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# Plantain (*Plantago lanceolata*): from weed to multi-functional component in sustainable dairy-farm systems

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## 1 Introduction

Narrow-leaved plantain (ribgrass, *Plantago lanceolata* L.) has long been a common adventive species in managed grasslands globally. Its value as a livestock forage was enhanced with the development of productive and erect cultivars from the mid-1990s. Another major development has been the observation of its effect in reducing livestock urinary-nitrogen concentration. Low tissue dry matter content has been verified as the main contributor to this, but studies also point to effects of plant characteristics on livestock nitrogen partitioning and reduced drainage and rate of nitrification in soils. This functionality provides a way of mitigating nitrogen losses to air and water in intensive, pasture-based livestock systems that is relatively simple to implement.

This chapter summarises the broad characteristics and uses of modern forage plantain and identifies scope for research relating to management

for persistence, effects on animal health and milk composition and a better understanding of the biochemical mechanisms behind nitrogen cycle effects.

## 2 Nitrogen loss from grazed pastures

Nitrogen (N) losses to the environment, notably nitrate leaching (contaminating groundwater and surface water) and nitrous oxide emission (a potent greenhouse gas), remain important unwanted impacts of productive, intensively grazed pastures. Over time, increased use of synthetic N fertiliser has increased pasture production and animal N intake per hectare, increased animal production and increased associated N losses to the environment (Chapman and Parsons, 2017; Pinxterhuis et al., 2015; Van der Meer and Van Uum-Van Lohuyzen, 1986). Additionally, this system inefficiency has economic consequences for farms and is also associated with indirect greenhouse gas emissions through energy use for production and transport of synthetic N fertilisers. Examples for farm-scale N use efficiency (NUE, the ratio of N in product: N in inputs) and N surplus (the difference between N in inputs and N in product) of well-managed dairy farms in New Zealand, Ireland and The Netherlands were given by Pinxterhuis et al. (2015), with NUE varying between 32% and 50% and N surplus between 73 kg N/ha and 257 kg N/ha, including N inputs from fertiliser, imported supplementary feeds, and N<sub>2</sub> fixation via legumes, rainfall, irrigation and deposition. This leaves large amounts of N at risk of loss to the environment.

Sown pastures comprised of perennial ryegrass (*Lolium perenne* L.) and N-fixing white clover (*Trifolium repens* L.) are often N deficient for maximum herbage yield, if no N fertiliser is used (Gray, 2023). However, these pastures have shown high herbage yields relative to grass-only swards with no or low N fertiliser application rates. For example, this unfertilised two-species pasture attained herbage dry matter yields equivalent to perennial ryegrass monoculture fertilised at 300–600 kg N/ha/year in New Zealand (Ball and Field, 1985). At three sites in Europe, perennial ryegrass/white clover/red clover (*Trifolium pratense* L.) pastures with N fertiliser at 70–150 kg N/ha/year produced equal or more herbage dry matter (19–29 t DM/ha/year) than perennial ryegrass only with approximately double the N fertiliser inputs of 165–350 kg N/ha/year (17–30 t DM/ha/year; Collins et al., 2014). High herbage yields and grazing of perennial ryegrass/white clover or N-fertiliser grass swards result in high levels of N returned to the soil via death and decay of roots and stubble and via animal excreta. Whitehead (1986) estimated these pathways amount to 200–350 kg N/ha/year for death and decay of roots and stubble and 150–300 kg N/ha/year for animal excreta at harvested yields of 10–12 t DM/ha/year. Soil biological processes determine the proportion of this cycling N that is lost, either to the atmosphere or via drainage below the reach of plants.

The urine excreted by grazing stock has long been identified as the main source of N loss from grazed pastures due to the uneven distribution of relatively high N loads (Ball et al., 1979; Corré et al., 2014; Di and Cameron, 2002; Garwood and Ryden, 1986). The benefits of N leaching of reducing urine patches by standing animals off pasture have been well documented (Beukes et al., 2017; Wachendorf et al., 2004). However, this requires capital investment and maintenance of infrastructure and feeding systems, which increases costs of production and reduces profitability, even if the potential benefit of less pasture damage in wet conditions is considered (Beukes et al., 2013; Laurenson et al., 2016; Laurenson et al., 2017).

Alternative forage options present another means of reducing nitrate leaching and nitrous oxide emission from grazed highly productive pasture. This may be at lower cost and higher profit than systems with off-pasture infrastructure or systems with substantially lower overall N inputs and consequently lower production, such as reported by Ledgard et al. (1997, 2006), Shepherd et al. (2017) and Beukes et al. (2024). Various options have been proposed, such as utilising plants that can maintain high production with lower synthetic N inputs and lower N content (Chapman et al., 2014), plants that reduce urinary N excretion or concentration (Bryant et al., 2019b), or plants that reduce soil nitrification rate (Judson et al., 2018a).

The standard pastures of New Zealand dairy farms consist of perennial ryegrass and white clover mixtures, supplemented with synthetic N fertiliser at rates up to 190 kg N/ha/year, offered to ruminants at the 2–3.5 leaf stage of perennial ryegrass. These pastures frequently have crude protein concentrations of 15–25%, well above animal requirements (Pacheco and Waghorn, 2008). Bryant et al. (2019b) illustrated this with a comparison of crude protein supply versus requirement in pasture-only diets of dairy cows producing 340 kg or 400 kg milksolids per year, which were averages for the Waikato and Canterbury regions of New Zealand, respectively. Only in November (at peak lactation of a spring-calving dairy cow) were demand and supply equal and in other months crude protein concentration could be up to 10 percentage points above demand. Most of the excess N is excreted in urine, resulting in a wide range of reported urinary N concentrations (0.9–20.5 g/L) and N loads in urine patches (200–2000 kg N/ha for cattle; Selbie et al., 2015).

New Zealand research in the period 2005–2015 investigated if the addition of multiple herb species to perennial ryegrass/white clover swards would be beneficial for herbage production, animal production and NUE. Woodward et al. (2012) and Totty et al. (2013) reported similar yields and milk production from multispecies perennial pastures containing ryegrass, white clover and the herbs chicory (*Cichorium intybus* L.) and narrow-leaved plantain (*Plantago lanceolata*; also ribwort plantain, ribgrass, lamb's tongue, forage plantain – plantain hereafter). A potentially beneficial environmental factor was the

reported lower urinary N concentration and urinary N excretion. Beukes et al. (2014) modelled the effects of the observed differences in herbage growth rates and feed composition in the Woodward et al. (2012, 2013) and Totty et al. (2013) studies and indicated N leaching could be reduced by 19% if half the farm area consisted of such grass–clover–herb mixture.

Animal feeding trials provided evidence that adding plantain to perennial ryegrass/white clover pasture lowered urinary N concentration (Cheng et al., 2017). Thus, the focus shifted from diverse grass–clover–herb mixtures to grass–clover–plantain mixtures. Judson et al. (2018a) suggested that plantain was a key species to achieve N leaching reductions via several mechanisms. These included reduced urinary N concentration, reduced partitioning of excreted N to urine and a soil nitrification inhibiting effect of plantain. It was suggested that this could occur both indirectly from urine patches of animals fed plantain and directly from plantain plant material and root exudates. These aspects of the role of plantain in the N cycle have been topics of ongoing research since.

The following sections provide a summary of current knowledge on plantain and are for a large part based on two review papers (Dodd et al., 2025; Pinxterhuis et al., 2024). Recent review papers also summarise current knowledge and confirm the potential of plantain in mitigating N losses to the environment from pasture-based grazed systems (Chesney et al., 2025; Eme and Roche, 2025).

