Rural R&D for Profit Program

More Profit from Nitrogen

RRDP1714 (July 2016 – November 2019)

Increasing Nitrogen Use Efficiency in Dairy Pastures

Final Report

30th November 2019

Report prepared by: David Rowlings[1], Johannes Friedl[1], Warwick Dougherty[2] and Michael Fitzgerald[2]

[1]Queensland University of Technology

[2]NSW Department of Primary Industries

Ownership of intellectual property rights

This publication (and any material sourced from it) should be attributed as: Rowlings D.W., Dougherty, W., Friedl, J,. Carrick, S,. & Fitzgerald, M., 2019, Increasing Nitrogen Use Efficiency in Dairy Pastures (RRDP1714). *Final report submitted to the Cotton Research and Development Corporation - More Profit from Nitrogen Program*, CRDC, Narrabri NSW 2390, Australia.

This publication is available at https://www.crdc.com.au/more-profit-nitrogen

Disclaimer

The views and opinions expressed in this publication are those of the authors and do not necessarily reflect those of the Australian Government, CRDC, Dairy Australia, Queensland University of Technology, NSW Government and any other partner organisations.

Acknowledgements

This project was supported by funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program, Dairy Australia, Queensland University of Technology and NSW Department of Primary Industries. We would also like to thank Mr Wayne Clark, the host farmer of trials conducted in the NSW Northern Rivers region, and Cathy Phelps and Cath Lescun of Dairy Australia.

Project team details

Provide details of all personnel involved in the project.

Name	Position	Organisation	Role	Duration of involvement
David Rowlings	Chief Investigator	Queensland University of Technology	Project lead (overall)	3 years
Warwick Dougherty	Partner Investigator	NSW Department of Primary Industries	Project lead (NSW DPI component)	3 years
Johannes Friedl	Partner Investigator	Queensland University of Technology		3 years
Michael Fitzgerald	Research assistant	NSW Department of Primary Industries		3 years
Sarah Carrick	Research assistant	Queensland University of Technology		3 years
Majella Mumford	PhD student	Queensland University of Technology		3 years

Contents

Plain English Executive Summary

Nitrogen fertiliser inputs along with the import of feed are the key drivers for increased productivity on intensively managed dairy pastures in Australia. Nitrogen is a key input for pasture productivity, with pasture-based dairy being the most economical means of suppling the energy and protein required to meet cow metabolic needs. However, pasture production in the summer dominated winter rye grass/summer kikuyu subtropical dairy regions of NSW and QLD is frequently constrained by extended periods of intense rainfall and drought, making matching pasture N demand to fertiliser supply challenging. The key to reducing the impact this climatic variability has on productivity and N losses is through the effective management of the amount, type and timing of N fertiliser application, and by ensuring that N application matches plant N uptake demand. This research project applied state of the art analytical methods in a series of field trials across different dairy pasture soils in the summer dominated winter rye grass/summer kikuyu subtropical dairy regions of NSW and QLD to answer four core interconnected themes:

- Quantifying the scale, pathway and timing of N losses to allow for the development of effective mitigation strategies
- Determining pasture demand for fertiliser N throughout the year in response to climatic and seasonal variation, and how N fertiliser application rates can be adjusted according to amount and timing of N from long and short/medium mineralisation of organic soil matter
- Evaluate the effect of soil moisture variations on N cycling and the effectiveness of adjusting irrigation frequency to limit N losses and increase NUE.
- Determine the agronomic, economic and NUE benefits of using enhanced efficiency fertilisers under both irrigated and dryland conditions in the Northern dairy region.

To address these questions, a series of field, laboratory, and modelling experiments were conducted on dairy soils collected from undertaken at the two core sites in Camden, NSW and in Casino, NSW, and at the satellite sites at commercial dairy farms in Taree and Berry in NSW and Gympie and Kerry in Queensland.

Key messages

The results of this research found the supply of N from mineralisation in high carbon dairy pastures (i.e. uncultivated) is substantial, ranging from 100 kg N annually in duplex soils to over 170 kg N in heavier textured soils. Generally speaking applied fertiliser N is immobilised (taken up into the soil organic pool) during periods of high plant N demand such as the period of maximum rye grass growth in the spring (leading to a soil N "deficit"), and released during low plant N demand periods over the summer/early autumn. It is particularly prone to loss during large rainfall events in this period.

- As such increasing N application during early spring, and reducing application rates as the rye grass declines and temperatures increase going into summer is recommended.

Pasture growth responded to additional N fertilisation following the classic plateauing of growth and decreasing marginal responses at the higher N rates. Application of N fertiliser can still be profitable however even at high rates under optimal conditions, particularly when feed costs are high (i.e. drought).

- Applying N above the optimum in terms of pasture response will decrease NUE, and increases N losses and should be avoided if possible because (a) the accumulation of nitrates in the pasture biomass can have a detrimental effect on heard health and milk production and (b) environmental issues associated with reactive N (i.e. nitrous oxide, nitrate leaching).

Effective irrigation can limit N losses if application rates don't exceed evapotranspiration rates, though losses rapidly increase if soils become saturated for extended periods of time (>12 hours). At the heavy clay Casino site N losses increased rapidly when irrigation or rainfall exceeded 100 mm, but were relatively minor below this threshold. More frequent irrigation (~every 4 days) saved water and increased irrigation use efficiency by 80% and saved pumping costs of $10-$14 per tonne of pasture produced per hectare by simply allowing more flexibility in scheduling irrigation in relation to rain events and reducing the reliance on rainfall predictions.

- Irrigation schemes should therefore account for estimated evapotranspiration loss, as a threshold above which major N loss can be expected. More frequent irrigation below this threshold will not reduce N loss, but increase irrigation use efficiency and improve accounting for rainfall events and is therefore recommended.

Climatic conditions during the winter/spring annual rye grass fertilisation period rarely produce conditions conducive for N loss of surface spread urea. The exception to this is occasional hot and windy conditions following cold fronts in late October/early November when application of urea should be avoided. As such there is no additional benefit in yield, N uptake or apparent NUE to using volatilisation inhibitors (such as green urea) under normal climatic conditions.

The application of the nitrification inhibitor DMPP (ENTEC) has been shown to reduce direct losses of N via denitrification during large rainfall events, increase immobilisation of N into the organic matter and increase pasture productivity during the winter/spring rye grass period.

- The nitrification inhibitor DMPP (ENTEC™) demonstrated a clear benefit in terms of pasture production at a lower application rate, particularly in the ryegrass. As such, the feed associated profit even accounting for the additional cost of the product increased by over 20%. Assuming 12 grazing a year this represents potential ***feed savings $212 ha^{-1} annually***.

Due to the high potential of N losses in subtropical dairy production systems, profitability from N fertiliser should be focussed on trying to match plant demand within the short-medium term (1-3 grazing cycles) as opposed to broad seasonal rules of thumb. The precision of these applications, and the room for error, is lower sandier soils with less carbon (i.e. Camden), which react rapidly to N fertilisation in a predictable and manageable manner, with the majority of N being available for plant uptake shortly after application. The heavier, higher carbon clay soils however absorb (immobilise) a significant greater proportion of applied N particularly under high-growth conditions, which is then released (mineralised) under warm and wet conditions when it can be prone to loss. The success of enhanced efficiency fertilisers appears directly tied to this fertiliser N interaction with the organic matter, and have greater potential in the clayeyer soils. As such their use should be used in conjunction with more strategic N management during the different growing seasons, while ensuring adequate soil moisture is available to optimise plant N utilisation.

Abbreviations and glossary

BD	Bulk density
C	Carbon
C:N	Carbon-to-nitrogen ratio
CO_2	Carbon dioxide
DL	Detection limit
DMPP	3, 4-dimethylpyrazole phosphate
D_p/D_0	Soil gas diffusivity
EF	Emissions factor
EEF	Enhanced efficiency fertiliser
GHG	Greenhouse gas
IRMS	Isotope ratio mass spectrometer
MDL	Method detection limit
N	Nitrogen
N_r	Reactive nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_2OH	Hydroxylamine
NH_3	Ammonia
NH_4^+	Ammonium
NO_x	Mono-nitrogen oxides
NO	Nitric oxide
NO_2^-	Nitrite
NO_3^-	Nitrate
NI	Nitrification inhibitor
NUE	Nitrogen use efficiency
fNUE	Fertiliser nitrogen use efficiency
O_2	Oxygen
SOC	Soil organic carbon
SOM	Soil organic matter
WFPS	Water filled pore space

1 Project rationale

Nitrogen fertiliser inputs along with the import of feed are the key drivers for increased productivity on intensively managed dairy pastures in Australia. However, only 15-30% of the applied N is recovered in milk and meat products, revealing one of the lowest N use efficiencies (NUE) reported for agricultural systems (Goulding et al., 2008; Gourley et al., 2012). The resulting N losses on a farm level raises concerns about inefficient N management and related N_r pollution from these agro-ecosystems, and create environmental and agronomic pressure on farmers to reduce N losses from intensively managed pastures.

At the same time N is a key input for pasture productivity, with pasture-based dairy being the most economical means of suppling the energy and protein required to meet cow metabolic needs. Farm-grown fodder reduces the need for imported feed (Gillespie and Nehring, 2014), and maximising yields is essential particularly in times of drought when feed costs are high. Intensive dairy pastures require annual fertiliser-N inputs (fN) of up to 680 kg N ha^{-1} (Lowe *et al.*, 2005) and frequent irrigation to supplement rainfall (Bethune and Armstrong, 2004). The rising cost of fN and the increasing scarcity of water resources, make the viability of dairy farming in Australia dependant on maximising pasture yield from fewer inputs.

Fertiliser represents the third greatest expense on Australian dairy farms, following only the cost of supplementary fodder and wages (Dairy Australia, 2018), and the dairy industry is the second largest user of irrigation water in Australian agriculture. The costs associated with the maintenance of irrigation equipment and the cost of electricity required for pumping are significant factors in the decision making process of landholders. Maximising pasture production per unit of irrigation and improving water use efficiency (WUE), as well as improving N use efficiency (NUE) by reducing Nr losses, must therefore be a focus of farm operations.

