gas emissions (GHG, estimated in WFM using New Zealand specific emission factors) and operating profit (OP).

Scenarios were established in the WFM based on real commercial or research farm data to simulate a representative spring-calving farm system for each of the four regions. For the Waikato, data from the Control farmlet at Scott farm, Hamilton were used (Farrell et al. 2025a). For the Manawatu, the farm system type was informed by data from a commercial farm extracted from DairyBase (DairyNZ 2026b), with soil type and supplementary feed type informed by data from the Massey University No. 4 Dairy Farm (Nguyen 2023). For Canterbury this was 2021-22 data for the standard perennial ryegrass-white clover treatment farmlet at the Lincoln University Research Dairy Farm (Hintz et al. 2026). For Southland, data from the standard intensity, fodder beet wintering farmlet at the Southern Dairy Hub were used (Southern Dairy Hub 2026).

The observed monthly herbage accumulation rate data for STD and PLA pastures were input to the WFM (Table 1), with data from different sites and years input separately. To capture farm-level impacts of the different pasture supply curves, management policies were used that conserved pasture during a feed surplus and used supplementary feed to fill a feed deficit, and the associated costs were included in modelled farm working expenses and OP. In the PLA scenarios an additional cost was included for plantain seed at pasture renewal, and for maintaining sward plantain content by over-sowing plantain seed via fertiliser applications. The pasture renewal cost reflects the replacement of 4 kg/ha of perennial ryegrass seed with superstrike-treated plantain seed, calculated with a seed cost of \$21.70/kg minus the ryegrass seed cost of \$17.00/kg on 10% of the milking platform. Seed costs were based on 2025 retail values (PGG Wrightson 2026). The oversowing cost reflects the decline in sward plantain content two or three years after sowing (Dodd et al. 2022) and was assumed to require oversowing on one third of the milking platform annually with 8 kg/ha prill-coated plantain seed (equivalent to ~4 kg/ha bare seed) at a cost of \$11.40/kg. The total annual plantain seed cost was \$32.00/ha, based on \$19.00/ha for 10% of the farm, \$91.20/ha for 33% of the farm, and no cost for 57% of the farm. Three years of farm financial data were used to estimate farm OP: 2020-21, 2021-22, and 2022-23, with milk prices of \$7.47/kg MS, \$9.28/kg MS, and \$8.69/kg MS, respectively (DairyNZ 2025b).

The WFM scenario outputs were input to the Urine Patch Framework (Romera et al. 2012) which predicts N leaching through accounting for all urination events, urine patch overlaps, soil conditions, rainfall, soil

Table 1 Summary of scenarios run in the Whole Farm Model and Urine Patch Framework, where the soil type and climate year (1 June - 31 May) were simulated to match the year that the observed herbage accumulation rate data was collected. Each scenario was modelled with three financial years.

Region	Farm system data source	Pasture data source	Soil type
Waikato	Scott Farm	Cut plots. 2022	Allophanic moderately well-drained
Manawatu	DairyBase commercial farm and Massey University No. 4 Dairy Farm	Grazed plots. 2021; 2022; 2023	Pallic poorly drained
		Cut plots. 2022	Pallic moderately drained
		Commercial farm. 2021	Allophanic moderately well-drained
Canterbury	Lincoln University Research Dairy Farm	Farmlet study. 2022; 2023; 2024	Pallic and Brown imperfect to well-drained
		Cut plots. 2023; 2024	Pallic moderately drained
Southland	Southern Dairy Hub	Research farm. 2024	Orthic brown well-drained
		Cut plots. 2023; 2024	Brown well-drained

drainage, plant uptake of moisture and N, fertiliser applications, and irrigation events. Climate data from Ruakura, Palmerston North, Lincoln, and Invercargill were used for the Waikato, Manawatu, Canterbury, and Southland scenarios, respectively (Earth Sciences New Zealand 2025). The N leaching estimates were made from a soil depth of around 550 cm, which is regarded as below the ryegrass root zone (Romera et al. 2012).