### **3 Introduction to narrow-leaved plantain (*Plantago lanceolata*)**

Plantain has long been seen as a weed species or minor contributor to pasture production, though valued for its animal health benefits (Burke, 2008; Pol et al., 2021; Stewart, 1996). Before research focussed on the effects of plantain on N loss to the environment, varieties of plantain were developed for agronomic attributes. These have been used in grazed pastures in New Zealand since the 1990s when two cultivars were released: Grasslands Lancelot, a prostrate cultivar best suited to close sheep grazing and Ceres Tonic, a more erect cultivar better suited to rotational cattle grazing. Their production and quality in summer-dry environments complemented perennial ryegrass/white clover pasture (Stewart and Judson, 2019) and they were mainly used in the drystock sector in mixtures with clover for finishing young livestock. However, the lack of persistence beyond 2–4 years of improved plantain cultivars as a monoculture forage crop or as a significant contributor in grass-dominant pastures has hampered their widespread use. The widespread use of dicot-specific herbicides in grass–clover pastures has also been a barrier to successful integration.

### 3.1 Growth habit

Wild-type plantain can be found throughout the world in a wide range of environments and is largely a winter-dormant prostrate perennial dicotyledon herb, forming rosettes with growing points emerging from axillary meristems on a crown below the soil surface. It has high phenotypic plasticity and will become more erect to avoid shading in higher vegetation. Commercial selection of genotypes resulted in upright cultivars with improved cool-season growth (Figure 1).

Flowering is initiated in spring when daylight lengthens and seed heads emerge more readily from the second year onwards. Fresh seeds are largely dormant and need after-ripening and cold stratification to germinate. Germination increases with higher temperatures, more light and greater availability of soil N. Plantain establishes relatively slowly in a multispecies sward and is susceptible to competition, particularly in environments conducive to strong grass growth, such as high N fertility, mild temperatures and sufficient soil moisture. Compared with perennial ryegrass, plantain tolerates higher temperatures and moisture stress, lower soil macro-nutrient fertility and lower soil pH.



**Figure 1** Modern genotypes of forage plantain (*Plantago lanceolata* L.) are more productive and upright than wild types. Left wild type, right cultivar AgriTonic.

The root system of plantain is a combination of fibrous roots at the surface and courser roots that can reach >1 m deep in the soil, making the species relatively drought resistant. However, water use efficiency of plantain is lower than that of ryegrass (Neal et al., 2011).

Troelstra et al. (1992) showed that plantain herbage yield increased with increasing N supply, with plants allocating more growth to leaf rather than root material. This partitioning was reversed under moisture stress and low N supply, when a greater proportion of biomass growth was invested in roots (Skinner and Comas, 2010).

### 3.2 Herbage yield

Even though several plantain cultivars are currently commercially available (Dodd et al., 2025), most of the agronomic and N management research has been conducted with Ceres Tonic and more recently its successor, Grasslands Agritonic. This is largely due to the longevity of market availability of Tonic in New Zealand (c. 30 years) and the substantial research investment by its breeder, PGG Wrightson Seeds. Tonic was selected from Mediterranean germplasm for improved cool-season growth, a more upright growth habit (i.e. more harvestable material) and improved grazing tolerance. Grasslands Agritonic has been selected from Tonic germplasm for improved competitiveness in multispecies swards, more resilience when herbicides are used and traits that have been associated with improved NUE (Box et al., 2023b).

Plantain is used in a range of pasture types (for references, see Dodd et al., 2025):

- Monoculture – sown at 10–12 kg/ha, persisting for ~2 years. Perennial or Italian ryegrass (*Lolium multiflorum*) and white clover can be drilled into this monoculture in autumn of the first or second year. Weed invasion can occur in these monocultures. Reported yields in New Zealand varied between 7.5 t DM/ha/year and 20.6 t DM/ha/year.
- Herb–legume mixture – plantain sown at 6–8 kg/ha with clovers and sometimes chicory. High-quality summer-active crop, mainly used in summer-dry non-irrigated systems. Can persist well in these circumstances, without grass competition, but weeds can become a problem. Yields varying from 9.3 t DM/ha/year to 20.8 t DM/ha/year have been reported from New Zealand studies.
- Grass–clover–plantain mixture – perennial ryegrass and white clover sown with plantain at 1–4 kg/ha. Can be sown as a new pasture, or plantain seed can be drilled or over-sown into existing pasture. Provides higher quality summer/autumn forage than perennial ryegrass/white clover swards in summer-dry non-irrigated systems. Reported yields in

New Zealand were 8.9–18.1 t DM/ha/year, which was often higher than that of perennial ryegrass/white clover. This mixture (Figure 2) has been the focus of research in the New Zealand Plantain Potency and Practice programme.

- Multispecies mixture – plantain sown at 1–4 kg/ha with a range of other pasture species. An increasingly used mixture consists of perennial ryegrass, white and red clover, plantain and chicory. Depending on region (climate) and farmer preference, other grasses are added or substitute perennial ryegrass, such as tall fescue (*Festuca arundinacea*), Italian ryegrass, timothy (*Phleum pratense*), cocksfoot (*Dactylis glomerata*), kikuyu (*Pennisetum clandestinum*) and/or prairie grass (*Bromus willdenowii*). Other legumes that may be added to these mixtures are lucerne (*Medicago sativa*) and bird's-foot-trefoil species (*Lotus pedunculatus* and *Lotus corniculatus*). Yields of 11.6–17.9 t DM/ha/year for dairy pastures in Waikato, New Zealand, were reported for multispecies pastures by Woodward et al. (2013), which were similar to perennial ryegrass/white clover. However, yields in summer and autumn were higher than for perennial ryegrass/white clover. Daly et al. (1996) reported yields for multispecies drystock pasture in Canterbury, New Zealand, of 4–11.5 t DM/ha/year, being 10–30% higher than perennial ryegrass/white clover yields. In this study, the benefit was due to higher yields in summer.



**Figure 2** Perennial ryegrass/white clover/plantain pasture in New Zealand.

As with any pasture, large differences in yield exist between regions, years, management treatments and sward types. In general, plantain in grass-based multispecies swards (grass–clover–plantain mixture and multispecies mixture pasture types described above) does not reduce annual average pasture or milk production, compared with perennial ryegrass/white clover pastures at similar N fertiliser rates or perennial ryegrass pasture with higher N fertiliser rates. However, plantain tends to grow less in winter and early spring than perennial ryegrass, but this is compensated for with greater summer and autumn growth, especially in summer-dry conditions (Dodd et al., 2025). Therefore, seasonality in the contribution of plantain to standing herbage in mixtures is often observed, with a greater proportion in late summer/autumn.

The development of a wider range of cultivars by various breeders in the last decade tended to focus on variation in winter growth activity and flowering date. In New Zealand, this started with the release of two cultivars in the 1990s: Ceres Tonic (erect, winter-active with large leaves) and Grasslands Lancelot (semi-erect, low winter growth, medium-to-large leaves; Box et al., 2023a). There have been surprisingly few inter-cultivar comparisons in the published literature. Differences between cultivars in annual and seasonal yield have been shown in South Africa (Ammann et al., 2021) and this is currently also under investigation in New Zealand in the Plantain Potency and Practice Program (DairyNZ: <https://www.dairynz.co.nz/research/science-projects/plantain-potency-and-practice/>).

### **3.3 Forage quality**

A meta-analysis of herbage quality data showed that compared with perennial ryegrass, plantain has similar digestibility, lower percent dry matter, similar total N concentration in dry matter, greater non-structural fibre concentration, and lower concentrations of structural fibre, soluble and degradable N (Minneé et al., 2019; Table 1). Similar results were found in an Irish study (Minogue et al., 2025), though they did not find differences in soluble carbohydrate content.