Nitrogen losses result from the mismatch between plant N demand and fN supply (Fig 1), and are suspected to occur via various pathways including runoff, leaching and via denitrification. Denitrification is a microbial mediated process, triggered by anoxic conditions in the soil. Rainfall and irrigation trigger these conditions by limiting the diffusion of oxygen into the soil, stimulating the reduction of plant available nitrate (NO_3^-) to nitrous oxide (N_2O) and further to dinitrogen (N_2). Both N plant uptake and N loss are driven and limited by the supply of mineral N through the mineralisation of organic matter and the application of N fertiliser. Improved management of N on dairy pastures needs to be therefore based on an improved quantitative understanding of (a) N cycling in pasture soils, (b) the fate of applied N fertiliser and (c) N loss pathways.

While periods of intense rainfall and drought will always be a feature of the summer dominated winter rye grass/summer kikuyu subtropical dairy regions of NSW and QLD, the key to reducing the impact this climatic variability has on productivity and N losses is through the effective management of the amount, type and timing of N fertiliser application, and by ensuring that fN application matches plant N uptake demand.

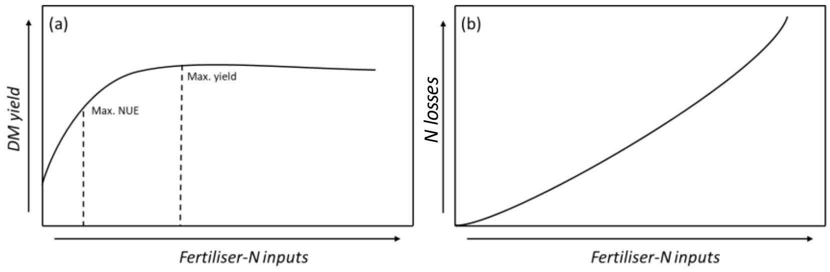


Figure. 1 (a) Generalised exponential rise to a maximum response of DM yield to increasing fertiliser N (fN) inputs (Godard et al., 2008) (b) Relationship between fN inputs and N losses (adapted from Shcherbak et al., 2014)

This research project applied state of the art analytical methods in a series of field trials across different dairy pasture soils in the summer dominated winter rye grass/summer kikuyu subtropical dairy regions of NSW and QLD to answer three core interconnected themes:

1) Determine the agronomic and economic effectiveness of applying fertiliser across different seasons, climatic conditions and soils and quantifying the scale, pathway and timing of N losses to allow for the development of effective mitigation strategies

2) How much and when does soil mineralisation contribution to plant available N?
    - What is the annual and seasonal supply of N from soil organic matter and how does it interact with fertiliser application and plant demand
    - What is the short and mid-term fate of applied N fertiliser on intensively managed dairy pastures
    - How do soil mineralisation rates vary between different dairy soil types?

3) Under what climatic and soil moisture conditions do N losses occur and can irrigation be manipulated to reduce losses? This issue was addressed by answering the following research questions:

    - When do gaseous N losses via denitrification occur?
    - What drives denitrification losses?
    - Can denitrification losses be reduced by altering the irrigation frequency (i.e. same amount of water applied over different intervals)?

4) What is the potential for enhanced efficiency fertilisers (EEF's) to reduce losses, improve NUE and increase profitability?
    - How important are volatilisation losses to pasture productivity and can urease inhibitors increase NUE?
    - When is the most economical time to apply nitrification inhibitors?
    - Can nitrification inhibitors reduced Nr losses to the environment?

Project findings:

Key recommendations for industry:

Nitrogen losses from subtropical dairy can be significant, and represent substantial real-world costs in terms of lost production potential, direct losses of applied fertiliser and environmental losses that contribute to the carbon footprint of the industry. Dairy has one of the largest per area greenhouse footprints of any agricultural industry with field scale losses >10 kg N_2O-N per hectare. A large proportion of farm N inputs (urine and fertiliser) are immediately immobilised into the soil organic matter (SOM), particularly on the heavier clay soils, during periods of high plant demand (such as spring ryegrass), and this N is released via mineralisation during large summer rainfall events when it is prone to large losses including as N_2O. Thus, better management of the timing of N fertiliser application to account for this uptake and release from the SOM not only has the potential to reduce fertiliser input costs, but also reduce the carbon footprint of the industry.

Key messages for dairy farmers:

Application of N fertiliser can still be profitable even at high rates under optimal conditions, particularly when feed costs are high (i.e. drought). Applying N above the optimum in terms of pasture response however decreases NUE, and increased N loss to the environment.

The supply of N from mineralisation in high carbon dairy pastures (i.e. uncultivated) can contribute substantially to annual nutrient budgets but is highly variable and difficult to manage. Generally speaking applied fertiliser N is immobilised (taken up into the soil organic pool) during periods of high plant N demand such as the period of maximum rye grass growth in the spring (leading to a soil N “deficit”), and released during low plant N demand periods over the summer/early autumn. It is particularly prone to loss during large rainfall events in this period. As such increasing N application during early spring, and reducing application rates as the rye grass declines and temperatures increase going into summer is recommended. The influence that mineralisation on productivity and fertiliser NUE is much greater in soils with higher clay and carbon contents.

Effective irrigation can limit N losses if application rates don’t exceed evapotranspiration rates, though losses rapidly increase if soils become saturated for extended periods of time (>12 hours). At the heavy clay Casino site N losses increased rapidly when irrigation or rainfall exceeded 100 mm, but were relatively minor below this threshold. More frequent irrigation (~every 4 days) saved water and increased irrigation use efficiency by simply allowing more flexibility in scheduling irrigation in relation to rain events and reducing the reliance on rainfall predictions. At the same time less frequent irrigation utilised stored moisture (and potentially nitrogen) in the soil profile better, with water utilisation recorded down to 70 cm compared when irrigation was applied in one event per grazing cycle compared to only 30 cm if applied over 4 events.

Climatic conditions during the winter/spring annual rye grass fertilisation period rarely produce conditions conducive for N loss of surface spread urea. The exception to this is occasional hot and windy conditions following cold fronts in late October/early November when application of urea should be avoided. As such there is no additional benefit in yield, N uptake or apparent NUE to using volatisation inhibitors (such as green urea) under normal climatic conditions.
The application of the nitrification inhibitor DMPP (ENTEC) has been shown to be both agronomically effective and economical, however should be applied at reduced rates from standard urea fertiliser to ensure profits are maximised.

2 Method and project locations

The methods used to investigate abovementioned research questions are briefly summarised for each experiment. Experiments were undertaken at the two core sites in Camden, NSW and in Casino, NSW, and at the satellite sites at commercial dairy farms in Taree and Berry in NSW and Gympie and Kerry in Queensland. Site characteristics including physical and chemical soil properties, are shown in Table 1.

Table 1: Selected soil characteristics intensively managed pasture sites under dairy production in New South Wales and Queensland.

Soil property	Casino	Camden	Gympie	Kerry	Taree	Berry
Latitude	-28.865	-34.12	-26.19	-28.109	-31.91	-34.79
Longitude	152.874	150.705	152.74	153.031	152.55	150.74
Mean annual rainfall	1107 mm	791 mm	1127 mm	907 mm	1244 mm	1467 mm
Soil type (ASC)	Vertosol	Chromosol	Dermosol	Tenosol	Chromosol	Chromosol
pH (H_2O)	6.3	5.5*	6.1	5.9		
Organic Carbon (%)	4.2	2.9	4.9	4.1	3.2	
Total Nitrogen (%)	0.36	0.24	0.5	0.4	0.3	
C:N ratio	11.4	12.1	9.8	10.4	9.4	

*pH_{ca}

2.1 Experimental design

The objectives of the project were addressed in the series of overlapping experiments outlined below across the core and satellite sites. Details are given in the technical report.

2.1.1 Determining N demand, predicting and accounting for mineralisation

Estimating plant available Nitrogen (PAN) is critical in dairy systems to maintain DM yield, while avoiding excess nitrate (NO_3^-) uptake into the aboveground biomass. PAN is usually based on soil mineral N levels in the soil (NO_3^- and NH_4^+). The constant plant N uptake under pastures however limits the usefulness of soil mineral N concentrations as a proxy for PAN, demanding more accurate ways of estimating PAN.

Pasture response to applied N fertiliser trials were conducted at both Casino and Camden to determine the long-term pasture N demand under different climatic conditions, and the long-term supply of N from mineralisation. Trials were conducted under controlled, “ideal” conditions (full irrigation) on experimental plots (Camden and Casino) as well as in grazed paddock plot representing real farm conditions.

Pasture demand for PAN and the potential of the soil to ***supply*** their requirements through mineralisation were assessed over three years at the core sites by comparing a zero N treatment to a non-limiting N treatment (“Fully fertilised” - FF) under optimised experimental plot conditions.

Fertiliser recoveries using ^{15}N labelled urea were conducted in conjunction with both the N rate trial and irrigation trials (see below) to estimate both short-medium term mineralisation/immobilisation dynamics of N and the interaction of added fertiliser N with the soil organic N pool.

^{15}N tracer experiments were conducted at the laboratory scale to determine gross N transformation in different pasture soils using a numerical ^{15}N tracing model.

2.1.2 Influence of Irrigation frequencies on N losses and turnover

This series of experiments investigated the impact of different irrigation frequencies on N turnover and N loss from dairy pastures. Irrigation treatments were based on a simple evapotranspiration model, with irrigation applied in one event, split into two events or split into four events. (LOW Frequency + High Rate, MEDIUM Frequency + Medium Rate, HIGH Frequency + Low Rate).

Annual irrigation trial: This experiment was conducted over ten months in Casino investigating the impact of irrigation frequencies on emissions of N_2O as an indicator for overall N loss, and on pasture BM yield. Gaseous N loss in the form of N_2O was monitored using a fully automated GHG system and pasture yield was quantified by mowing.

Winter irrigation campaign: The winter campaign was conducted in 2017 in Camden and Casino. This campaign investigated the impact of different irrigation frequencies on key components of N cycling and loss from pasture soils: (a) Above ground biomass yield, (b) Short and mid-term ^{15}N fertiliser fate in the soil-plant and atmosphere system over three grazing cycles, (c) N_2 and N_2O losses from fertilised pasture soils, and (d) N_2 and N_2O losses from urine patches.

Irrigations impact on N loss following intense rainfall: This experiment in Casino investigated the effect of LOW and HIGH irrigation frequency on N_2 and N_2O losses in response to a simulated rainfall event in November 2017.

2.1.3 Effectiveness of Enhanced Efficiency Fertilisers

A series of experiments were conducted at both core sites to determine if and under what conditions different EEFs are effective. The experiments investigated the performance of the nitrification inhibitor DMPP (ENTEC™) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBTT - Green Urea™).

