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REDUCING HARMFUL NITROGEN FLUXES TO THE ENVIRONMENT BY REDUCING NITROGEN CONTENTS IN ANIMAL FEED

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Pastoral agriculture can have negative environmental impacts through contributing to net greenhouse gas emissions (enteric CH_4 and soil N_2O emissions), NH_3 volatilisation and leaching of nitrogen into waterways. The harmful N fluxes to the environment (NH_3 volatilisation, N-leaching and N_2O fluxes) are directly proportional to the excess N ingested by grazing animals.

Feed available to cattle in New Zealand (from pastures + supplements) generally supplies N that exceeds the animals' needs. Reducing N supply in animal feed is, therefore, likely to be a highly effective and feasible way to reduce those harmful N fluxes.

Here, we summarise available evidence from modelling and experimental work to ascertain whether N_2O emissions, nitrogen (N) losses via leaching and NH_3 volatilisation can, indeed, be reduced through lowering feed N contents. We found that lowering N contents in animal feed resulted in lower urine N excretion and consequently reduced leaching losses and emissions of N_2O and NH_3. In practice, feed N contents could be reduced through

a) feeding low-N supplements
b) reducing pasture N by growing low-N pasture species (e.g. plantain)
c) reducing pasture N through plant breeding (e.g. growing high-sugar grasses)
d) reducing pasture N through management (e.g. by reducing fertiliser application rates).

While these approaches can lower harmful N fluxes to the environment, N availability must remain within the N range required to meet the animals' requirements for good health and productivity. The overuse of some feed additives can also impact animal welfare. Whole-farm system approaches, therefore, need to be tailored towards achieving the way farming outcomes within a variety of considerations.

1. Introduction

Grazed grasslands contribute to global greenhouse gas emissions through enteric CH_4 emissions from grazing animals and N_2O emissions from the microbial breakdown of animal excreta and nitrogen (N) fertilisers in the soil. N can also be lost from the soil via NH_3 volatilisation and NO_3^- leaching, which can contribute to secondary N_2O emissions and affect local air and water quality (Cameron et al., 2013).

New Zealand's agriculture sector is predominantly based on grazed pastures and accounts for 48% of the country's gross greenhouse gas emissions (MfE, 2021). Of these emissions, CH_4 from enteric fermentation accounts for 73% and (direct and indirect) N_2O emissions from managed soils for 20%, with the remainder coming from manure management, burning of field residues and CO_2 emissions from urea and lime.

There is much interest in methods to reduce agricultural greenhouse gas emissions while maintaining productivity (Luo et al., 2008; de Klein and Eckard, 2008; Eckard et al., 2010; Dijkstra et al., 2013 de Klein et al, 2020; Bryant et al., 2020; Giltrap et al., 2021). Here, we focus specifically on the most salient aspects of the connection between feed N contents and harmful N fluxes to the environment. We try to show how careful manipulation of feed N content holds considerable promise in reducing these harmful N fluxes that has received insufficient focus in the past. This present work specifically focuses on dairy systems as they typically have some of the highest N fluxes per hectare from New Zealand's grazed pastures.

2. The N cycle

In grazed pastures, harmful N fluxes predominantly originate from urine spots (Selbie et al., 2015) because local N contents in those spots can reach effective N loading rates of 500 – 1000 kgN ha^{-1}, which greatly exceeds the ability of plants to take up and utilise the available N. Effort to control these harmful N fluxes from grazed pastures, therefore, centres on understanding and controlling the N fluxes originating from urine spots.

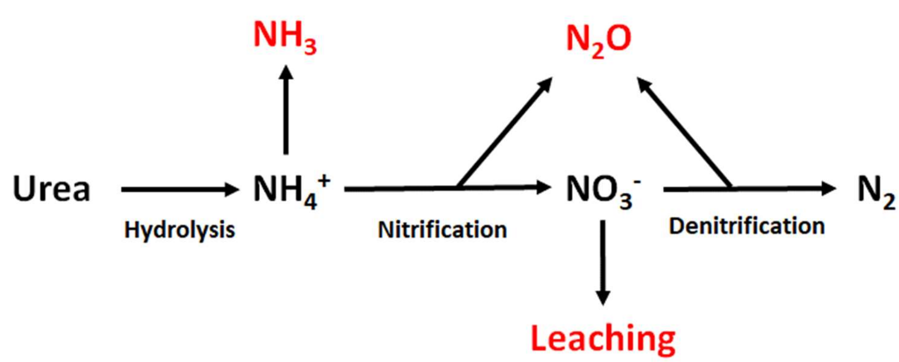

Figure 1: Schematic diagram of the main nitrogen fluxes after urine deposition on the soil. Harmful fluxes to the environment are shown in red.