The concentration of crude protein declines more in plantain in late summer compared with other species such as chicory and ryegrass (Dodd et al., 2022; Kemp et al., 2010). Plantain also has greater concentrations of trace elements than perennial ryegrass, when these are sufficiently available in the soil (Moorhead et al., 2002). However, these herbage characteristics of plantain will have a minor effect on multispecies pasture quality if plantain does not comprise a substantial proportion of the pasture. Plantain/clover mixtures have consistently shown better feed quality than perennial ryegrass/white clover swards in drystock systems, particularly in summer (Cranston et al., 2015a, 2015b; Somasiri et al., 2015), but this may be due to clover making up a higher proportion of the sward in these two-species swards.

**Table 1** Herbage nutritive quality of perennial ryegrass and plantain monocultures. Shown are least square means and upper and lower 95% confidence limits, resulting from a meta-analysis of predominantly New Zealand data

	Perennial ryegrass	Plantain	<i>P</i>
Dry matter (%)	21.1 (19.2–23.0)	14.8 (12.9–16.7)	<0.001
Digestibility (%)	77.8 (n.p.)	77.2 (n.p.)	0.339
Total nitrogen (% of DM)	3.1 (2.7–3.4)	3.2 (2.8–3.5)	0.5207
Soluble N (% of total N)	38.4 (31.8–45.0)	12.0 (5.3–18.6)	0.0012
Degradable N (% of total N)	69.2 (65.9–72.5)	56.0 (52.7–59.3)	0.0011
Neutral detergent fibre (% of DM)	43.1 (40.0–46.2)	28.7 (25.5–31.8)	<0.001
Acid detergent fibre (% of DM)	24.6 (22.7–26.6)	20.8 (18.8–22.7)	<0.001
Non-structural carbohydrate (% of DM)	21.1 (19.6–22.6)	29.9 (28.4–31.4)	<0.001
Ash (% of DM)	10.2 (n.p.)	12.8 (n.p.)	<0.001

Source: Minneé et al. (2019).

Longer grazing intervals generally lead to lower crude protein concentration and higher neutral detergent fibre concentration of plantain (Labreveau et al., 2004, Lee et al., 2015a, Navarrete, 2015). Box et al. (2017) reported no effect of morning versus afternoon harvesting on nutritive value of plantain, compared with higher soluble carbohydrate concentration in the afternoon for perennial ryegrass.

Low palatability of plantain is sometimes cited by dairy farmers observing livestock reluctant to graze it, but this has yet to be experimentally verified. Other farmers report no palatability issues with plantain, especially when livestock have been exposed to it for some time or on a regular basis. There is certainly the potential for old leaf tissue and hardened seed heads to be less palatable, whether as a result of long grazing intervals or the persistence of previously ungrazed material in residual herbage.

### 3.4 Management of grazed pastures

New Zealand pastoral systems are generally based on year-round in-situ rotational grazing of perennial ryegrass/white clover or other multispecies pastures. Forage crops are utilised where pastures do not provide sufficient feed in dry summers or cold winters. In summer-dry regions, plantain monocultures or plantain/clover mixtures have been shown to have greater herbage accumulation in summer and autumn than perennial ryegrass-based swards (Dodd et al., 2022). This marginal gain in forage supply can help fill moisture stress-induced feed gaps.

Optimum grazing management for high yield and improved persistence of plantain is still under investigation. In a field experiment with monocultures,

Lee et al. (2015a; Waikato, New Zealand) reported higher seasonal and annual yields with longer grazing intervals (21.3 t DM/ha grown over 18 months after sowing for defoliation at 150 mm extended leaf height vs. 29.8 t DM/ha for 450 mm extended leaf height). However, stem-to-leaf ratio increased and in-vitro digestibility decreased, indicating a trade-off between yield and feed quality. The effect of residual heights was smaller (26.1 t DM/ha and 24.6 t DM/ha over 16 months for 30–50 mm and 60–80 mm sward height, respectively).

In chicory/plantain/red and white clover mixtures, Navarrete (2015; Manawatū, New Zealand) observed no significant herbage yield difference in two consecutive growing seasons between 2-week and 4-week grazing intervals with dairy cows. The proportion of plantain in this mixture was unaffected by grazing interval but decreased in the second year. In a cutting experiment with herb/clover mixtures, plantain yield was greatest at either a cutting interval of 7 days and a residual height of 75 mm or a cutting interval of 42 days and a residual height of 25 mm; taproot diameter was greater with longer intervals but not impacted by residual height (Cranston et al., 2021).

Cranston et al. (2015b) showed that under a sheep grazing regime of chicory/plantain/red and white clover swards with 3–5-week rotations and low (~4 cm) or high (~8 cm) residuals, the size of plantain's taproot and its water-soluble carbohydrate concentration remained stable over time and between grazing treatments, suggesting that these regrowth intervals were sufficient to maintain root mass and carbohydrate reserves irrespective of post-grazing residuals. In another field study, using monocultures, plantain root non-soluble carbohydrates declined for 14 days post-defoliation in summer and took another 21 days to reach pre-defoliation levels (Lee et al., 2015b). This meant dry matter production was reduced at defoliation intervals less than 35 days. Defoliation height was less influential, indicating that root reserves are more important for regrowth than remaining leaf area.

In a glasshouse study with constructed perennial ryegrass/white clover/plantain swards, increasing defoliation intensity from no cutting (average plant height approximately 40 cm) to cutting to 35 cm, 25 cm, 15 cm and 10 cm residual height above ground level every 2 weeks during spring resulted in the greatest proportion of plantain in the shoot mass in the 25 cm residual height treatment and the greatest plantain shoot production in the 15 cm residual height treatment (Mikola et al., 2001).

In ryegrass-dominant rotationally grazed dairy pastures, managed to standard industry guidelines for ryegrass/clover swards, the plantain proportion of herbage dry matter generally declines within a few years (Dodd et al., 2025). The results of the grazing or cutting experiments summarised above suggest that the optimal rotation length for mixed-species swards containing plantain may be longer than standard practise for ryegrass/clover swards to enable plantain to persist. However, the seasonality of such adjustments is important,

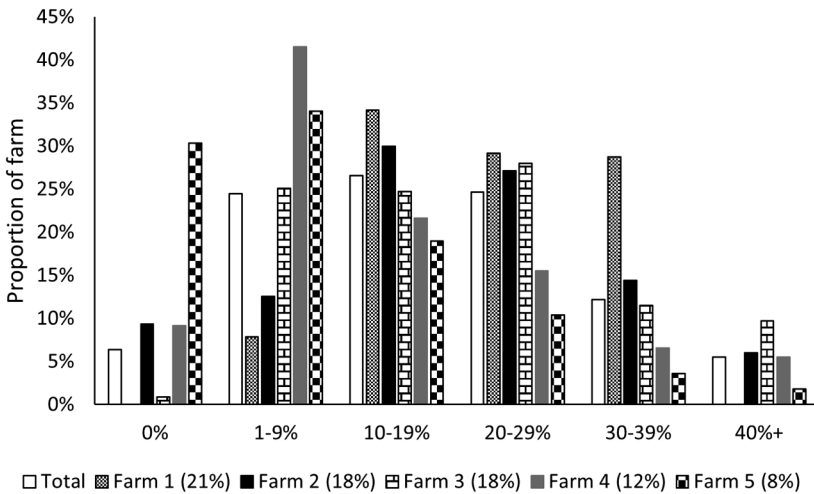
as Wilson et al. (2024) suggested shortening rotation lengths in spring to avoid suppression by the more competitive ryegrass at this time of year.