The ***Long term DMPP trial*** in Casino evaluated different application strategies of DMPP on biomass and pasture N yield. Treatments were applied to the same plots over three years to ensure any long-term effects associated with increased fertiliser immobilisation from the inhibitor (as seen in Friedl *et al.*, 2017a) and was conducted on grazed paddock plots to replicate "real" farm conditions.

The effect of DMPP on direct fertilizer and urine N losses: This trial was conducted at Casino to determine the magnitude of N losses from urine patches fertilised with broadcasted urea following grazing, and if urea coated with the inhibitor DMPP (ENTEC™) could reduce N losses. Treatment application mimicked the typical summer dairy practice in the region where the urea fertilisers were applied prior to every second grazing.

Agronomic importance of NH_3 volatilisation N losses and effectiveness of Green urea: Two trials to determine the agronomic importance of NH_3 volatilisation losses and the potential of the commercial EEF "Green Urea" to reduce losses. Standard urea (U) and urea coated with the urease inhibitor NBTT (GU) were compared over two campaigns at Camden and Casino. To ensure any potential savings in NH_3 were detectable in the harvested biomass, the trial was conducted on a section of the 4-year-old zero N and farmer's practice plots representing extremely N limited and non-N limited soil conditions.

2.1.4 Experimental methodology

Methods applied across different experiments are briefly summarised below.

Pasture productivity: Pasture production was typically monitored over both the annual rye grass and kikuyu growing periods. Grazing was simulated by mowing plots to a height of 5 cm with clippings removed from the plots. Pasture samples were dried and ground prior analysis for total N. From this data, total N removed via plant uptake was calculated and an apparent fertiliser recovery performed. Full details can be found in the technical report and in Mumford et al. (2019).

Measuring denitrification losses from intensively managed pastures: Gaseous N losses in the form of N_2 and N_2O were measured using the ^{15}N gas flux method in both laboratory-based trials and the field. This method requires the application of highly enriched ^{15}N fertiliser and analysis of gas samples using Isotope ratio mass spectrometry. Gas samples were analysed at the Isotope facility at QUT's central analytical facility. High temporal resolution N_2O measurements were obtained using fully automated sampling system in Camden and Casino, consisting of 12 pneumatically operated gas-sampling chambers and a gas chromatograph housed in a trailer at each site.

Fertiliser ^{15}N recovery: The use of ^{15}N fertiliser allows tracing applied N fertiliser in the soil plant and atmosphere system. Using apparent N fertiliser recoveries, the contribution of N fertiliser to a specific N pool is the balance between N recovered in this pool and N recovered in this pool from a zero N fertiliser treatment. This method however neglects the interaction between N fertiliser and mineralisation. The application of ^{15}N fertiliser at the different pasture sites allowed to establish accurate N fertiliser budgets, specifying plant fertiliser N uptake, the contribution of mineralisation to plant N and occurring N losses over several grazing cycles.

Incubations: Incubations to quantify denitrification losses and rates of mineralisation and nitrification were conducted using a triple ^{15}N labelling setup described in detail in Friedl et al. (2016). The numerical model n-trace was used to quantify different N transformation and losses.

Research Site Type	**Name**	**Location**	**Coordinates**	**Active Site Period**	**Experimental treatments**
Farmer	Wayne, Paul and Vicky Clarke	Dobies Bight, Casino, NSW	-28.81, 152.98	2016-2019	Irrigation frequencies, rainfall simulation, N fertiliser rates and EEF products, Urine patches
Research station	Elizabeth McArthur Agricultural Institute	Menangle NSW 2568	-34.13, 150.72	2016-2019	Irrigation frequencies, N fertiliser rates and EEF products, Urine patches
Farmer	Rob and Reuve Thef	Cedar Pocket, QLD	-26.19, 152.74	2016-17	^{15}N recoveries, N turnover processes
Farmer	Sally and Michael Undery	Kerry, QLD	-28.109, 153.031	2016-17	^{15}N recoveries, N turnover processes
Farmer	James Neale	Oxley Island, Taree	-31.91, 152.55	2019	^{15}N recoveries, N response
Farmer	Wayne and Gail Brown	Berry	-34.79, 150.74	2019	^{15}N recoveries, N response

The experiments and trials cover intensively managed dairy pastures with a Kikuyu/rye grass rotation in the norther subtropical regions in southeast Queensland and New South Wales dairy regions across different soil types (Table1). Agronomic metrics and findings are applicable primarily in those regions with similar climatic conditions and farming practice. However, the general relationships between (a) soil water and N loss via denitrification and (b) efficacy of the nitrification inhibitor DMPP demonstrated in this project are also applicable in other regions and cropping systems.

3 Project Outcomes

The outcomes of this project are summarised according to the objectives outlined above:

1. *Agronomic, NUE, losses and economic indicators of N fertiliser application to dairy pastures*

Agronomic responses to applied N and subsequent NUE and economic indicators varied greatly across soil and management types, seasons and even between grazing cycles. Highest and most consistent responses to applied N were in the precisely managed (adequate moisture and grazing interval) at Camden where response to applied N was mostly linear, but were much more variable under the real-world conditions in Casino, Berry and Taree (Figure 2). Responses to fertiliser application in summer kikuyu at Casino ranged from flat (no response) under dry conditions in late February, low but linear responses under marginal conditions in March to the classic exponential rise to a maximum response curve under optimal conditions. Overall 90% of maximum yield (Ymax90) was achieved at 23 kg N ha^{-1} application (1.5 kg N ha^{-1} day^{-1}) for kikuyu and 36 kg N ha^{-1} (1.7 kg N ha^{-1} day^{-1}) under paddock conditions. The economical benefits of applying N under different scenarios is presented in section 3.3.

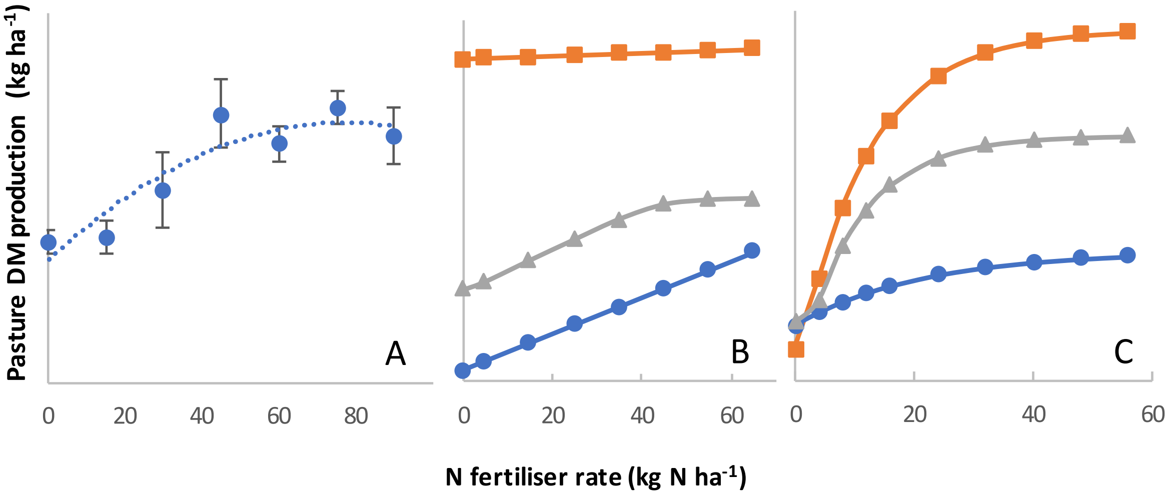


Figure 2. Examples of the variation in pasture production in response to N application rate response curves on farm trials at (A) Berry - dryland, (B) Casino –irrigated ryegrass, and (C) Casino irrigated- kikuyu.

Key findings:

The research findings highlight the potential to grow large quantities of pasture feed under well managed conditions with adequate water supply in sandy soils. There was only a minor decrease in marginal dry matter production with increasing N rate and the DM production rates per unit of N were high under non-moisture limiting conditions.

- Under paddock conditions even with irrigation, the N response trials demonstrated mostly the classic plateauing response to N application rates across sites, with the benefit of addition N applications declining at the higher N rates.
- Smaller, frequent applications are much more effective than larger, less frequent applications in clay soils but this is less important in sandier soils.

- Application of N fertiliser can still be profitable even at high rates under optimal conditions, particularly when feed costs are high (i.e. drought). Applying N above the optimum in terms of pasture response however decreases NUE, and increases N loss to the environment.
- However a substantial amount of applied N (30-40%) is still lost from the soil-pasture system, more when urine is taken into account.
- The overapplication of N fertiliser above the optimum should be avoided because (a) the accumulation of nitrates in the pasture biomass can have a detrimental effect on heard health and milk production; and (b) losses of applied N from dairy systems (30-40%)

2. Predicting and accounting for mineralisation and timing of N fertiliser application to match plant demand

The capacity of soil to ***supply*** pasture N requirements through mineralisation was assessed over three years and a wide range of climatic conditions at Casino and Camden. This was done by analysing the production and N removal rates from Zero N plots that received no N inputs over the duration of the study. Annual removal rates also allowed the long-term contribution of mineralised N to plant uptake (Figure 3). ***Plant demand*** for N for fertiliser was then assessed by examining the variability in maximum production under non-limiting conditions (adequate N + irrigation), and subtracting this from the soils capacity to supply N via mineralisation (zero N plots). Highest pasture production of up to 70-80 kg DM ha day^{-1} typically occurred between September and October, representing the peak of the rye grass where daily N uptake exceeded 2.5 kg N day^{-1}.

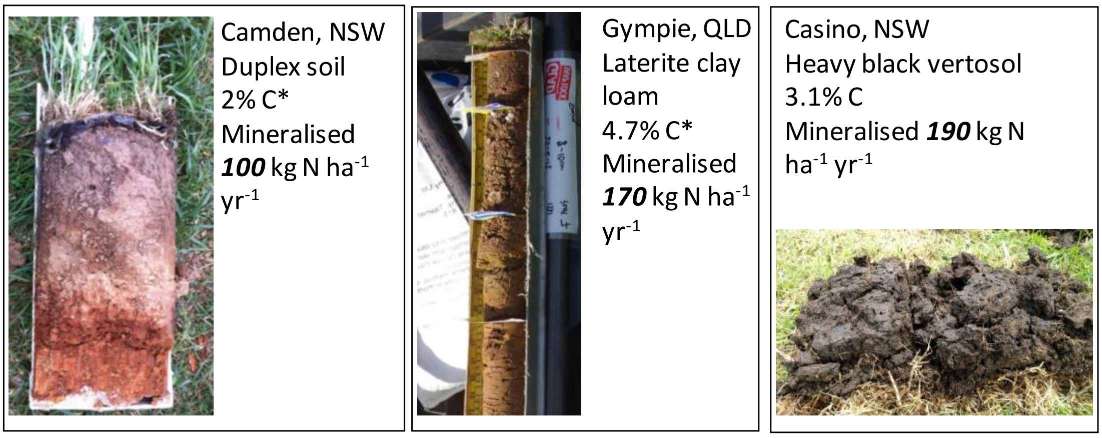


Figure 3. Potential annual N mineralisation rates from different soils typical of the subtropical dairy region.