When cattle urinate onto the soil, N is mostly deposited in the form of urea. When urea reaches the soil, it is readily hydrolysed to NH_4^+ (Fig. 1). Depending on soil moisture, pH and the proximity of NH_4^+ to the soil surface, a substantial proportion of NH_4^+ can be volatilised as NH_3 which loses N from the originating pasture, while the volatilised NH_3 deposits somewhere else in the environment with further harmful consequences. NH_4^+ in excess of plant requirements can be nitrified to NO_3^-, with the greenhouse gas N_2O released as a by-product.

NH_4^+ does not normally leach out of the soil because of its positive charge, but NO_3^- can leach more freely and is the primary molecule responsible for N leaching to waterways. Under anaerobic conditions, NO_3^- can also be denitrified, which constitutes the conversion of NO_3^- to N_2O or N_2 depending on the conditions. Only a small fraction of nitrogen is typically lost as N_2O (Cameron et al., 2013) but, because of its potency as a greenhouse gas, those small fluxes are nonetheless very important in a greenhouse gas context. In addition to the direct N_2O emissions, some N can be volatilised as NH_3 or leached as NO_3^- of which a small fraction will eventually also be converted to N_2O, adding to the total N_2O load resulting from urea addition to the soil system.

The three harmful N fluxes to the environment shown in red in Figure 1 are all proportional to the amount of urine N. This is shown more explicitly in Figure 2 (Giltrap et al., 2021). It shows modelled changes in N fluxes for 10 tDM ha^{-1} yr^{-1} feed intake for feed with different amounts of feed N quantified here through feed-N contents. The N content of a ryegrass-clover pasture depends on the proportions of clover within the ryegrass-clover pasture and can range from 23 gN $kgDM^{-1}$ for a pure ryegrass pasture up to 35 gN $kgDM^{-1}$ for a pasture mixture with 75% clover (Harris et al., 1997). It also varies seasonally and with other factors such as fertiliser application rates. These factors are further explored below.

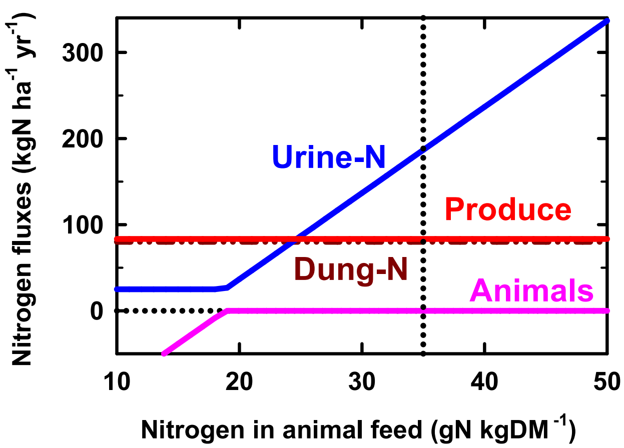

Figure 2: Nitrogen exported in animal produce and excreted in urine and dung, and the consequent animal N balance, plotted as a function of N contents in feed intake. The dotted vertical line shows fluxes at a typical feed N content. Adapted from Giltrap et al. (2021).

In principle, any ingested N can leave the animals' bodies as dung, produce or urine. Animals may also grow and accumulate N in their bodies or lose body conditions if N supply is insufficient, or if animal condition declines for other reasons. Intra-seasonally, changes in animal N, especially over the phases of lactation, can be important additional factors to consider, as will be shown further below, but we start with the simpler case of a constant of N in the body of animals.