Results

National

The relative differences in key performance metrics for PLA pastures versus STD pastures, averaged across regions, soils, climate and economic years are shown in Table 2. Overall, PLA pastures had slightly higher annual pasture yield than STD (0.3 t DM/ha, i.e., 2% greater) due to the higher growth rates through late-spring, summer and early-autumn (Table 3). The greater warm season PLA pasture growth rates were somewhat offset by slower growth rates through the cooler winter months. Differences in annual milk production and GHG emissions were minimal. On average N leaching was reduced by 5 kg/ha (17%) for PLA pastures. OP was \$11/ha lower, indicating that most of the \$32/ha cost for plantain seed was mitigated by profit gains from changes in the pasture supply curve. Some of this gain is due to the late spring-early summer pasture surpluses allowing greater quantities of pasture to be conserved (486 and 456 kg DM/cow/year of pasture conserved for PLA and STD, respectively). This conserved pasture was able to be utilised as a low-cost feed during pasture deficit periods. Conversely, PLA pastures had lower growth rates than STD during cooler autumn and winter months, leading to a larger feed deficit early in the milking season. Accordingly, use of the additional conserved pasture resulted in a minimal increase in

feed costs (\$1.63 vs \$1.61/kg MS for PLA and STD, respectively) and farm working expenses (\$6.33 vs \$6.32/kg MS for PLA and STD, respectively).

Regional

The largest difference in OP with the PLA pastures was predicted for the Waikato region (\$145/ha, i.e. 5% greater Table 2). Though the winter growth rates of PLA pastures in the Waikato were relatively low, which created a noticeable feed gap with the late-June start of calving, use of conserved pasture from a summer-autumn surplus resulted in feed related expenses being \$0.06/kg MS lower than with STD pasture. For the Manawatu, summer pasture growth was greater with PLA pastures but impacts on annual pasture yield and OP were small, i.e., OP \$16/ha lower. The \$87/ha, i.e., 2%, lower OP with PLA pastures for Canterbury was driven by the 0.2 t DM/ha lower annual pasture yield and costs associated with sowing plantain. Southland appears to be well suited to plantain pastures, with a substantial increase in annual pasture yield and winter growth compared with STD pastures, translating to an OP gain of \$72/ha, i.e. 2% (Table 2 and Table 3). Predicted N leaching reductions with PLA pastures ranged from 11% in the Waikato to 18% and 19% for the Manawatu and Southland, respectively.

Discussion

This study used various sources of herbage accumulation rate data, which confirm that including plantain in perennial ryegrass-white clover dairy pastures maintains annual pasture yield, with lower growth in winter and early spring and higher growth in summer and autumn, particularly under dry conditions (Dodd et al. 2025). The exception in the current study was the increased June pasture growth from including

Table 2 Average differences in modelled key farm performance metrics based on inputting observed herbage accumulation rate data from perennial ryegrass and white clover pastures with or without plantain inclusion at 11% to 32% (averaging 25%) of sward DM. Results are combined across soils, climate and economic years. Absolute differences and relative differences (%) for inclusion of plantain versus no plantain are given.

	Waikato	Manawatu	Canterbury	Southland	Overall
Pasture yield (t DM/ha)	+0.5	+0.4	-0.2	+1.0	+0.3
Pasture yield (%)	+4	+3	-1	+6	+2
Milksolids (kg/ha)	-2	+6	+10	-6	+4
Milksolids (%)	0	+1	+1	0	0
N leaching (kg/ha)	-4	-7	-5	-4	-5
N leaching (%)	-11	-19	-15	-18	-17
GHG (t CO ₂ -eq/ha)	-0.2	-0.1	0.0	-0.2	-0.1
GHG (%)	-1.3	-0.4	+0.2	-1.3	-0.5
Feed related expenses* (\$/kg milk-solids)	-0.06	+0.04	+0.03	+0.02	-0.02
Feed related expenses (%)	-3	+1	+2	+1	+1
Farm working expenses (\$/kg milk-solids)	-0.06	+0.05	+0.02	+0.06	-0.01
Farm working expenses (%)	-1	-1	+0	+1	0
Operating profit (\$/ha)	+145	-16	-87	+72	-11
Operating profit (%)	+5	+2	-2	+2	+1

*Expenses for purchased feed, pasture conservation, and cropping

Table 3 The average difference in daily herbage accumulation rates (relative %) across months as a result of including plantain at 11% to 32% (averaging 25%) of sward DM in perennial ryegrass-white clover pastures. Values are averaged across soils and climate years for four dairy regions.

Month	Waikato	Manawatu	Canterbury	Southland
Jun	- 4	- 15	- 4	+ 26
Jul	- 4	- 7	+ 1	- 8
Aug	- 4	+ 7	- 8	+ 9
Sep	+ 1	0	- 7	0
Oct	+ 1	0	- 1	+ 10
Nov	+ 1	+ 6	+ 9	+ 3
Dec	+ 10	+ 12	0	+ 14
Jan	+ 10	+ 6	+ 11	+ 11
Feb	+ 10	+ 13	+ 9	+ 14
Mar	+ 12	+ 6	- 1	+ 3
Apr	+ 12	- 2	- 9	0
May	+ 12	+ 1	- 3	0

plantain in Southland pasture, which should be interpreted cautiously as the broader dataset used in the study supports the overall trend described above. Two herbage accumulation datasets, from Canterbury and Southland, used the winter rising plate meter equation, which may have influenced estimated pasture herbage mass and calculated accumulation rates in plantain-containing swards (Al-Marashdeh et al. 2026). This should be considered when basing plantain pasture growth estimates on rising plate meter data.