<u>Key findings:</u>

- N mineralisation in high carbon dairy pastures (i.e. uncultivated) ranges from 100 kg N annually in duplex soils to over 170 kg N in heavier textured soils and represents a key resource. However this resource typically only becomes available under warm and wet summer conditions, and is easily lost via denitrification.
- Plant demand (Figure 4) is highest during the peak rye grass growing period (Sept-December) and lowest just after rye establishment (low plant demand) and in late summer (high mineralisation)

- Applied fertiliser N is immobilised during periods of high plant N demand (spring rye)
- Immobilised N is released during low plant N demand periods over the summer/early autumn. These findings are confirmed by the results of the ^{15}N recovery tracing the fate of applied N fertiliser over three grazing cycles.

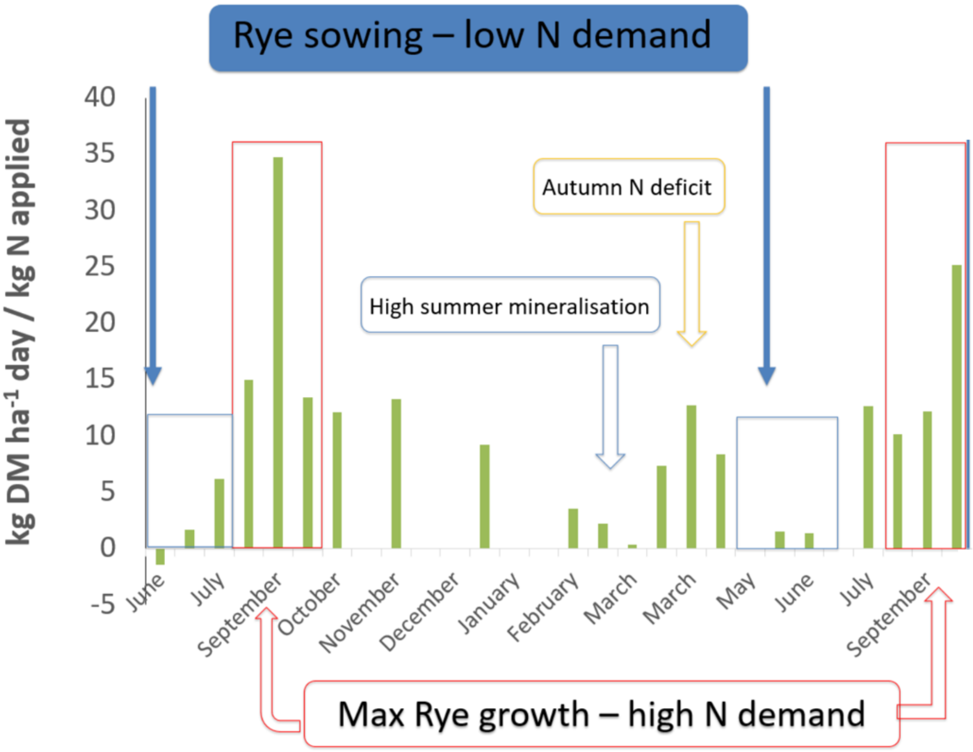


Figure 4. Averaged pasture N demand as expressed as kg dry matter per kg N applied from subtropical dairy pastures. N demand was calculated by subtracting the zero N plot biomass from the fully fertilised farmer practice treatment.

3. *Impact of different irrigation frequencies on denitrification losses from dairy pastures*

This research investigated the potential of different irrigation frequencies to reduce denitrification losses from pasture soils.

Annual irrigation trial: This trial used emissions of N_2O as an indicator for gaseous N loss as affected by different irrigation frequencies. Highest cumulative N_2O losses of 5.9±0.5 kg N ha^{-1} were measured from the LOW-Frequency treatment, which was significantly higher than the MEDIUM and HIGH-Frequency treatments with 3.2.±0.2 kg ha^{-1} and 3.8±0.5 kg ha^{-1}, respectively. Despite the significant reduction in N_2O losses by the HIGH and MEDIUM treatment, these N savings did not translate into a benefit to pasture production and NUE as was hypothesised. Over the ten month measurement period, the difference between the irrigation treatments was less than a tonne of DM. Less frequent irrigation utilised stored moisture (and potentially nitrogen) in the soil profile better, with water utilisation recorded down to 70 cm compared when irrigation was applied in one event per grazing cycle compared to only 30 cm if applied over 4 events. However, large differences were seen in the efficiency metrics, especially that of N_2O intensity, the combined metric of N_2O intensity per unit of irrigation water use efficiency (WUE) and the irrigation related electricity costs of each treatment. This largely resulted from the high-frequency irrigation better being able to account for unexpected rainfall events, allowing 200 mm of irrigation to be saved and increasing WUE by 80%.

Table 2 Summary of, pasture yield and N removal, N_2O emissions, Emission Factors (EF) and treatment intensity metrics an irrigated dairy pasture in Casino, Australia. The standard error is given in parentheses; the statistical significance is denoted by subscript letters (Mumford 2019).

	High-Frequency	**Medium-Frequency**	**Low-Frequency**
Biomass yield (t DM ha^{-1})	13.2 (0.3)$_a$	12.5 (0.3)	12.6 (0.5)$_a$
Total N yield (kg ha^{-1})	437.2 (20.1)$_a$	411.7 (13.3)$_a$	410.1 (13.2)$_a$
Daily biomass yield (kg DM ha^{-1} d^{-1})	38 (1.3)$_a$	37.6 (0.9)$_a$	37.3 (1.5)$_a$
Total N_2O loss (g N ha^{-1})	3790 (417)$_a$	3282 (232)$_a$	5855 (534)$_b$
Emission Factor	0.62 (0.12)	0.49 (0.05)	1.17 (0.14)
Irrigation Water Use Efficiency (kg DM mm^{-1})	44.8	29.6	25
N_2O intensity (kg N_2O kg DM^{-1})	0.29	0.26	0.46
N_2O intensity per unit of Irrigation Water Use Efficiency (kg N_2O kg DM^{-1} mm^{-1})	0.08	0.11	0.23

Winter irrigation campaign: Table 3 summarises denitrification losses under three different irrigation frequencies from fertilised pasture and from urine patches in Camden and Casino, NSW. Denitrification losses at both sites were ranged from 1 to 5 kg N ha^{-1} over 20 days from the fertilised pasture plots. These losses are considerably lower than the 20-28 kg ha^{-1} observed over 21 days in Gympie and Casino, respectively, when a large rainfall event of 200 mm was simulated. The low N_2 and N_2O losses at both sites demonstrate that accounting for the evapotranspiration rate limits denitrification losses from intensively managed pastures. Losses from the Urine patches were higher than those from the fertilised plots, with up to 28 kg of N lost via denitrification over 60 days. For the fertiliser only plots, the irrigation frequency had no significant effect on overall denitrification losses, and there was no significant difference between Casino and Camden. MEDIUM and HIGH frequency irrigation reduced N_2O losses in Casino, representing a reduction of environmental harmful N losses from dairy pastures. However, the magnitude of these N_2O emissions is agronomically not significant. As other rural industries such as MLA move towards carbon-neutral production, reducing emissions of the GHG gas N_2O is likely to become more important also in dairy systems. Marketing of carbon neutral products frames the term “More profit for N” differently, making a reduction of the GHG footprint of a farming system also an economically interesting option. Our findings regarding N_2O reduction are site/soil specific, showing that further research is needed to evaluate on which soil type a reduction of N_2O can be achieved by increasing the irrigation frequency.

Table 3 Denitrification losses under three different irrigation frequencies from fertilised pasture and from urine patches in Camden and Casino, NSW.

Site	Season	Days	Nitrogen	Treatment	N_2	N_2O	N_2+N_2O
Casino	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	HIGH irrigation frequency	4.97 ± 0.89	0.21 ± 0.03	5.18 ± 0.87
Casino	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	MEDIUM irrigation frequency	0.92 ± 0.10	0.28 ± 0.05	1.20 ± 0.09
Casino	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	LOW irrigation frequency	4.50 ± 0.66	0.72 ± 0.25	5.22 ± 0.76
Casino	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1})	HIGH irrigation frequency	28.34 ± 3.18	1.91 ± 0.26	30.28 ± 3.48
Casino	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1})	LOW irrigation frequency	27.91± 5.56	2.81 ± 0.22	30.74 ± 5.75
Casino	Rye/November	15	Urea-N fertiliser (30 kg N ha^{-1})	HIGH irrigation frequency + rainfall of	5.55 ± 0.91	1.75 ± 0.60	7.30 ± 1.48
Casino	Rye/November	15	Urea-N fertiliser (30 kg N ha^{-1})	LOW irrigation frequency + rainfall of	6.32 ± 0.64	2.27 ± 0.75	8.59 ± 1.33
Camden	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	HIGH irrigation frequency	4.31 ± 0.58	0.04 ± 0.01	4.35 ± 0.58
Camden	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	MEDIUM irrigation frequency	2.32 ± 0.52	0.07 ± 0.03	2.39 ± 0.55
Camden	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	LOW irrigation frequency	3.03 ± 0.82	0.09 ± 0.03	3.12 ± 0.84
Camden	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1})	HIGH irrigation frequency	17.78 ± 2.28	0.59 ± 0.13	18.39 ± 2.42
Camden	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1})	LOW irrigation frequency	12.71 ± 1.88	0.32 ± 0.06	13.05 ± 1.95

* Urine was applied at an equivalent rate of 800 kg N ha^{-1}

- Improved N management on dairy farms should aim to adjust irrigation by replacing the evapotranspiration rate to limit denitrification losses (N_2+N_2O) triggered by irrigation. However, our results do not show a reduction of overall denitrification (N_2+N_2O) by increasing the irrigation frequency from LOW to HIGH. The reduction of N_2O in the MEDIUM and HIGH treatment observed in Casino indicates a viable option to reduce environmental harmful N losses from these pastures, requiring further research.