Importantly, though, for a given amount of feed-C ingestion, the losses in produce and dung are either constant or change only slightly with feed N contents. Dairy cows normally also do not significantly change the N contents in their bodies. That leaves urine-N excretion as the only pathway for significant N losses from the system and the only way to remove excess N from the animals' bodies to regain their N balance (Kebreab et al., 2001; Dijkstra et al., 2013). That means that urine-N excretion equates to the excess N ingested by animals, and urine-N fluxes above the threshold N content needed for maintaining animal condition must, therefore, be proportional to feed-N contents (Fig. 2).

These urine-N fluxes can then be used to estimate the magnitude of harmful N fluxes to the environment (Giltrap et al., 2021). For a typical herd of cows ingesting 10 tDM ha^{-1} yr^{-1}, the resultant NH_3 emissions from urine ranged from 2.5 kgN ha^{-1} yr^{-1} at the lowest feed N content of 10 gN $kgDM^{-1}$ to 34 kgN ha^{-1} yr^{-1} at the very high N content of 50 gN $kgDM^{-1}$ (Fig. 3a). Leaching losses were calculated to be slightly lower, with up to 23 kgN ha^{-1} yr^{-1} lost with feed with the highest N content. N_2O losses from the system were numerically much smaller with maximum losses of less than 4 kgN ha^{-1} yr^{-1} but, because of its potency as a greenhouse gas, these fluxes nonetheless constitute very important greenhouse gas fluxes (Fig. 3a). The actual modelled fluxes per units of excess N is a function of soil and environmental factors. So, the numbers calculated here are only valid for the specific site conditions for which the model had been run, but the dependence on excess urine is a generic property that would generally be expected for any soil or environmental conditions.

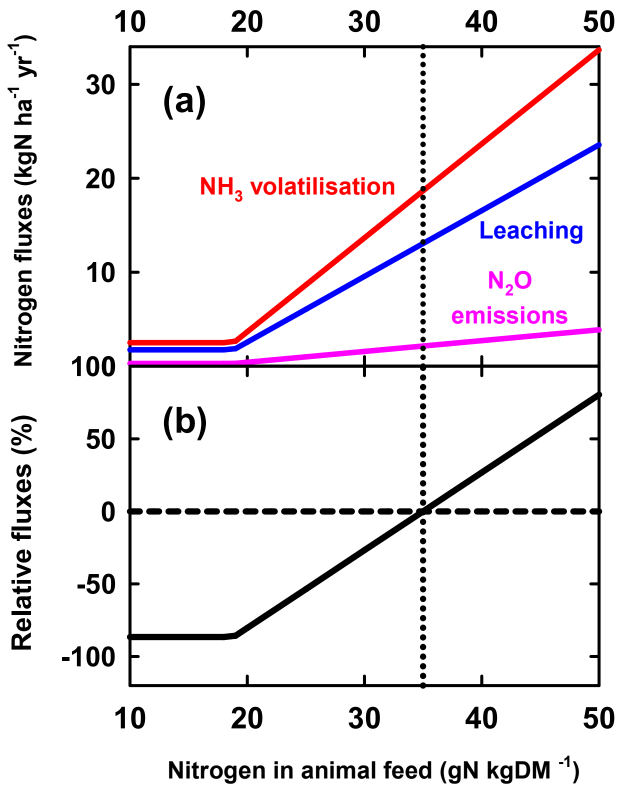

Figure 3: Urine-induced N fluxes of NH_3, N_2O and N-leaching (a), and percentage changes from a base line with 35 gN $kgDM^{-1}$ animal feed for all three N fluxes (b). All numbers are expressed as a function of N content in animal feed. The dotted vertical line shows fluxes at a typical feed N content. Adapted from Giltrap et al. (2021).

Because of the linear dependence of harmful N fluxes on urine N excretion and the linear dependence of urine N on excess ingested feed N, the simulations suggested that the fluxes of NH_3, N_2O and NO_3^- leaching all scale linearly with the N content in animal feed above the ~19 gN $kgDM^{-1}$ feed-N maintenance level (Fig. 3b).