Incorporating observed pasture herbage accumulation rate datasets into a whole farm bio-economic modelling exercise demonstrated that there was minimal impact on milk production, GHG emissions and operating profit, which aligns with previous controlled farm system studies. In Ireland, Minogue et al. (2025) observed similar results, with 6% lower daily MS yield in early lactation and 9% higher MS yield in late lactation when including plantain in perennial ryegrass and white clover pastures. In a replicated farm system study in Canterbury, Hintz et al. (2026) observed similar MS production and estimated profitability for perennial ryegrass and white clover pastures with and without plantain. The potential reduction in winter and early spring growth rates observed when including plantain at 30% of sward DM were also modelled by Chikazhe et al. (2023) as part of simulating stacked N mitigations

for a Canterbury system. They predicted that additional requirements for imported feed to fill a feed deficit due to low winter growth rates would reduce operating profit by 5% but they did not assume any other changes in pasture supply.

The current study also indicated benefits in terms of lower N leaching losses with PLA pastures (Table 2), consistent with Chikazhe et al. (2023) who modelled an 18% lower N leaching loss. These levels of N leaching reduction are based on inclusion of the well-demonstrated “animal mechanisms” in models, i.e., urinary N dilution and reduced urinary N partitioning (Eme and Roche 2025). There is evidence of additional N leaching reducing “soil mechanisms” associated with biological nitrification inhibition activity (Pinxterhuis et al. 2024) and reduced drainage rates (Egan et al. 2025). Understanding and quantifying this “soil effect” is a key topic of the current Plantain Potency and Practice programme (DairyNZ 2026a). Addition of such effects to N dynamic models such as Overseer and Urine Patch Framework can be expected to increase their predictions of N leaching reduction associated with incorporation of plantain in the dairy farm pasture feed base.

These modelling studies support the idea that plantain is a low-cost N leaching mitigation that should be considered by farmers after good management practice options have been implemented, and before more expensive mitigations such as de-intensification and off-paddock infrastructure are considered. Chikazhe et al. (2025) have modelled the marginal abatement costs of various N leaching mitigation options for Hauraki District and Horizons Region case study dairy farms and predicted plantain to have marginal abatement costs ranging from \$8 to \$56 lower OP per kg of N leaching reduced, reducing N leaching by 2% to 16% from the baseline level. That study classified plantain as being amongst the most cost-effective mitigation options, together with implementing good management practices around nutrient recycling and improved N use efficiency. The marginal abatement costs from the current study showed variability across regions, from gains in OP per kg of N reduced of \$18 and \$36 for Southland and Waikato to OP losses of \$2 and \$17 per kg of N reduced for the Manawatu and Canterbury, respectively (Table 2). These latter losses are low to moderate abatement costs compared with options such as de-intensification and off-paddock infrastructure (Chikazhe et al. 2025; Romera et al., 2017b).

While N leaching can be most effectively managed at the scale of individual farms, where management decisions are made, the resulting water quality problem occurs at a catchment scale. The value of plantain as an N leaching mitigation option has also been demonstrated in farm and catchment scale modelling

by Farrell et al. (2025b) and Fransen et al. (2025). These previous studies showed that at catchment scale, the inclusion of plantain in the pasture base at 20% of sward DM achieved an average N leaching reduction of 31% for 26 dairy farms with a saving in dairy operating profit for the catchment of \$500,000 per year compared with achieving the same N leaching reduction without use of plantain.

Practical implications

This modelling study demonstrated the value of including plantain in the pasture feed base to achieve substantial farm N leaching reductions without significant negative trade-offs for productivity, profitability, or GHG emissions, making plantain an attractive option for wide-scale adoption. Key aspects that farm managers should consider include the likely changes in seasonal pasture supply and the need for regular re-sowing of plantain due to low persistence of plantain in most perennial ryegrass-white clover swards.

ACKNOWLEDGEMENTS

This research was conducted as part of the DairyNZ-led Primary Sector Growth Fund Plantain Potency and Practice Programme, funded by DairyNZ, Ministry for Primary Industries, Fonterra and PGG Wrightson Seeds. This work benefitted from our consultation with fellow project members including Kate Fransen, Ina Pinxterhuis and Tai Chikazhe.

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