Impact of different irrigation frequencies on denitrification losses triggered by a rainfall event: The research question of this study was if increased irrigation frequency could increase the resilience of a dairy pasture to denitrification losses after a simulated rainfall event. The experiment included the HIGH and LOW irrigation frequency, and a simulated rainfall event of 100 mm ten days after fertiliser application. After fertilisation, denitrification losses responded to the treatments, with higher emissions for LOW frequency treatment compared to HIGH frequency treatment. Subsequent N_2 and N_2O emissions from LOW decreased, while cumulative N_2 and N_2O emissions with every HIGH irrigation event, offsetting the initially higher N losses from the LOW frequency treatment nine days after fertiliser application. Peak N_2+N_2O losses were affected by irrigation frequency. However, the relative change in the N_2:N_2O ratio showed a shift from N_2O to N_2. These findings show that the constant irrigation in HIGH frequency treatment did not reduce overall N losses, but led to constant stimulation of denitrification, resulting in the same N losses as in the LOW treatment after three irrigation events. The experiment confirmed however the expected legacy effect regarding the N_2:N_2O ratio, suggesting increased irrigation frequency as a means to reduce N_2O.

- Irrigation frequency had showed no effect on overall N loss via denitrification, and strategies such as the use of EEF's (see EEf trials)need to applied when large rainfall events are expected to contribute to considerable N loss via denitrification.

Key findings:

- Results from the irrigation and denitrification trials demonstrated that only small, but significant N losses (1-5 kg or 3-15% of applied N per grazing cycle) occur under irrigation regardless of irrigation amount/frequency, up to irrigations of 80 mm per application.
- However losses increase exponentially the longer soils stay saturated under large (>100 mm) rain events, when losses can exceed 20 kg N ha^{-1} or equivalent to >60% of applied N. Casino has averaged over five, >100mm rain events per year so this represents the dominant N loss pathway.
- The effect of soil type on the magnitude of denitrification was less than expected, with similar losses observed from the sandy Camden site and the heavy clay Casino soil. This is most likely due to the good soil structure from the permanent pasture at Casino allowing rapid infiltration, and losses would be higher in cultivated, low organic matter, compacted or sodic soils.
- Denitrification losses from urine patches can exceed 30 kg N in the first 2 months, relatively minor compared to the >700 kg N inputted. However, more losses are likely following large rainfall events
- Improved pasture N management should aim to maximise soil aeration to minimise conditions conducive for denitrification and the formation of excess mineral N in the soil. Management options include improved irrigation, minimising compaction while ensuring adequate water supply for plant growth.

- More frequent irrigation (~every 4 days) saved water and increased irrigation use efficiency from 25 kg per mm of irrigation to 45 kg per mm of irrigation by simply allowing more flexibility in scheduling irrigation in relation to rain events and reducing the reliance on rainfall predictions.
- Less frequent irrigation utilised stored moisture (and potentially nitrogen) in the soil profile better, with water utilisation recorded down to 70 cm compared when irrigation was applied in one event per grazing cycle compared to only 30 cm if applied over 4 events.

4. *Potential of enhanced efficiency fertiliser to improve NUE and pasture productivity*

Urease inhibitors (Green Urea): While climatic conditions were not severe during the duration of the trial, they represent the range of conditions that farmers would reasonably be expected to apply urea during the primary ryegrass fertilisation period. Results of trials at both Camden and Casino on the agronomic effectiveness of the urease inhibitor NBPT demonstrated that although there was a clear response to N in these trials (ensuring any potential N saving effect of the inhibitors should elicit a yield response), there was no additional benefits to biomass production. This suggests that under typical winter-spring growing conditions when the majority of fertiliser is applied, the risk of N loss through volatilisation is minimal.

Effect of DMPP on direct N_2O fertiliser and urine N losses: The combination of fertiliser urea on top of the urine patch increased losses by over 50%. However, total N_2O-N losses over the experiment totalled less than 4 kg N ha^{-1}, extremely low considering the 750 kg N applied and once again emphasizing that major losses are mainly limited to extreme rainfall events. The combination of DMPP and urine reduced N_2O emissions by 24%, with the majority of this reduction occurring within the first week after urine application. However there was no immediate additional benefits in pasture production observed from the inhibitor, though the short duration of the study most-likely limited the opportunity to detect a biomass response to any additional N saved (after adding 750 N in a urine patch), and potential responses could still occur later once the soil N reserves decline.

Potential for DMPP to increase pasture yields following long-term application: The longitudinal DMPP trial in the clay Casino soil demonstrated the effectiveness of using the nitrification inhibitor DMPP to increase yields and agronomic efficiency of N fertiliser (AE_N) at both reduced and comparable application rates to urea (Figure 5). Applying DMPP at lower N application rate (35 kg N ha^{-1} grazing) compared to the urea (45 kg N ha^{-1}) resulted the same amount of biomass being produced and therefore a subsequent improvement in AE_N, the amount of biomass produced per unit of applied N, by 24% and 26 % for the ryegrass and kikuyu respectively.
Direct comparison of DMPP and urea at the reduced rate showed a clear production advantage of the inhibitor, with an average increase for the 2017 and 2018 ryegrass of 15% per grazing, or an additional 71 kg DM ha^{-1} $grazing^{-1}$. This effect was further enhanced in the third ryegrass season of trial (2018) when 156 kg ha^{-1} of N applied as DMPP produced an additional 856 kg DM ha^{-1}, an **increase of over 70%** compared to the equivalent N rate as urea only. Overall, DMPP had the strongest effect on pasture production during wet periods and at the rate of 20-30 kg N ha^{-1} application, with limited benefit observed at the higher rates where the retention of N in the soil-plant system has less impact on yield. Previous work from the sandier Camden soil showed limited benefit of the DMPP, most likely due to lower mineralisation rates and loss potential.

Key findings:

- Climatic conditions during the winter/spring annual rye grass fertilisation period rarely produce conditions conducive for N loss of surface spread urea.
- Urease inhibitors therefore have limited potential under normal conditions
- The exception to this is occasional hot and windy conditions following cold fronts in late October/early November when application of urea should be avoided.
- Nitrification inhibitor (DMPP) shows good potential during winter/spring annual rye grass
- DMPP has been shown to reduce direct losses of N via denitrification during large rainfall events, increase immobilisation of N into the organic matter and increase pasture productivity during the winter/spring rye grass period.
- as a **rule of thumb that DMPP application always be applied at a 15-30% reduction to the optimal N rate of standard urea**

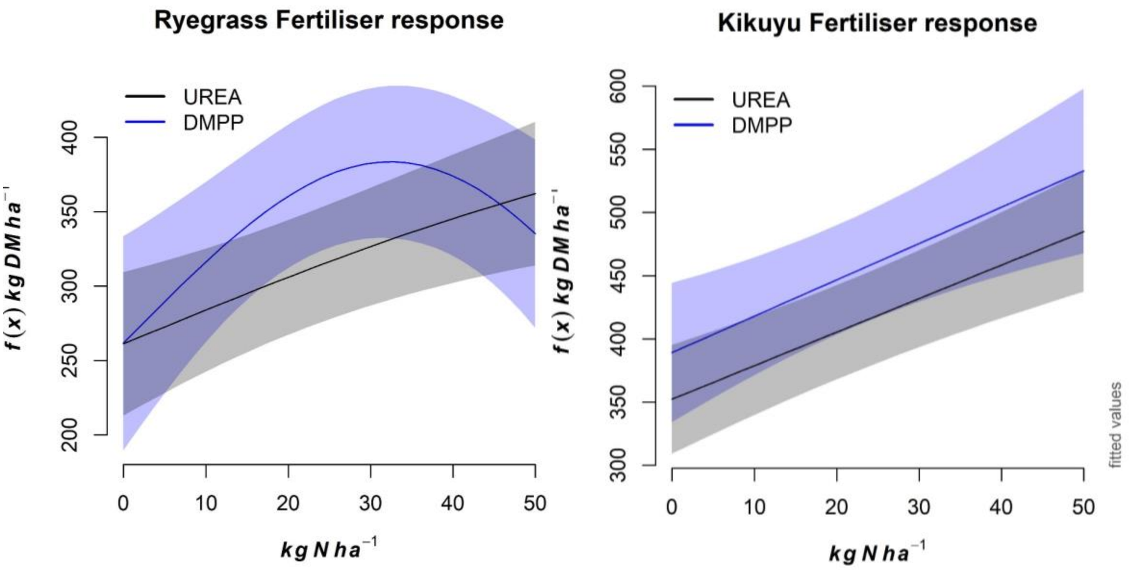


Figure 5. Pasture biomass response (kg DM ha-1) for standard UREA and DMPP coated urea to increasing N fertiliser application rates (kg N ha^{-1} grazing^{-1}) in winter/spring Rye and summer Kikuyu at Casino.

3.1 Project level achievements

Provide a description of project achievements against the final KPIs and outputs of the research project. As these final KPI have been worded to conclude the body of long-term investigation, please ensure the final findings are clearly articulated and linkage to impact upon current and future industry knowledge and practice is explained.

KPI no. and description	**KPI Due Date**	**Relevant CRDC FRP Milestone Number/s.**	**Final outcome of the body to reserarch concluded by this KPI**
KPI 6.7 – Provide an update on the EEF blend test outcomes in NSW (Output 4(m)).	30 November 2019	4.1	☒ Achieved ☐ Partially achieved ☐ Not achieved *All experiments completed including 1) a >3 year field trial evaluating the effectiveness of nitrification inhibitors (DMPP/ENTEC) under normal grazing conditions, and 2) campaigns to evaluate the effectiveness of EEFS to reduce losses from urine patches (DMPP/ENTEC) and 3) volatilization (Green urea) at both Casino and Camden. Results presented at farmer field days at Casino (Nov 2018), Berry (March 2019) and Bega (July 2019).*
KPI 6.10 – Provide commentary on the development of Best Management Practices for the dairy industry and the outcome of sharing these findings at workshops and field days (Outputs 5(j) and 5(k))	30 November 2019	5.3	☒ Achieved ☐ Partially achieved ☐ Not achieved *Collaborations with Uni Melbourne projects led by Eckard has included sharing of mineralisation data collected at all subtropical dairy sites and the joint development of dairy industry NUE metrics BMPs*

3.2 Contribution to MPfN program objectives

Provide a description of how the project has contributed to the achievement of the relevant MPfN

This project has developed and used innovative methodological tools and sensors to achieve a better understanding on N loss processes, the mechanisms and drivers and potential mitigation methods. Likewise, novel experiments combined with ^{15}N tracer models to follow fertiliser N through the interaction with the soil organic matter greatly adds to our general understanding of immobilisation and mineralisation processes, and the potential way these processes may effect the efficacy of EEFs. The techniques for the quantification of total denitrification established in Australia for the first time in this project have since been used in cotton and sugar systems, along with the automated greenhouse gas chambers developed by QUT for the analysis of N_2O. Denitrification losses also represent a major uncertainty for models simulating the N cycle such as APSIM and DSSAT due to the general lack of data regarding N loss via denitrification, and the same factors control these process in dairy soils also dictate losses in other industries. The dataset produced in this project is one of the most thorough produced in Australia to date and will greatly contribute to the understanding of N loss processes across all agricultural industries.