Modern plantain cultivars establish well in newly sown pastures, but the success of establishment into existing pastures via under-sowing or broadcasting is mixed. Bryant et al. (2019a) showed greater plantain plant survival following an early grazing (21 days cf. 42 days after direct-drilling plantain into an existing ryegrass/clover pasture), when plantain seedlings were small enough to avoid defoliation and shading by existing pasture was reduced. Generally, plantain proportion increases over the first year after sowing into existing grass-dominant swards (Bryant et al., 2019a; Dodd et al., 2017; Hearn et al., 2024b) but rarely contributes more than 15% to herbage mass 2–3 years after sowing. To maintain a moderate proportion of plantain in existing swards that makes a meaningful contribution to seasonal herbage yield and animal intake (e.g. >20%), some New Zealand farmers add plantain seed to fertiliser applications on an annual or biennial basis. In this situation, coated seed reportedly spreads more evenly due to being closer in size and density to the fertiliser granules, i.e. there is less segregation of seed and fertiliser granules during transport or handling (resulting in smaller seed settling beneath larger fertiliser granules), and the seed is thrown as far as the fertiliser granules.

Poor persistence in grass-based swards was also reported for rotationally grazed sheep systems and rotationally grazed and cut beef systems in Ireland (Baker et al., 2023; Grace et al., 2018). Various reasons have been suggested, depending on environmental conditions, such as strong competition from grasses, insufficient replenishment of root reserves, weed ingress, pests and disease pressure, or plant damage from treading under wet conditions (Wilson et al., 2024).

The variable success of plantain establishment and relatively poor persistence in grass-based swards results in large differences in plantain content between paddocks within a farm, as illustrated in Fig. 3. Here, results are shown from five Plantain Potency and Practice Partner farms, where annual over-sowing of plantain across the whole farm is practised (Fransen et al., 2025). This variability makes it impractical to adjust management to plantain content per paddock, and farmers generally manage all paddocks the same.

Weed management when introducing multispecies pastures is challenging, given that most herbicides used in dairy systems target herbaceous dicotyledon weeds. For example, Gawn et al. (2012) showed that flumetsulam controlled broadleaved weeds in herb–clover pastures but severely suppressed plantain initially. It is therefore important to control weeds prior to establishing plantain. Some farmers also control weeds on a 3-year cycle, followed by re-introducing plantain via over- or under-sowing. The plantain cultivar Agritonic was bred to better persist when herbicides are used (Box et al., 2023a) and this has been



**Figure 3** Distribution of Rotorua Lake Partner Farms' farm area across bins of visually assessed plantain content (% of total herbage DM), for autumn 2025. Average plantain content per farm is shown between brackets. Source: Fransen et al. (2025).

confirmed in dose–response experiments with phenoxy herbicides (Shrivastav et al., 2023).

Pests can also be a reason for declining proportion of plantain in pasture. Common pests in New Zealand are plantain moth (*Scopula rubraria* and *Epyaxa rosearia*), the native New Zealand grass grub (*Costelytra zealandica*), porina (*Wiseana* spp.) and slugs (Gerard et al., 2017). Cultivar selection procedures can include pest resistance (Gerard et al., 2018) and targeted insecticides are available (Dodd et al., 2025).

In terms of soil N fertility management, while the wild-type plantain prefers a lower soil N status (Berendse, 1982), modern cultivars are very responsive to added N fertiliser. Using the Ceres Tonic cultivar, Martin et al. (2017a) found plantain had a greater response to N fertiliser than cocksfoot, chicory, perennial ryegrass, white clover and red clover, measured over a 1–4-week regrowth interval of these monocultures during autumn in Canterbury, New Zealand. Measured over a full year at 0–450 kg N/ha, response of plantain was similar to perennial ryegrass (19.8 kg DM/kg vs. 21.1 kg DM/kg N; Martin et al., 2017b). Over three full years in an Irish experiment with ten different pasture mixtures (Hearn et al., 2024a), herbage DM yields were similar for perennial ryegrass/white clover and perennial ryegrass/white clover/plantain pastures. Increasing N fertiliser rates increased annual herbage DM production irrespective of sward mixture (e.g. 9.4 t DM/ha vs. 10.0 t DM/ha for perennial ryegrass/white clover and perennial ryegrass/white clover/plantain, respectively, at 0 kg N/ha/year, and 12.4 t DM/ha vs.

12.3 t DM/ha, respectively, at 200 kg N/ha). No significant N fertiliser rate x pasture mixture, nor N fertiliser rate x pasture mixture x year interactions were apparent for herbage DM yield. Additionally, no significant effects of N fertiliser rate nor second- or third-order interactions between N fertiliser rate, pasture mixture and year were apparent for the proportion of plantain (Hearn et al., 2024a).

## 4 Effect of plantain on nitrogen leaching

A large body of research on the effect of plantain on N losses from grazed pastures has emerged in the last decade, e.g. through major New Zealand research programmes and more recent research in Ireland. In New Zealand, the benefits for reductions in N leaching were first explored in the Forages for Reduced Nitrate Leaching programme (2013–2019) and the Greener Pastures programme (2014–2018) and are currently under investigation in the Plantain Potency and Practice programme (2021–2027).

Significant reductions in N leaching from simulated urine patches have been measured in several New Zealand lysimeter studies comparing perennial ryegrass/white clover swards and plantain monoculture or mixed-species swards, including plantain (summarised in Pinxterhuis et al., 2024). A recent Irish study added to these results using lysimeters with varying soils, from free- to poorly draining (Egan et al., 2025).

Lysimeter studies have inherent limitations associated with pasture and soil confinement. Leaching measurements from longer-term farmlet or paddock scale studies, where cows graze a specific pasture treatment, provide an environment where these limitations are obviated. A recent trial in New Zealand's summer-moist North Island (no irrigation) measured leaching from perennial ryegrass/white clover/plantain pastures compared with perennial ryegrass/white clover pastures in grazed, hydrologically isolated large plots (800 m<sup>2</sup>). During a relatively low N drainage year, nitrate leaching was reduced by 60% in the first year. The reduction was 20–46% in the second year under higher drainage conditions (Navarrete et al., 2023). Plantain ranged from 30% to 50% of the sward DM offered and from 21% to 39% in the diet of the grazing dairy cows, lower than offered in pasture due to supplement feeding. In another New Zealand farmlet trial in a summer-dry environment with irrigation (Lincoln, Canterbury, South Island), total oxidisable N leaching (i.e. nitrate-N and nitrite-N) was reduced in the first 2 years of the trial by on average 18% in pastures with 20–30% plantain, compared with perennial ryegrass/white clover pasture (Fransen et al., 2024).

A further feature of these system trials is that they incorporate all of plantain's mechanisms so far purported to have a role in modifying the N cycle of grazed systems. These mechanisms include the following:

Effects on animal urinary N excretion:

- 1 Reduced urinary N concentration, associated with increased daily urine volume of the grazing animals and
- 2 Reduced total urinary N excretion, associated with a greater proportion of N intake partitioned to faeces and milk.

Effects on soil N processes:

- 1 Reduced rate of soil nitrification, associated with secondary compounds found in urine excreted by the grazing animals and from root exudates and herbage litter and
- 2 Reduced drainage, associated with greater water use by swards that include plantain.

These effects are briefly discussed in the following sections.

#### **4.1 Animal urinary nitrogen excretion**

To date, the most consistently demonstrated effect of including plantain in the dairy cow's diet is the effect on daily urination volume (associated with more urinations per day) and hence N concentration in urine. This was also observed when N intake was greater with increasing proportion of plantain in the grazed sward (Box et al., 2023a). This is thought to be mainly the result of plantain's relatively low dry matter percent (Minneé et al., 2019), i.e. animals ingesting more water with their feed, even if they compensate for this by drinking less from the water trough (Cheng et al., 2017; Minneé et al., 2020). A higher mineral concentration of plantain compared with grass (Minneé et al., 2019) may also contribute to greater overall water intake. Additionally, plantain in the diet can result in less N partitioned to urine and more to faeces and/or milk (Minneé et al., 2020).