In practice, feed N supply and demand is more complicated, with seasonal changes in both. Bryant et al. (2020) compiled relevant estimates for seasonal changes in both the warmer Upper North Island and the cooler South Island (Fig. 4). Plant N contents reach highest levels between late winter and early spring as plant growth is still slowed by cool winter conditions. As conditions for plant growth become more favourable in late spring to early summer, carbon gain increases rapidly while nutrient uptake typically cannot increase to the same extent. Plant N contents then increase gradually again over summer, autumn and into winter (Fig. 4 a, b).

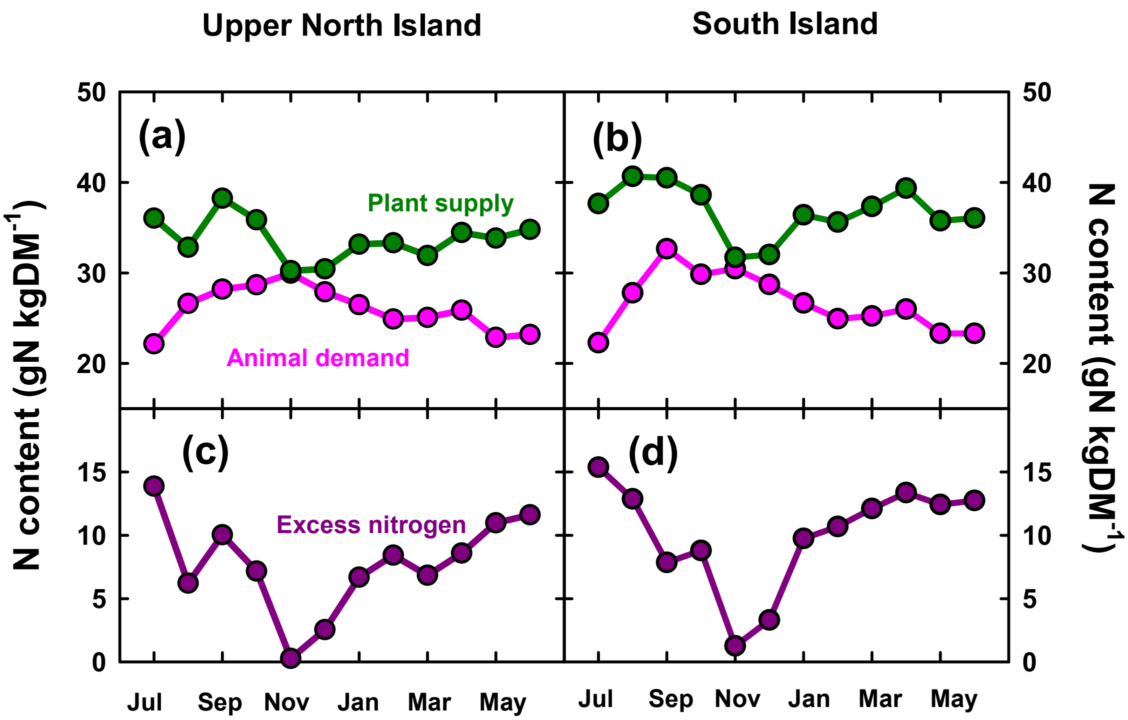

Figure 4: Seasonal changes in plant N supply and nutritional N demand (a, b) and resultant excess N in animal feed (c, d), calculated for the Upper North Island (a, c) and the South Island (b, d). Redrawn from the data compiled by Bryant et al. (2020).

Animal N demand also undergoes important changes, especially related to lactation, with greatest N demand during early lactation, which then gradually decreases through the later stages of lactation to reach lowest values for dry cows (Fig. 4a, b).

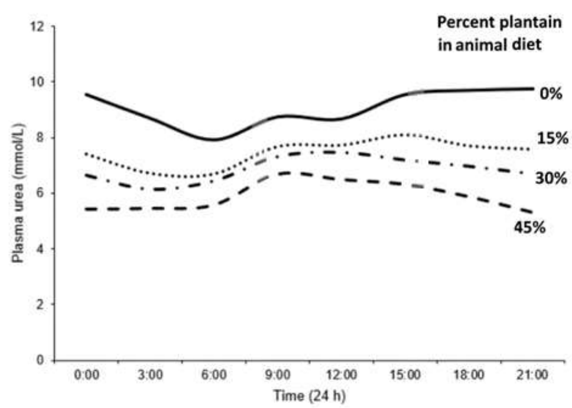

Figure 5: Relationship between feed N content, here quantified through the percentage of plantain in the animal diet, and urea concentration in the animals' blood. Redrawn from Minnée et al. (2020).