3.3 Demonstrable more profit from nitrogen

This project demonstrated the potential for farmers to increase profit in a number of ways including:

- Developing ***pasture growth response***, harvest return, profit and marginal revenue from different N application rate scenarios from a range of northern dairy soils under different seasonal and climatic conditions, accounting for ***soil mineralisation*** and ***pasture growth potential*** (Table X)
- Quantifying the benefits of ***optimal management of soil moisture and irrigation*** Assessing the agronomic and economic benefits of using (or not) ***Enhanced Efficiency Fertilisers*** – and when to use them for maximised profit.

Our findings produced site specific N response curves in both Kikuyu and rye across different dairy pastures, and linked differences in soil type to differences in N response. Results show that N application can still be profitable even at high rates under optimal conditions, particularly when feed costs are high (i.e. drought).

The lighter textured, lower carbon soils (i.e. Chromosols) demonstrated the potential to grow large quantities of pasture feed under well managed conditions with adequate water supply (irrigation), with near-linear responses to pasture production responses and potential profit up to high rates of N application. For example, profit (cost of fertiliser - value of feed produced) from Camden increased from **$1137** ha^{-1} yr^{-1} following the application of 120 kg N ha^{-1}, to **$3890** ha^{-1} yr^{-1} when 480 kg N ha was applied. However, this response was much more variable under dryland farms, with only low or no response to N fertiliser (flat or declining profitability) at the Taree and Berry sites on marginal moisture.

The heavier clay sites of Casino and Gympie demonstrated more variability in biomass production and subsequent profit due to the greater contribution and impact of N mineralised from soil organic matter has on N response. The profit "break-even" point for the amount of N fertiliser applied at individual grazing events ranged from 1 to 2.4 kg N day^{-1} depending on soil moisture availability, temperature and grazing interval. Seasonal averages for kikuyu and ryegrass are displayed in Table 4, with marginal revenue declining rapidly after 24 kg N ha^{-1} and 35 kg N ha^{-1} for the kikuyu and ryegrass respectively. This suggests ***applying higher N rates during the spring ryegrass peak*** when demand from plants is high, and ***lower rates during summer kikuyu*** when high temperatures and moisture contents promote release of N from the soil organic matter via mineralisation could ***reduce input costs while maximising profit***.

Table 4. Average seasonal agronomic N fertiliser response metrics and basic economic analysis for summer kikuyu pasture production at Casino

N fertiliser rate (per application)	Pasture production	Marginal response to fertiliser N	Harvest return#	Profit	Marginal revenue
kg ha^{-1}	kg DM ha^{-1}	kg DM ha^{-1}/kg N	\$ ha^{-1}	\$ ha^{-1}	\$ ha^{-1}
Summer kikuyu					
0	142				
16	475	14.9	$119	$98	$9.7
24	542	8.4	$136	$104	$6.4
32	572	3.8	$143	$102	-$2.8
40	586	1.7	$147	$95	-$6.9
56	595	0.4	$149	$76	-$9.7
Annual ryegrass					
0	304				
15	402	7.0	$100	$81	$4.6
25	470	6.8	$118	$85	$4.1
35	537	6.7	$134	$89	$3.7
45	585	4.8	$146	$88	-$1.0
65	605	0.5	$151	$67	-$11.8

This project demonstrated that over-application of ***irrigation*** via inefficient, uneven or leaky irrigation infrastructure, can trigger substantial N losses via denitrification, as can large rainfall events. While the exact amount of water required varies according to soil type and antecedent soil moisture, as a rule of thumb ***soil saturation*** over 12 hours in duration can promote losses >20 kg N per event. Assuming only 10 events per year, this can total over ***\$260 ha^{-1} yr^{-1}*** in equivalent fertiliser value alone, without accounting for lost pasture production and environmental impacts.

While adjusting the timing of optimised (replacement of evapotranspiration only) irrigation only had a marginal impact on N losses, more frequent, smaller application events allowed better utilisation of sporadic rainfall events, decreasing water use over 12 months by over 200 mm, increasing water-use efficiency from 25 to 45 kg DM/ mm irrigation and reducing pumping costs by $10-14 per tonne of pasture produced per hectare.

Enhanced efficiency fertilisers attract a premium price of 20-100% over conventional urea depending on the product. As such, use of these products needs to either demonstrate a substantial increase in pasture production or a reduction in application rates to reduce input costs. The urease inhibitor Green Urea was demonstrated to have little impact on yields or the capacity to reduce input rates so can be considered uneconomical for application under normal growing conditions. However the nitrification inhibitor DMPP (ENTEC™) demonstrated a clear benefit in terms of pasture production at a lower application rate, particularly in the ryegrass. As such, the feed associated profit jumped from \$18 ha^{-1} grazing^{-1} from \$89 ha^{-1} to \$114 ha^{-1} at the 35 kg N ha^{-1} fertiliser application rate. Assuming 12 grazing a year this represents potential feed savings \$212 ha^{-1} annually at conservative prices. However the price premium of DMPP combined with the plateauing N response in pasture production meant this profit rapidly declined once N application exceeded this optimum.

4 Collaboration

Describe the MAJOR collaborations established over the life of the project, how these collaborations have or will aid future innovation, and the likelihood that collaborations will continue beyond the duration of the project.

Tim Clough – (Lincoln University, New Zealand)

Tim Clough is a leading researcher at in the field N turnover and loss from pasture soils, and has done some pioneering work highlighting the importance of soil aeration for N loss from intensively managed pasture soils. Currently we are working together on a review paper on N loss from pasture soils, summarizing key findings from this project. Further research using the fully automated GHG system in NZ is ongoing.

Christoph Mueller (University Giessen, Germany)

The work with Christoph Mueller using of the numerical n-trace model to quantify N transformations has yielded in comprehensive datasets on N turnover in pasture soils, and we have so far written up our findings in two publications. The ongoing interest in measuring and predicting in situ mineralisation across different cropping soils makes future collaborations likely.

Katharina Keiblinger (University of applied Life sciences Vienna, Austria)

Work with Katharina Keiblinger over the time of the project focussed on microbial process work aiming to explain results observed in the field, and we worked together on two experiments. The collaboration with her team of experts in the field of molecular biology is a valuable add-on to QUT's expertise, and future collaborations are planned covering the use of soil amendments to increase the nutrient holding capacity of highly weathered soils.

Clemens Scheer (Karlsruhe Institute of Technology, Garmisch, Germany)

Clemens Scheer leads a group at the KIT, using the biogeochemical model Landscape DNDC to establish N budgets from different agro-ecosystems. We are planning an exchange of researchers, sharing our dairy dataset to expand our findings and run different scenarios for the sites. Furthermore, we'll be working together on a similar project in sugarcane.

Professor Jani Garcia (University of Sydney), Peter Beale (Local Land Services, Taree) and Bill Fulkerson (NORCO, Lismore) put together a proposal with QUT to extend and adapt an innovative, user-friendly and multi-platform decision support tool "FeedSense" that integrates real-time pasture growth information from semi-autonomous sensors with whole herd feed requirements. The tool would allow farmers to accurately predict pasture growth and quality to inform herd energy requirements, allow precise allocation of supplementary feed required to maximise milk production, and give immediate recommendations of nitrogen fertiliser and irrigation practices. The proposal was submitted to the National Landcare Smart Farming Partnerships but was not successful.

5 Extension and adoption activities

5.1 Extension of the research to the end-user

Extension activities in this research project consisted of well-attended and received field days in each major regions (north-coast and south-coast), as well as a number of opportunistic/invited presentations at dairy or industry field days conducted by other research groups (i.e. Dairy Research Foundation annual symposium hosted by the University of Sydney). There have also been direct, one-on-one discussions with key industry leaders in the farming, agronomy, research extension fields. Through these mechanisms' findings have been extended to approximately 200 dairy farmers and 50 service providers. Ultimately however, due to the short duration of the project and the longitudinal nature of the research, a lot of the findings presented in this report have not yet been disseminated to industry. Future collaboration with Dairy Australia and University of Melbourne researchers (KPI 6.10) will extend the outcomes of this research further via the Dairy Australia extension platforms such as Fert$mart.

5.2 Recommendations to industry on adoption of the research outcomes.

While this project helped establish some broad rules of thumb for the economic and environmental sustainability of N fertiliser N use, the high spatial and temporal variability in key drivers of NUE at a paddock, farm and region scale limit the potential effectiveness of these guidelines. With a challenging and changing climate predicted in the future this variability will only increase. Ultimately precision management of N is required to better predict pasture N demand and adjust N application rates accordingly.

There are a growing number of precision management tools becoming available on the market (i.e. drones, proximal sensing, IOT and telemetric systems for soil moisture, temperature etc), but little knowledge of how to implement the outputs into farm decision making. Due to the diverse nature of day-to-day operational and management requirements of dairy farms, the general time-poor nature of farmers and the steep knowledge gap requirement for precision management, there is a requirement for autonomous or semi-autonomous decision-making tools connected to real-time sensors. This project has provided the baseline process understanding, management options and prediction equations required for this next step to occur.