Nguyen et al. (2022a) conducted a meta-analysis of animal experiments and reported the following relationships between plantain proportion in the animal diet and excreta characteristics:

- 1 Relative change of urinary N concentration (%) =  $-0.0645 \times \text{plantain proportion (g kg}^{-1} \text{ DM)} + 0.61$  ( $R^2 = 0.69$ ,  $P < 0.001$ ).
- 2 Relative change of daily urine volume (%) =  $0.0659 \times \text{plantain proportion (g kg}^{-1} \text{ DM)} - 12.73$  ( $R^2 = 0.64$ ,  $P < 0.001$ ).
- 3 Relative change of total daily urinary N excretion (%) =  $-0.0297 \times \text{plantain proportion (g kg}^{-1} \text{ DM)} - 5.86$  ( $R^2 = 0.22$ ,  $P = 0.036$ ).

Apart from less urinary N excretion per cow per day when plantain was fed to dairy cows, the analysis of Nguyen et al. (2022a) also indicated higher total milk and milk protein yield in late lactation (autumn), i.e. greater partitioning of N to milk. These authors did not report partitioning of N to faeces; however, some of the results used in this meta-analysis also showed that this was elevated when plantain was fed (Minneé et al., 2020; Marshall et al., 2021).

Plantain's effect on urinary N concentration and urine volume excreted per day have also been reported for red deer (Beck et al., 2020) and greater urine volumes have been reported for sheep (Judson et al., 2018b; O'Connell et al., 2016).

The main plant-based drivers of N partitioning in the animal are plant crude protein concentration (i.e. N concentration  $\times$  6.25, consisting of true protein and other nitrogenous compounds), protein degradability and water-soluble carbohydrate/crude protein ratio (Castillo et al., 2000; Bryant et al., 2019b; Minneé et al., 2020). Crude protein concentration of pasture in intensive forage-based livestock systems often exceeds animal requirements. For lactating dairy cows, requirements equate to approximately 3% N of dry matter (Pacheco and Waghorn, 2008) and lactating dairy cows utilise only 13–31% of N consumed (Castillo et al., 2000). The remaining N is excreted, mainly in urine (Kebreab et al., 2001).

Much of the protein in forages is degradable in the rumen (75–90%; Waghorn and Clark, 2004). Degradable protein consists of soluble protein which is rapidly degraded and insoluble degradable protein which is more slowly degraded in the rumen. The rumen degradable and soluble protein concentrations of forage influence the rate of ammonia accumulation in the rumen and in turn, urinary N excretion (depending on energy supply). Rumen undegradable protein is largely associated with plant cell walls and is difficult for rumen microbes to access. This protein fraction is either digested in the small intestine (digestible rumen undegradable protein) or is excreted in faeces. Minneé et al.'s (2019) meta-analysis showed that on average, plantain herbage contains less soluble protein than perennial ryegrass (12% vs. 38% of total N) and more rumen undegradable protein (64% vs. 31% of total N). In accordance, a greater plantain proportion in the diet of lactating dairy cows increased partitioning of N to faeces in the experiments of Marshall et al. (2021) and Minneé et al. (2020).

Soluble carbohydrates (i.e. sugars) are a key source of energy for rumen microbiota. With sufficient supply of soluble carbohydrates in the rumen, dietary N is synthesised in microbial protein, which is then available for use by the animal for production or growth. If energy is limiting, compared with available N, N accumulates in the rumen as ammonia, which is absorbed into the bloodstream and recycled or processed into urea in the liver and excreted in urine. Temperate pastures generally contain high concentrations of N and

low concentrations of soluble carbohydrates. Edwards et al. (2007) showed that increasing soluble carbohydrate concentration in perennial ryegrass herbage reduced urinary N excretion. The same may occur when plantain is added to the diet, since plantain herbage contains greater soluble carbohydrate concentration than ryegrass (on average 299 g kg<sup>-1</sup> vs. 211 g kg<sup>-1</sup> DM) with similar total N concentration (Minneé et al., 2019).

Plant secondary metabolites in forages, such as terpenoids and tannins, can also impact rumen N processes (Bryant et al., 2019b), e.g. through their antimicrobial properties or functioning as an alternative energy source. Terpenoids known to be present in plantain are aucubin, acteoside (also known as verbascoside) and catalpol (Box et al., 2019). Navarrete et al. (2016) found ammonia production was reduced by 40% after 24 h of incubation when plantain was used as a substrate in an in-vitro study, compared with chicory as the substrate. In that case, the chicory forage did not have detectable levels of aucubin and acteoside, which were present in the plantain forage used. Addition of aucubin or acteoside to the chicory, at higher rates than were found in the plantain herbage used, reduced 24 h ammonia production by 5–20%. Minneé et al. (2017) measured lower rumen ammonia concentrations when late-lactation cows fed perennial ryegrass/white clover were supplemented with plantain or chicory, but no difference between the supplementation with chicory or plantain. In this study, secondary metabolites were not measured.

The concentrations of secondary compounds aucubin, acteoside and catalpol in plantain are highly variable both spatially and temporally and also vary between cultivars (e.g. Dietz et al., 2013). This presents a substantial challenge to identify potential effects of these compounds in feeding trials with plantain where the levels of secondary compounds are difficult to control.

## **4.2 Soil nitrogen processes**

Plantain has been shown to impact several soil N processes, notably (1) nitrification rate, either directly via plant root and litter exudates or indirectly via compounds excreted in the urine of animals consuming herbage containing plantain, (2) leaching rate indirectly through influencing drainage. Inhibiting or reducing nitrification in the soil retains N in the form of ammonium for longer, which is less susceptible to leaching than nitrate. Reduced drainage will also retain mineral N in the rooted zone for longer, extending the time for plant N uptake.

Several studies have explored the impact of plantain on soil nitrification. Carlton et al. (2019) used micro-plots to assess changes in soil mineral N concentration following the application of standardised dairy cow urine. Nitrification appeared to be delayed under perennial ryegrass/white clover/plantain swards (with 20–30% plantain) compared with perennial ryegrass/

white clover alone. This was shown by a lower soil ammonium-N concentration under perennial ryegrass/white clover up until day 30 after urine application. Also, soil nitrate-N concentration peaked earlier under perennial ryegrass/white clover (151 mg N/kg soil, day 14) compared with perennial ryegrass/white clover/plantain (140 mg N/kg soil, day 30). This was accompanied by higher growth rates of ammonia oxidising bacteria under perennial ryegrass/white clover.

Using Dutch peat soils and applying ammonium sulphate, rather than cow urine, Pijlman et al. (2020) found 39% lower potential nitrification in mesocosms with a plantain monoculture compared with a perennial ryegrass monoculture. They did not detect any significant differences between treatments in soil nitrate and ammonium concentration, but there were significant negative correlations between soil potential nitrification and soil nitrate concentration.

Peterson et al. (2023) collected root exudates from plantain grown in hydroponics (Fig. 4) and showed these exudates reduced rates of nitrification in a bioassay with a nitrifying bacterium. They also showed differences



**Figure 4** Peterson et al. (2023) collected root exudates from plantain grown in hydroponics; shown are plants from the AgriTonic cultivar. These exudates reduced rates of nitrification in a bioassay with a nitrifying bacterium. However, results were variable between exudates from different plantain cultivars and within cultivars.

between exudates from different plantain cultivars and within cultivars and correlations with root exudate chemistry. Dietz et al. (2013) also showed a delay in nitrification rate in soil incubation studies, with no nitrate detected for the first 28 days, when soil samples were incubated with plantain leaf material, aqueous extract of plantain leaves or aucubin. However, they also showed varying levels of aucubin, catalpol and verbascoside in plantain leaf material over time, differences between two plantain cultivars, and variation between leaves from plants in vegetative or generative state. This presents a challenge in quantitatively linking sward plantain proportions with secondary metabolite abundance and their effects on soil N processes in the field.