The difference between plant N supply and animal N demand can be used to calculate any excess N availability, which changes greatly throughout the season (Fig. 4c, d). Pasture N contents may be only just sufficient to meet animal needs during the early lactation stage as highest N demand can coincide with the period with lowest N supply. This is a critical period for animal management as N shortages need to be avoided for reasons of productivity and animal welfare. For the rest of the year, however, N supply from typical dairy pastures greatly exceeds the requirements of animals to meet their nutritional needs. That excess then needs to be excreted in animal urine and is the primary cause for harmful N fluxes to the environment (Fig. 3).

Excess N then leads to increases in animal blood urine-N concentrations (Fig. 5), shown in an experiment where variations in plantain in the animal diet were used to vary feed-N contents (Minnée et al., 2020). It clearly confirms the chain of events from variations of N contents in animal diets leading to variations in animals' blood urea concentrations (Fig. 5) to then lead to the excretion of excess N (Figs. 2, 4) in urine in concentrated urine spots.

3. Matching N supply and demand

In principle, the supply of N in animal feed can be reduced by

a) feeding supplements with lower N contents;
b) growing pasture species with lower N contents;
c) selecting pasture cultivars with lower N contents;
d) reducing pasture N through management.

The first two of these options are the strongest candidates for reducing feed N contents and are explored in the following Sections. Options c) and d) provide only subtler benefits that could be useful if they can be implemented cost-effectively, but they are not further explored here.

3.1 Feed supplements

Figure 6 shows the N contents of various feed supplements commonly fed to dairy cows in New Zealand. N contents vary from about 7 gN $kgDM^{-1}$ in molasses and straw to 55-60 gN $kgDM^{-1}$ in lupin concentrates and canola meal. Available feeds thus stretch all the way from supplements with N contents that are below animals' requirements to those that exceed the animals' needs. It provides a management tool for farmers to carefully match the N needs of their herds.

During early lactation when N demand is high (Fig. 4), supplements with high N contents (lucerne, lupins, canola) could be fed to animals to ensure that their N needs are met, whereas for the rest of the year, molasses, straw or maize silage (Fig. 6) could be used to lower N intake and minimise the excretion of excess N.