6 Lessons learnt

Describe lessons learnt and key messages developed during the life of the project at the:

6.1 Research level

There is always a major constraint to doing agronomic N efficiency research on farmers' fields as typically these systems are saturated with N, making some of the subtle but critical improvements in NUE hard to detect from the high baseline. This is further confounded by the large variability in dairy production systems, not just in terms of pasture establishment/competition, pasture utilisation rates, changing grazing intervals, spatial distribution of urine N deposition, inefficient irrigation etc, but also the metabolic requirements of the cows. While biomass DM production and profitability of production is ultimately the end game, it can be a very course parameter to measure, being affected by all the variability mentioned above, and not including key metrics such as milk conversion efficiency (i.e. high leaf protein or nitrate contents aren't converted to milk efficiently). Removing (some of) these constraints by controlling experimental plots more concisely or conducting laboratory studies is therefore critical for the progress of dairy NUE research, though these need to be combined with farm scale studies or modelling scenarios to ensure the same assumption hold up in the real world.

- This project used the ^{15}N gas flux method to directly quantify N_2 and N_2O emissions from subtropical pastures in Australia. These results, along with gross rates of N turnover obtained from ^{15}N pool dilution and ^{15}N tracer methods, provide one of the most comprehensive datasets on N cycling and N loss from intensively managed pastures. The nature of the method however limits the number of field studies that can be undertaken, and covering the large amount of samples proved to be very challenging during this project. The next logical step is to use the obtained data in bio-geochemical models, to extrapolate our findings across spatial and temporal scales.

- Model evaluation however is important: Denitrification losses are a major uncertainty for models simulating the N cycle such as Dairy Mod due to the general lack of data regarding N loss via denitrification. Nevertheless, Dairy Mods focus is pasture production, and not necessarily N cycling and N loss. Our datasets provide a solid base for model inter-comparison (Daycent, DNDC), and can help to improve the performance of models such as Dairy mod regarding denitrification, validating findings against experimental data. This will help to improve general recommendations for best farming practice on intensively managed dairy pastures.

- Mineralisation was and is a hot topic across different industries, and the discussion regarding methods to determine mineralisation is interesting and helpful to a certain extent. Our results obtained with a ^{15}N tracing model disagree with those obtained with the seemingly popular PMN assay, which did not reflect differences between sites/soils. We therefore think that PMNs alone are not the tool of choice when investigating mineralisation, and may lead to erroneous conclusions regarding N availability and supply for PAN.

6.2 Industry level

Our findings show site specific N response curves in both Kikuyu and rye across different dairy pastures, and link differences in soil type to differences in N response. Our findings regarding **plant NO_3^- accumulation**, in particularly in ryegrass show that a positive response of pasture yields to high N fertiliser rates does not necessarily mean a productivity benefit, if the application of N fertiliser results in excessively high plant NO_3^- levels. Future research should investigate the animal's response and adaption to high NO_3^- levels in the biomass, and its potential effects on utilisation and milk production. Nitrification inhibitors as a means to reduce excess NO_3^- in the soil are further discussed in the section on enhanced efficiency fertilisers.

This project demonstrated some findings that had clear benefits to environmental outcomes such as reducing N_2O, but little impact pasture production and profitability. For instance, numerous strategies for reducing losses from urine patches have been developed (both in this project and elsewhere), however the magnitude of this reduction is hard to quantify agronomically. As other rural industries such as MLA act towards carbon-neutral production for social licence and natural capital, reducing emissions of the GHG gas N_2O is likely to become more important also in dairy systems. Marketing of carbon-neutral products frames the term “More profit for N” differently, making a reduction of the GHG footprint of a farming system also an economically interesting option.

6.3 Service Provider Level

To best understand whether or not an enhanced efficiency fertiliser product is suitable for a production system it is essential for service providers making agronomic recommendations to understand firstly the scale of N losses and which loss pathway should be targeted. For example recommending Green Urea in irrigated systems or for winter applications would have no agronomic or economic benefit. The law of diminishing returns also dictates that every system will no longer respond to additional N inputs at some point, and as most agronomic recommendations already account for maximum production, recommending applying EEF's at the same rate as conventional urea application will not increase production and reduce farm profitability.

6.4 Primary Producer Level

The exceptionally dry summer experienced across many dairy regions in NSW and Southern QLD limited some of the planned summer experiments and pushed them into the autumn period. The increase in fodder prices from this event has also changed the traditional economic assumptions around increasingly diminishing marginal N responses compared to normal production conditions. Some basic economic analysis of the responses was conducted in this study but a more thorough cost-benefit analysis at a farm-scale, accounting also for the dietary demands of cattle and the spatial movement of N, is required.

An additional consideration for optimising irrigation regimes is the potential to “strand” N in the surface soil during extended dry periods. This became evident during an extended dry period where despite 60 mm of irrigation and sufficient N fertiliser applied, growth rates were limited as plant roots followed the water into the deeper soil layers “stranding” the fertiliser N in the dry surface. This was on an 8-day irrigation cycle suggesting higher frequency irrigation may lead to optimal growth, though the water use efficiency also needs to be considered.

There is a major challenge in communicating findings of nitrogen research due to the large disparities between the level of background knowledge of different farmers. This leads to situations where it the communication material might be too complicated for some and too simple for others and it’s quite difficult trying to communicate complex interactions and management in a simplified manner.

The extremely diverse nature of the NSW and subtropical dairy industries, both in terms of soil type but also management (i.e. rate and frequency of N application, irrigation type, stocking rate and utilisation), also creates difficulties in comparing results to “standard farmer practice”. The project therefore worked on “current best practice” comparisons where possible.

7 Appendix - additional project information

7.1 Project material and intellectual property

Include a summary of all **journal publications & conference papers** and **all intellectual property created** or arising during the period covered by the project. You need to restate these here even if they have been entered into the MPfN M&E Data-base

7.1.1 Journal Papers published

Mumford, M.T. Rowlings, D.W. Scheer, C. De Rosa, D. Grace, P.R. (2019). Effect of irrigation scheduling on nitrous oxide emissions in intensively managed pastures. Agriculture, Ecosystems & Environment, 272, 126-134, https://doi.org/10.1016/j.agee.2018.11.011

Friedl, J., De Rosa, D., Rowlings, D.W., Grace, P.R., Müller, C., Scheer, C., (2018). Dissimilatory nitrate reduction to ammonium (DNRA), not denitrification dominates nitrate reduction in subtropical pasture soils upon rewetting. Soil Biology and Biochemistry 125, 340-349. https://doi.org/10.1016/j.soilbio.2018.07.024

Friedl, J., Scheer, C., Rowlings, D.W., Mumford, M.T., Grace, P.R., (2017). The nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) reduces N2 emissions from intensively managed pastures in subtropical Australia. Soil Biology and Biochemistry 108, 55-64. https://doi.org/10.1016/j.soilbio.2017.01.016

Friedl, J., Scheer, C., Rowlings, D.W., McIntosh, H.V., Strazzabosco, A., Warner, D.I., Grace, P.R., (2016). Denitrification losses from an intensively managed sub-tropical pasture – Impact of soil moisture on the partitioning of N_2 and N_2O emissions. Soil Biology and Biochemistry 92, 58-66. https://doi.org/10.1016/j.soilbio.2015.09.016

7.1.2 Journal Papers in preparation and review

Friedl, J., Scheer, C., Rowlings, D.W., Deltedesco, E., Gorfer, M., De Rosa, D., Grace, P.R., Müller C., and Keiblinger, K.M. Effect of the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) on N-turnover, the N_2O reductase-gene nosZ and N_2O:N_2 partitioning from agricultural soils., under review Scientific Reports (expected Jan 2020).

Friedl, J., De Rosa, D., Rowlings, D.W., Grace, P.R., Müller, C., Scheer, C. Sources of nitrous oxide from intensively managed pasture soils. To be submitted to Soil Biology and Biochemistry (Jan 2020).

Johannes Friedl, Clemens Scheer, Katharina M. Keiblinger , Evi Deltedesco, Markus Gorfer, Daniele De Rosa, Peter R. Grace, and David W. Rowlings. The legacy effect of different irrigation frequencies on N_2 and N_2O emissions triggered by an intense rainfall event. To be submitted to Biogeosciences (March 2020).

Laura M. Cardenas, Tim J. Clough, Johannes Friedl and Benjamin Wolf. Nitrous oxide emissions from perennial pasture systems. Nitrous oxide emissions from perennial pasture systems. Invited review for Current opinions in environmental sciences. (March 2020).

Johannes Friedl, Laura M. Cardenas, Timothy Clough, Michael Dannenmann, Chunsheng Hu and Clemens Scheer. Measuring denitrification and the N2:N2O emission ratio from agricultural systems. Invited review for Current opinions in environmental sciences. (March 2020).

Rowlings, D.W., Friedl, J., De Rosa, D. and Grace, P.R. DMPP reduces N_2O emissions from urine in subtropical dairy pastures. To be submitted to Agriculture Ecosystems and Environment (Jan 2020).

7.1.3 Conference Papers

Friedl, J., Scheer, C., Rowlings, D.W., McIntosh, H.V., Strazzabosco, A., Warner, D.I., Grace, P.R., 2016. Short-term effect of the nitrification inhibitor DMPP on N-turnover and denitrification losses from two agricultural soils in subtropical Australia, EGU General Assembly Conference Abstracts, p. 1833.

Friedl, J., De Rosa, D., Rowlings, D.W., Grace, P.R., Müller, C., Scheer, C., 2019. Nitrate reduction in subtropical pasture soils – the role of dissimilatory nitrate reduction to ammonium (DNRA) and denitrification upon rewetting, EGU General Assembly Conference Abstracts.

Johannes Friedl, Clemens Scheer, David Rowlings, 2019. Measuring denitrification and the N_2:N_2O emission ratio from agricultural systems. Proceedings of the workshop on “Climate change, reactive nitrogen, food security and sustainable agriculture”15-16 April, 2019 Garmisch-Partenkirchen, Germany

David Rowlings, Johannes Friedl, Peter Grace, 2020. N2O losses from urine patches following application of DMPP coated urea in dairy pastures. International Nitrogen Initiative Conference, Berlin 2020.

Daniele De Rosa, Johannes Friedl, Bill Fulkerson, Clemens Scheer, Martin Labadz, Peter Grace, David Rowlings 2020. Field scale management and environmental drivers of N_2O emissions from pasture based dairy systems. International Nitrogen Initiative Conference, Berlin 2020.

Friedl, J., De Rosa, D., Rowlings, D.W., Grace, P.R., Müller, C., Scheer, C., 2020. Sources of nitrous oxide from intensively managed pasture soils. International Nitrogen Initiative Conference, Berlin 2020.