Other work has shown indirect biological nitrification inhibition effects of plantain, i.e. a nitrification reduction effect of the urine of animals consuming plantain compared with perennial ryegrass/white clover (Judson et al., 2018a; Judson et al., 2018b; Judson et al., 2019; Peterson et al., 2022, 2023). This lower rate of nitrification was attributed to the organic fraction of urine and breakdown molecules of plantain's secondary compounds. The extent of the "urine effect" depended on the length of time the animals were grazing swards with plantain, the plantain cultivar and the amount of plantain in the diet. Additionally, seasonal differences may be expected due to temporal variability in secondary compounds in plantain (Box and Judson, 2018) and differences between soil types may be expected too (Clark et al., 2021). As yet, it is not clear which compounds are responsible and how they affect nitrification rate. Peterson et al. (2023) suggested an inhibiting effect on the enzymes that convert ammonium to nitrite.

The magnitude of the "plant-soil effect" of plantain on nitrate leaching was shown by Carlton et al. (2019), Welten et al. (2019), Talbot et al. (2021) and Egan et al. (2025). Carlton et al. (2019) applied standardised fresh dairy cow urine at 700 kg N/ha to lysimeters and measured on average 82% less nitrate leaching from a perennial ryegrass/white clover/plantain sward than from a perennial ryegrass/white clover sward when urine was applied in December (early summer) and 74% less when urine was applied in February (late summer). Drainage in these mesocosms was reduced by on average 21% and 28% for the December and February treatments, respectively, by inclusion of plantain. These results occurred despite the total herbage dry matter yield and N uptake being lower for perennial ryegrass/white clover/plantain than for perennial ryegrass/white clover in this study (12.2–14.2 t DM/ha vs. 13.3–14.9 t DM/ha and 355–441 kg N/ha vs. 408–466 kg N/ha, respectively).

Welten et al. (2019) applied urine collected from dairy cows grazing a perennial ryegrass/white clover pasture to lysimeters with either ryegrass or plantain monocultures. They observed 15% less N leaching from plantain swards than from ryegrass swards when urine was applied in summer and 50% less N leached when the urine was deposited in winter.

Talbot et al. (2021) also applied urine collected from dairy cows grazing a perennial ryegrass/white clover pasture to lysimeters with swards containing none or 25–35% plantain and found reductions in N leached of 14–24% with plantain, irrespective of the seasonal timing of urine application. These authors suggested the smaller reductions they found could have been due to the shallow stony soils in their study, i.e. more freely draining than the deeper loam soils used by Carlton et al. (2019) and Welten et al. (2019).

Egan et al. (2025) applied a mixture of urine, collected from cows grazing either perennial ryegrass only, perennial ryegrass/white clover or a multispecies sward including plantain to lysimeters, over two years and five soil types. Hence also here, the “animal effects” of plantain in the cows’ diet were excluded as a factor. In their study, reductions in N leaching from perennial ryegrass/white clover/plantain mixtures compared with perennial ryegrass/white clover were much greater in the second drainage season after establishment than in the first drainage season (reductions of on average 97% in year two, compared with 46% in year one). In this study, there was limited additional benefit from the treatment aiming at 50% plantain in the sward DM, compared with the 30% plantain sward.

In a context where soil type and rainfall resulted in high drainage following urine application, no reductions in N leaching associated with plantain were observed (Graham et al., 2024; Healy et al., 2024). The variable results across studies imply that soil type and climate may be critical determinants of the magnitude of plantain impact on nitrification rates and leaching losses. This is an important consideration to understand the efficacy of plantain as a tool to reduce N losses to sensitive water bodies under a wide range of soil and climate combinations. Current research in the New Zealand “Plantain Potency and Practice” programme attempts to unravel these sources of variation by examining N dynamics in four different regions with different soils and climate.

## **5 Case study: use of plantain to reduce nitrogen leaching at catchment scale**

In some New Zealand regions, N discharge into waterbodies is regulated. This case study illustrates the environmental and economic impact of implementing plantain in pasture to achieve the N reduction targets in the Rotorua Lake catchment, Bay of Plenty. Details of this case study are provided in Farrell et al. (2025) and Fransen et al. (2025).

This case study utilised two DairyNZ models: the Dairy Sector Pathways (DSP) model and the Catchment Accounting Framework (CAF). The Dairy Sector Pathways model simulates the production and economic changes in a population of dairy farms over time as they adopt farm system and management

changes to achieve N leaching reductions. The CAF combines land use and geographical data with farm system data to account for N losses within a catchment for baseline scenarios and when farm systems or management changes are implemented.

The Plantain Potency and Practice Programme partnered with five dairy farmers in the Rotorua Lake catchment to investigate the implementation of plantain in pasture. Annual monitoring of plantain content (% of herbage DM) indicated that plantain could feasibly amount to 20% of DM in pasture (see Fig. 3), so this level was assumed in the modelling.

OverseerFM (<https://overseer.org.nz/overseerfm/>) and Farmax (<https://www.farmax.co.nz/>) models were used to estimate the impact of plantain and other N leaching mitigative actions on farm-level N leaching and operating profit for three of the partner farms. Other mitigative actions were reductions in imported supplementary feeds and/or N fertiliser, removal of cropping, utilising supplements with reduced N content, stand-off facilities to remove cows from pasture at critical times of the year and retiring land to unharvested pine forestry. Results of this modelling were used to validate and inform the DSP and CAF models. Of note is that OverseerFM currently only reflects the effects of plantain on urinary N excretion and dilution, and not the potential soil effects. Therefore, it is possible that N leaching reductions are underestimated.

Based on dairy statistics, DSP generated a population of 26 dairy farms in the Rotorua Lake catchment. On average, these farms were required to reduce N leaching by 31% relative to their baseline of 2017/18 to achieve their 2032/33 targets, as set by the Bay of Plenty Regional Council. For all farms, scenarios with or without plantain were modelled to assess the future value of the implementation of plantain at catchment scale. For individual farms, N leaching reduction targets ranged from 7% to 47%, hence the combination of generated mitigative actions varied widely between farms. In general, reductions in supplementary feed imports and N fertiliser use were necessary, which resulted in fewer cows and reduced milk production and operating profit, relative to the baseline.

Table 2 shows the impact at farm and catchment scale of the required mitigations with or without plantain. At catchment scale, implementing plantain meant that 151 ha of dairy land and 429 more dairy cows could be retained, producing 202 tonnes more milk solids per year and returning \$0.6 million more operating profit per year. The total reduction in N leaching achieved from the dairy farms amounted to 35 t N/year from 20% plantain alone, which was 36% of the total required reduction.

The results of this catchment scale scenario modelling indicate a significant value of plantain as a mitigation option. Clearly, results will differ depending on variances in, e.g., milk price, costs of inputs, plantain % of DM achieved,

**Table 2** Predicted average performance for 26 dairy farms in the Rotorua Lake catchment for the 2017/18 season (baseline) and two scenarios for the 2032/33 season when 31% nitrogen leaching reduction, compared with the baseline, needs to be met

	Baseline	P0	P20
Farm-scale parameters*	2017/18	2032/33	2032/33
Milksolids production (kg/ha)	1115	897	943
Gross farm revenue (\$/ha)	7927	6466	6778
Operating expenses (\$/ha)	5380	4783	4920
Operating profit (\$/ha)	2547	1683	1858
Carbon sequestration revenue (\$/ha)	0	38	6
Catchment-scale parameters			
Total dairy farm area (ha)	4498	4229	4380
Cow numbers (head)	12 327	10 782	11 211
Milksolids produced (tonnes)	4759	3752	3954
Operating profit (\$ millions)	11.3	7.4	8.0

\*Per hectare of land effectively used for milk production.