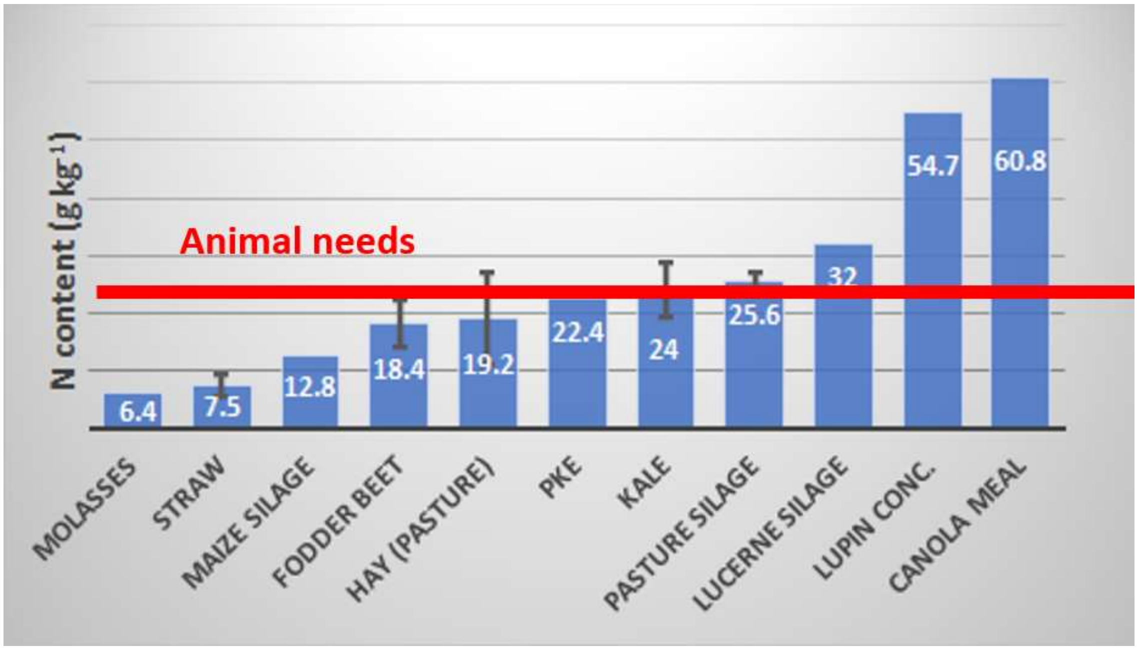

Figure 6: N contents in various feed supplements (Dairy NZ, 2020). The red line is indicative of animals' average N needs.

Figure 7 illustrates the potential emission reductions that could be achieved by partially replacing clover/ryegrass pasture with maize silage (e.g. Bryant et al., 2020; Dalley et al., 2020; Giltrap et al., 2021). The substitution percentages were calculated on the basis of metabolisable energy (ME) requirements to keep total ME intake constant. The simulations showed that N losses could potentially be reduced by up to 80% before the animals' maintenance metabolism would limit any further reduction requiring about 60% of ME to be provided by maize silage. Further increases in maize silage would lead to insufficient N intake to meet the animals' N requirements, and they would start losing condition with no further reduction in urine-N.

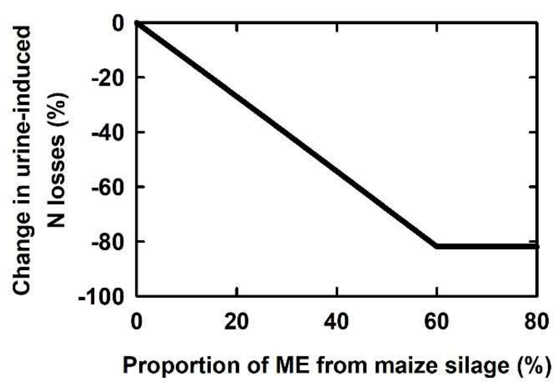

Figure 7: Reduction in urine-induced N losses (via leaching, NH_3 and N_2O emissions) with different proportions of pasture replaced by maize silage in animal feed. In these simulations, the total metabolisable energy (ME) consumed remained constant. Redrawn from Giltrap et al. (2021).

These simulations are only indicative in showing the potential reductions of harmful N flows to the environment that could be achieved through modification of feed-N intake. Further work is needed to operationalise these saving potentials with a view to constraints by management, ongoing productivity and animal welfare. Existing experimental studies, however, have confirmed the direction of these trends. Luo et al. (2008), for example, observed a 22% reduction in N_2O emissions per unit of milk production when cows were fed low-N maize supplements. While experimental work has confirmed the direction of changes, operational constraints will determine how much of the theoretical potential will be realised.

3.2 Growing pasture species with lower N contents

The New Zealand milk-production system is mostly based on grazing by animals on pastures growing throughout most of the year, which restricts the extent of managing feed-N intake through feed supplements. An important alternative management option is, therefore, to consistently lower feed-N intake by growing alternative pasture species (e.g. Mangwe et al., 2019). Over recent years, in particular, there has been increasing interest to grow plantain-based pastures (e.g. Box et al., 2017; Bryant et al., 2020; Minnée et al., 2017, 2020; Simon et al., 2019; Nkomboni et al., 2021) that can provide animal feed with lower N contents (Fig. 8).

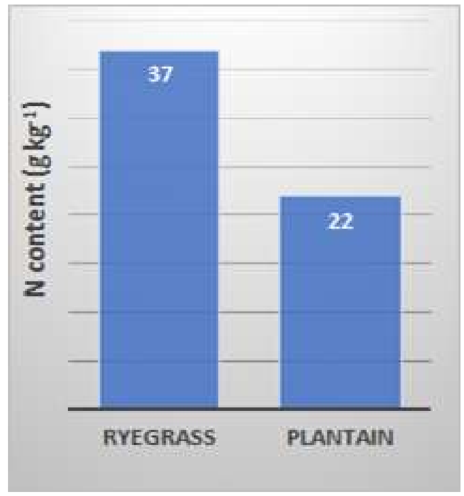

Figure 8: N contents in ryegrass and plantain. Data from (Minnée et al., 2020).