P0 is a scenario without plantain; P20 is a scenario with on average 20% plantain in pasture dry matter across the farm.

N fertiliser response rates, and effect of plantain on N leaching and herbage production. Some examples of the impact of varying assumptions are provided by Chikazhe et al. (2024). Their (limited) variations resulted in abatement costs varying from \$11/kg N to \$45/kg N leaching reduction, illustrative of the large uncertainty farmers face when deciding on steps to achieve future N leaching targets.

## 6 Effect of plantain on nitrous oxide emissions

To date, studies looking at both the “animal-urine effect” and the “plant-soil effect” have shown the inclusion of plantain can also reduce nitrous oxide emissions.

To investigate “animal-urine effects”, Gardiner et al. (2017) added either plantain leaf extract or aucubin to the urine of dairy cows grazing perennial ryegrass/white clover swards and applied this urine to a perennial ryegrass/white clover sward. This resulted in 50% and 70% lower urinary nitrous oxide emissions, respectively, than from the same urine without additives.

Rodriguez et al. (2023) also investigated the effects on nitrous oxide emission and nitrate leaching of plantain, aucubin and urine derived from cows fed plantain monocultures or perennial ryegrass/white clover swards, with the latter diluted to the same N concentration as the plantain urine. These authors did not find an effect of plantain urine on nitrous oxide emission or nitrate leaching. Instead, nitrous oxide emission was reduced from perennial ryegrass/

white clover swards when aucubin was applied and from plantain swards compared with perennial ryegrass/white clover swards. However, in the latter case, they did not find aucubin in the plantain root exudates; rather, catalpol was the main compound detected.

In an investigation of “plant-soil effects”, Luo et al. (2018) collected urine from dairy cows grazing perennial ryegrass/white clover sward and adjusted the N concentration to about 6.22 g N/L by adding urea or diluting the urine, before applying this urine to lysimeters. They showed a 39% and 35% reduction in cumulative nitrous oxide emissions (total over twelve weeks) from plantain monoculture lysimeters compared with ryegrass monoculture, when applying urine in March or May (early and late autumn), respectively. When urine was applied in February (late summer), emission from plantain was not significantly different from ryegrass. Luo et al. (2018) also measured nitrous oxide emission from field plots growing monocultures and reported a 22% lower emission from plantain than perennial ryegrass without urine applied and 74% lower emission with standardised urine applied in June (early winter).

Chibuike et al. (2024) also reports significant nitrous oxide emission reductions of on average 39% from soil columns with plantain, compared with perennial ryegrass, when synthetic urine was applied. In the field study of Pijlman et al. (2020), the presence of plantain resulted in 39% lower cumulative nitrous oxide emission compared with the monoculture of perennial ryegrass.

Simon et al. (2019) showed cumulative nitrous oxide emissions over a 15-week period decreased linearly with increasing proportions of plantain in both the diet and sward simultaneously. They also showed a linear decrease in nitrous oxide emissions with increasing plantain proportion in the sward when urine from dairy cows grazing perennial ryegrass/white clover swards was applied or when no urine was applied at all. These results imply an impact of plantain on the emission factor (ratio of N emitted to N applied), an important metric for assessing the efficacy of greenhouse gas mitigations. However, only with the standard urine treatment was the decline in the emission factor with increasing plantain proportion in the sward significant. Simon et al. (2019) also showed lower total nitrous oxide emissions when urine from cows grazing 45% plantain swards was applied to perennial ryegrass/white clover swards, compared with urine from cows grazing ryegrass/clover swards. There were no significant differences in emission factors between these treatments, nor was there a difference between the “45% plantain urine” treatment and a treatment with urine from cows grazing perennial ryegrass/white clover swards that was diluted to the same N concentration as the plantain urine. This implied that there were no measurable effects of plant secondary compounds via urine, rather only an effect of the lower N concentration in the urine.

## 7 Future research trends

Despite a burgeoning body of research on the use of plantain in intensive pastoral systems, many questions remain. These span microbial to catchment scales and cover the domains of biochemistry, biology, soil chemistry, agronomy, hydrology, animal physiology, animal production and product quality. Because of the diffuse nature of the environmental impact of N within agricultural systems, future research will need to address some pertinent questions farmers and other stakeholders have regarding implementing plantain at scale and putting its use into the context of other novel mitigation options and systems configurations. For example, a modelling exercise indicated that the effectiveness of reduced urinary N concentration on N leaching and nitrous oxide emission can be less with higher stocking rates (Snow et al., 2025).

Specific areas for future research pursuit are indicated below.

### 7.1 Farm-scale impact of plantain on production and profit

To date, limited information is available on the productivity and profitability of farm systems with plantain in mixed-species pastures, relative to farm systems based on perennial ryegrass or perennial ryegrass/white clover pastures. At the paddock scale, various studies have shown either no significant or a beneficial impact of adding plantain in perennial ryegrass/white clover pasture on herbage yield (Dodd et al., 2023; Hearn et al., 2024a; Herath et al., 2023; Minneé et al., 2013; Monique et al., 2025; Nguyen et al., 2022b). However, it is important to understand the implications for farm-scale milk production and profitability, if plantain is to be recommended to dairy farmers as a cost-effective means of reducing N loss to the environment.

The meta-analysis of Nguyen et al. (2022a) showed pastures with plantain on average increased milk yield by 0.07 kg MS/cow/day across a season, and 1.4 kg MS/cow/day in late lactation, i.e. autumn, in New Zealand conditions. However, a higher milk yield per cow does not necessarily mean higher milk production per hectare. A one-lactation Irish study showed similar annual milk yield per cow for perennial ryegrass/white clover pastures with or without plantain under the same stocking rate (Minogue et al., 2025). The key difference was 6% lower daily milksolids yield in early lactation and 9% higher milksolids yield in late lactation for pastures with plantain. In a replicated farm system study, comparing farmlets with perennial ryegrass/white clover swards and farmlets with perennial ryegrass/white clover/plantain swards, Herath et al. (2023) showed similar pasture production (13.0 t DM/ha), milksolids production (1356 kg MS/ha) and profitability (NZ\$4347/ha) for the first year of the study. These limited results suggest that the addition of plantain to pasture

mixtures would be a low-cost and revenue-neutral means of reducing N loss from grazed pasture on dairy farms, compared with other mitigations involving reducing stocking rate, reducing N inputs and implementing off-paddock infrastructure.

## **7.2 Plantain persistence in mixed-species pasture**

Challenges persist in establishing and maintaining relevant proportions of plantain in New Zealand grass-based mixed-species pastures (Dodd et al., 2025; Eme and Roche, 2025), especially where conditions are conducive to high growth rates for perennial ryegrass. By stark contrast, in Ireland, Hearn et al. (2024a) observed the highest plantain proportion of on average 37% plantain in the third year after sowing across a range of species mixtures and fertiliser rates (0–200 kg N/ha/year). None of the possible reasons for poor persistence in New Zealand (suggestions include grazing management, pests, treading damage etc.) have yet been conclusively identified. To date, the only methods shown to improve the proportion of plantain in existing swards, without spraying and tillage, have been over-sowing or direct drilling, with best results if competition from the existing sward is managed during establishment, e.g. by hard grazing before over-sowing (Hearn et al., 2024b) and/or a light grazing after over-sowing (Bryant et al., 2019a). For successful application on commercial farms, it will be crucial to understand how the proportion of plantain in pasture can be maintained or improved after establishment, since frequent pasture renewal is undesirable from cost and environmental perspectives. An example of the detrimental environmental impact of pasture renewal was shown by Graham et al. (2024), with significantly higher N leaching after pasture renewal.

Further research could investigate the potential effects on plant longevity and/or recruitment of new plants of differing grazing rotation lengths, e.g. shorter intervals to avoid flowering and potentially extend plant longevity, or longer intervals during the flowering stage to support natural reseeding. There is also a need to explore the use of highly diverse species mixtures or grass species less competitive than perennial ryegrass. Silvia Cid et al. (2011) reported greater contribution of plantain to annual yield when sown with tall fescue and cocksfoot (compared with annual ryegrass), in a seasonally dry climate in Argentina. However, Dodd et al. (2017) observed no significant difference in the proportion of plantain in perennial ryegrass or tall fescue-based pastures in summer-dry Waikato in New Zealand.

## **7.3 Weed and pest management**

Another challenging aspect of maintaining sward productivity and quality that farmers consistently identify is the management of weeds and pests. In pastures

where white clover and plantain are desirable species, the ability to chemically control weeds is limited, and other non-chemical preventative management practices warrant further research. Some pasture species control weeds better than others (Connolly et al., 2018). Biocontrol of some weeds has been shown to be effective in New Zealand (Hayes et al., 2013), presenting an unexplored approach to minimising the detrimental effects of broad-action herbicides on plantain.

For most relevant invertebrate pests, pesticides are available and some opportunities for non-chemical management have been identified, such as the potential biopesticide bacterium *Yersinia entomophaga* (Jones et al., 2015) and potential for genetic selection within plantain to improve resistance to pests (Gerard et al., 2018).

The weed and pest challenges for plantain represent an example of a core challenge for research: they are a barrier to widespread uptake of a novel forage species, which in turn hinders the justification for research investment in relevant solutions.

#### **7.4 Cow health and milk composition**

To date, there has been limited research on minor milk components and fatty acid composition (Pinxterhuis et al., 2024). The inclusion of plantain in cow diets led to small reductions in milk fat concentrations (Nguyen et al., 2022a), greater concentration of poly-unsaturated fatty acids (Mangwe et al., 2018; Marshall et al., 2022) and differing concentrations of phytochemicals (Marshall et al., 2022). These results indicate that the potential human nutritional benefits of including plantain in the cow's diet warrant further research. To date, no risks to human health nor processability of milk has been found from milk originating from cows grazing pastures with plantain (unpublished results from the Plantain Potency and Practice programme; <https://www.mpi.govt.nz/dmsdocument/70348-March-to-May-2025-Plantain-Potency-and-Practice-progress-report/>).

A potential risk to animal and human health is the higher uptake of cadmium from the soil by plantain, compared with perennial ryegrass and white clover (Stafford et al., 2016). Where soil cadmium levels are high, e.g. through the repeated use of cadmium-containing phosphorus fertiliser, cadmium can accumulate in plantain leaves and via feed intake can lead to elevated concentrations in the animal's liver and kidney.

No immediate animal health issues have been reported to date, when plantain was included in the pasture or fed as a monoculture crop. However, some potential issues may occur as results to date have been derived from short-term research results and there may be merit in further investigation in longer-term experiments or on commercial farms where plantain is a structural component of the animals' diet. The short-term studies showed reduced water

intake from the trough with increasing proportions of plantain in the dairy cows' diet (Minneé et al., 2020), which has implications for dosing minerals or animal health products via the water trough (e.g. bloat-prevention products).

The generally higher dietary sodium and calcium concentration and lower potassium concentration associated with plantain (Minneé et al., 2020) may impact dietary cation anion difference (DCAD) status and calcium absorption, potentially forming a risk or a benefit for the health of lactating dairy cows.

### **7.5 Methane and ammonium emissions**

Enteric methane emission from grazing livestock systems is an important contributor to global greenhouse gas emissions (Hristov et al., 2013). While ammonia is not considered an environmental issue in New Zealand, it is regulated in Europe. *In vitro* studies indicate the potential for plantain to reduce both methane and ammonia emissions relative to other herb and brassica species (Durmic et al., 2016) and to perennial ryegrass/white clover (Sivanandarajah et al., 2025a). Further *in vitro* compound-specific work showed less methane and net ammonia production from plantain substrates with varying content of aucubin and acteoside, compared with perennial ryegrass, which does not contain these secondary compounds (Sivanandarajah et al., 2025b). Incubations of perennial ryegrass enriched with commercially available aucubin, acteoside and catalpol showed no reduction in methane production rates but a decrease in ammonia production rates. Li et al. (2025) investigated a range of binary pasture mixtures and showed a negative correlation between *in vitro* methane yields and saponins and condensed tannins; plantain had elevated concentrations of these compounds in their study.

Very few publications to date investigate the effect of plantain on methane emission from dairy cattle, and what is published has shown variable effects of multi-species pastures on methane emission from dairy cattle compared with perennial ryegrass/white clover pastures. Della Rosa et al. (2022) measured 15% and 28% less methane emission/kg DM intake from non-lactating cows when fed plantain in vegetative and reproductive growth stage, respectively, compared with perennial ryegrass, and attributed this to lower herbage digestibility. Koning et al. (2024) measured higher methane production (g/cow/day) and yield (g/kg DM intake) from lactating dairy cows grazing perennial ryegrass/plantain mixtures (maximum of 25% plantain in DM) compared with perennial ryegrass monocultures. They also suggest an effect of a lower herbage digestibility of the swards with plantain, due to higher acid detergent fibre (ADF) and acid detergent lignin (ADL) content than perennial ryegrass swards in their study.

Clearly, the mechanisms of the effects of herbage composition, and specifically plantain, on methane emission requires further research, and the overall effect of incorporating forage plantain on the various gaseous emissions from livestock systems has yet to be clearly quantified.

### **7.6 Effects of secondary compounds on rumen and soil microbiome**

The mechanisms of the observed impacts of plantain and its secondary compounds or their derivatives on microbial processes in the rumen and in soil need to be better understood, to ensure optimal use of plantain to reduce environmental impact of grazed, productive dairy pastures and to guide future plant breeding efforts and research in other potentially successful forage options. Effects of secondary compounds and their derivatives, either directly from the plantain plant or via excreted urine from animals consuming plantain (Peterson et al., 2023), are apparent but variable. It is not clear which compounds matter most for which processes, and under which circumstances (e.g. potential interactions with animal breed, overall feed composition, soil type, climate). It is also not clear what their impact is relative to other traits of plantain that reduce N losses, and if there are any unintended consequences of elevating secondary compounds and associated changes in soil microbial communities. No risks to human health and processability of milk derived from swards with plantain have been identified to date.

Additionally, concentration of some secondary compounds has been shown to vary over time in plantain (e.g. Box and Judson, 2018), so further understanding of these variations and whether the concentration can be managed or bred for will be needed to support consistent positive environmental effects over time.

## **8 Conclusion**

Including plantain in perennial ryegrass/white clover pasture appears to be a low-cost option to reduce N leaching and nitrous oxide emission, without any substantive negative effects on pasture production, animal production, milk quality and animal health. On the contrary, under certain situations various positive effects of plantain on all these factors have been observed.

Some gaps in current knowledge have been identified that require further investigation to optimise the implementation of plantain on farm and to achieve maximum environmental benefits. Notable areas for deeper study include management of mixed-species swards to maintain the proportion of plantain in the sward and understanding the mechanisms in which plant secondary compounds and their derivatives impact rumen and soil processes and their relative importance for reducing N loss to the environment.

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## 10 Where to look for further information

Plantain webpage DairyNZ is regularly updated with new research results from the Plantain Potency and Practice programme. It includes links to case studies on commercial farms and management guidelines. <https://www.dairynz.co.nz/feed/crops/plantain-overview/>.

The Forages for Reduced Nitrate Leaching research programme (2013–2019); <https://www.dairynz.co.nz/frnl>. includes a link to the FRNL New Knowledge Register, which summarises research results and provides links to published scientific manuscripts.

Reviews:

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