Differences in species compositions can then lead to differences in average N contents in feed intake to lead to the postulated differences in N losses to the environment through the need to excrete different amounts of urine N to maintain their overall N balance (Fig. 9).

Combining the findings of the studies by Simon et al. (2019) and Minnée et al., (2020) showed how urine N loss scaled directly with the N content of ingested feed (Fig. 9). This relationship confirmed the theoretical expectation of the relationship between these factors (Fig. 2). It confirmed the potential of reducing harmful N fluxes to the environment by modifying feed-N contents.

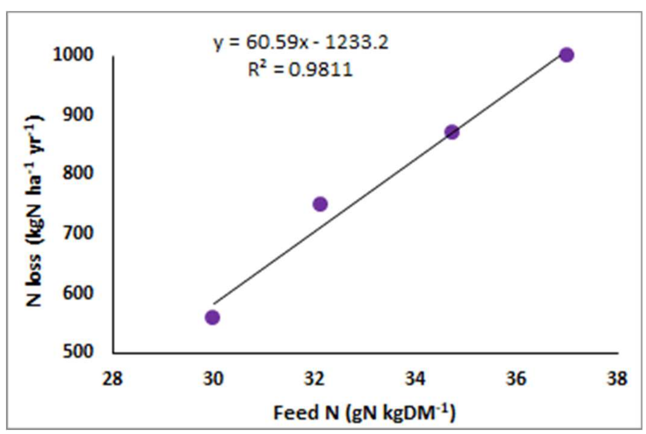

Figure 9: Urine N excreted by grazing animals fed by diets with different N contents, generated here through different plantain percentages in animal feed. Feed N contents are from Minnée et al. (2020) and N loss measurements from Simon et al. (2019).

4. Constraints

Theoretical analyses have pointed to the clear potential of reducing harmful N fluxes to the environment through manipulation of feed-N contents (e.g. Giltrap et al., 2021). Previous experimental studies have similarly shown that urine N losses are correlated with feed N contents in plant diets and supplements ingested by grazing animals (e.g. Castillo et al., 2000; Kebreab et al., 2001; Misselbrook et al. 2005; Dijkstra et al., 2013; Arndt et al. 2015; de Klein et al., 2020; Bryant et al., 2020).

It is challenging to exactly match the animals' N requirements throughout the year. The animals' N requirements continuously change as they pass through different life stages such as growth, gestation, and lactation. However, while it might be difficult to achieve an exact match between N supply in feed and animal requirements, most pastures currently provide a considerable N excess (Fig. 4) so that slight to moderate reductions in N would reduce excess N without posing the risk of pushing animals into N deficiency.

A more challenging constraint lies in the requirement for high pasture N content to maximise dry matter production (Gastal and Lemaire, 2002). The requirement to maintain maximum pasture growth, therefore, constrains a reduction of pasture N contents through fertiliser management. However, using low-N feed supplements (Fig. 6) could reduce the overall dietary N content (Kebreab et al., 2001; Pacheco and Waghorn, 2008; Dalley et al., 2020) without that constraint.

The evidence provided here and in previous publications (e.g. Castillo et al., 2000; de Klein et al., 2020; Dalley et al., 2020) documents the considerable potential of using reductions in feed N contents as a mitigation option. Key future research directions therefore need to focus on devising the most practical way to achieve this N reduction in a typical grazed pasture system. Additional feed supplements would also need to be assessed for their effects on enteric CH_4 emissions, animal health, and animal productivity (e.g. Gastal and Lemaire, 2002; Dalley et al., 2020).

5. Conclusions

Modification to the N content in animal feed provided the most promising results, with reduced N content resulting in lower urine N excretion and consequently reduced N_2O and NH_3 emissions, and N-leaching losses. In principle, feed N contents could be modified through changes in pasture N contents, either by changing species or by breeding cultivars of existing pasture species with lower N contents, or by providing supplemental feed with lower N contents.

6. Acknowledgements

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