7.1.4 Intellectual property

The research has been published in the public domain through peer reviewed papers, conference papers and industry publications and guidelines. All intellectual property is therefore deemed to have been placed in the public domain.

References

Friedl, J., Scheer, C., Rowlings, D.W., Trappe, J., Grace, P., 2016. Nitrogen turnover and N_2: N_2O partitioning from agricultural soils–a simplified incubation assay, International Nitrogen Initiative Conference, "Solutions to improve nitrogen use efficiency for the world", Melbourne. Retrieved from http://www.ini2016.com/conference-proceedings-2012.

Goulding, K., Jarvis, S., Whitmore, A., 2008. Optimizing Nutrient Management for Farm Systems. Philosophical Transactions: Biological Sciences 363, 667-680.

Gourley, C.J.P., Aarons, S.R., Powell, J.M., 2012. Nitrogen use efficiency and manure management practices in contrasting dairy production systems. Agriculture Ecosystems & Environment 147, 73-81.

Mumford, M., Rowlings, D., Scheer, C., De Rosa, D., Grace, P., 2019. Effect of irrigation scheduling on nitrous oxide emissions in intensively managed pastures. Agriculture, Ecosystems & Environment 272, 126-134.

8 Appendix – Project technical report

More Profit from Nitrogen

RRDP1714 (July 2016 – November 2019)

Increasing Nitrogen Use Efficiency in Dairy Pastures

Final Technical Report

30th November 2019

Report prepared by: David Rowlings[1], Johannes Friedl[1], Warwick Dougherty[2] and Michael Fitzgerald[2]

[1]**Queensland University of Technology**

[2]NSW Department of Primary Industries

Table of Contents

Table of Figures

Tables

Introduction

Previous research has highlighted the high potential for N losses from northern dairy soils, and the difficulties faced by farmers in deriving practical, on-farm options the management of this very leaky element in an extremely variable climatic and production system. Up to 40% of N applied as fertiliser is known to be lost in subtropical pastures (Rowlings *et al.*, 2016), and while some mitigation options such as enhanced efficiency fertilisers have been tested, previous findings have been mixed (Dougherty *et al.*, 2016; Koci and Nelson, 2016; Friedl *et al.*, 2017). As such, this project built on previous research from QUT and NSW DPI and aimed to identify options for farming practice, improving Nitrogen Use Efficiency (NUE) while limiting N loss from intensive dairy systems.

This project had the following objectives

- Quantifying the scale, pathway and timing of N losses to allow for the development of effective mitigation strategies
- Determining the amount and timing of N from long and short/medium mineralisation of organic soil carbon and the potential to adjust N fertiliser application rates accordingly
- Evaluate the effectiveness of adjusting irrigation frequency to limit N losses and increase NUE.
- Determine the agronomic, economic and NUE benefits of using enhanced efficiency fertilisers under both irrigated and dryland conditions in the Northern dairy region.

Methods

Site descriptions

The methods used to investigate abovementioned research questions are briefly summarised for each research objective. Experiments were undertaken at the two core sites in Camden, NSW and in Casino, NSW, and at the satellite sites at commercial dairy farms in Taree and Berry in NSW and Gympie and Kerry in Queensland. Site characteristics including physical and chemical soil properties, are shown in Table 1.

The Camden field site is part of the NSW Department of Primary Industries' 'Elizabeth Macarthur Agricultural Institute' (EMAI), approximately 50 km SW of Sydney. Average annual rainfall over the last ten years is ~650 mm. However, longer-term (100 years) average is ~ 791 mm (Bureau of Meteorology). The site has a slope of ~4%. The soil is a Eutrophic Red Chromosol (Isbell, 1997), or Haploxeralf (Soil Survey Staff, 1999; Dougherty et al., 2016).

The Casino field site (28.8 °E, 152.9 °S) is a commercial dairy farm, which has been intensively managed for more than thirty years, stocking an average of six head of cattle per hectare and currently milking around 300 cows. The farm has year-round irrigation and annual N fertiliser inputs reach around 340 kg N ha-1. Mean annual rainfall at the site is 1037 mm, with summer dominant rainfall accounting for 40% of the annual total. The experimental plots were level. The soil is a black Vertosol (Isbell, 2016) with a clay content of 44% which increases to>50% at depth(Mumford *et al.*, 2019). Following the usual practice in the region, the summer dominant Kikuyu pasture is mulched in autumn and oversown with annual ryegrass (Lolium perenne) at both sites.

Table 1 Selected soil characteristics intensively managed pasture sites under dairy production in New South Wales and Queensland.

Soil property	**Casino**	**Camden**	**Gympie**	**Kerry**	**Taree**	**Berry**
Latitude	-28.865	-34.12	-26.19	-28.109	-31.91	-34.79
Longitude	152.874	150.705	152.74	153.031	152.55	150.74
Mean annual rainfall	1107 mm	791 mm	1127 mm	907 mm	1244 mm	1467 mm
Soil type (ASC)	Vertosol	Chromosol	Dermosol	Tenosol	Chromosol	Chromosol
pH (H_2O)	6.3	5.5*	6.1	5.9		
Organic Carbon (%)	4.2	2.9	4.9	4.1	3.2	
Total Nitrogen (%)	0.36	0.24	0.5	0.4	0.3	
C:N ratio	11.4	12.1	9.8	10.4	9.4	

*pH_{ca}

Experimental design

The objectives of the project were addressed in the series of overlapping experiments outlined below across the core and satellite sites.

Determining N demand, predicting and accounting for mineralisation

Estimating plant available Nitrogen (PAN) is critical in dairy systems to maintain DM yield, while avoiding excess nitrate (NO_3^-) uptake into the aboveground biomass. Concentrations of > 0.14 % NO_3^- (DM basis) in the aboveground biomass can decrease milk production and may result in abortions, affecting the productivity of dairy farms. Estimating PAN is usually based on soil mineral N levels in the soil (NO_3^- and NH_4^+). The constant plant N uptake under pastures however limits the usefulness of soil mineral N concentrations as a proxy for PAN, demanding more accurate ways of estimating PAN.

Pasture response to applied N fertiliser trials were conducted at both Casino and Camden to determine the long-term pasture N demand under different climatic conditions, and the long-term supply of N from mineralisation. Trials were conducted under controlled, "ideal" conditions (full irrigation) on experimental plots (Camden and Casino) as well as in grazed paddock plot representing real farm conditions. Fertiliser was applied at rates equivalent to 0.5 to 3.5 kg N ha^{-1} day^{-1}. Biomass was harvested every grazing and pasture production (kg DM ha^{-1}) and pasture N removal (kg N ha^{-1}) determined. Trials included a zero N treatment, which was used as an indicator for long-term N mineralisation. Pasture N response was also investigated in a trial in Berry, NSW, with pasture cuts further analysed for plant NO_3^- accumulation.

Pasture demand for PAN and the potential of the soil to ***supply*** their requirements through mineralisation were assessed over three years at the core sites by comparing a zero N treatment to a non-limiting N treatment ("Fully fertilised" - FF) under optimised experimental plot conditions.

Fertiliser recoveries using ^{15}N labelled urea were conducted in conjunction with both the N rate trial and irrigation trials (see below) to estimate both short-medium term mineralisation/immobilisation dynamics of N and the interaction of added fertiliser N with the soil organic N pool.

Influence of Irrigation frequencies on N losses and turnover

This experiment investigated the impact of different ***irrigation frequencies*** on N turnover and N loss from dairy pastures in Camden and Casino. Irrigation treatments were based on a simple evapotranspiration model, with irrigation applied in one event, split into two events or split into four events. (LOW Frequency + High Rate, MEDIUM Frequency + Medium Rate, HIGH Frequency + Low Rate).

Annual irrigation trial

The first experiment was conducted in Casino over a whole season from April 2015 to April 2016. In addition to the abovementioned irrigation treatments, this trial included the Farmers' Practice treatment (FP) with 10-day irrigation intervals, and the Zero nitrogen control (ZN) with 10-day irrigation intervals. This study is based on two experimental hypotheses (i) an irrigation regime which limits the time the soil is subject to water content greater than field-capacity will have lower emissions of N_2O as an indicator for overall N loss and (ii) that by reducing N_2O loss and potentially therefore total denitrification, higher yields can be achieved through greater plant available N stocks leading to improved NUE. Gaseous N loss in the form of N_2O was monitored using a fully automated GHG system and pasture yield was quantified by mowing.

Winter irrigation campaign

The winter campaign was conducted in 2017 on both field sites in Camden and Casino. This campaign investigated the impact of different irrigation frequencies on key components of N cycling and loss from pasture soils: (a) Above ground biomass yield, (b) Short and mid-term ^{15}N fertiliser fate in the soil-plant and atmosphere system over three grazing cycles, (c) N_2 and N_2O losses from fertilised pasture soils, and (d) N_2 and N_2O losses from urine patches.

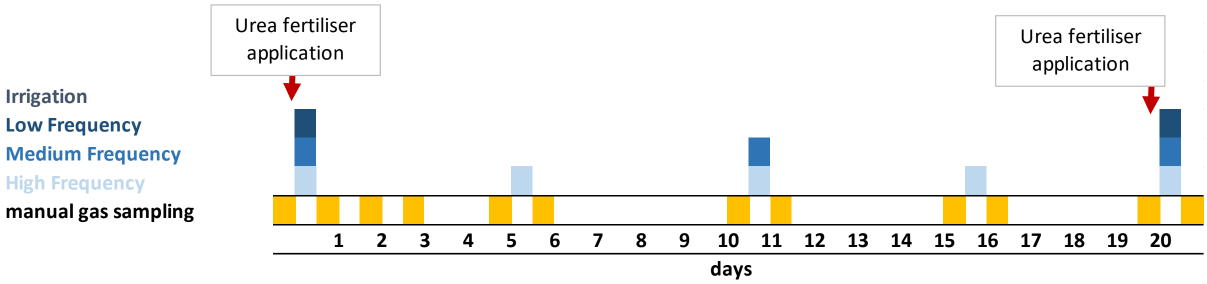


Figure 1 Timeline of a grazing cycle with fertiliser application, irrigation and manual gas sampling events.

The experiment started on the first of August 2017 in Casino and 14th of August in Camden, with the final harvest conducted on the third of October and on the 16th of October in Casino and Camden, respectively. Animals were excluded from the plots in Casino. A complete ^{15}N fertiliser recovery was done after each grazing cycle of the experiment, except for the follow-up experiment in Casino.

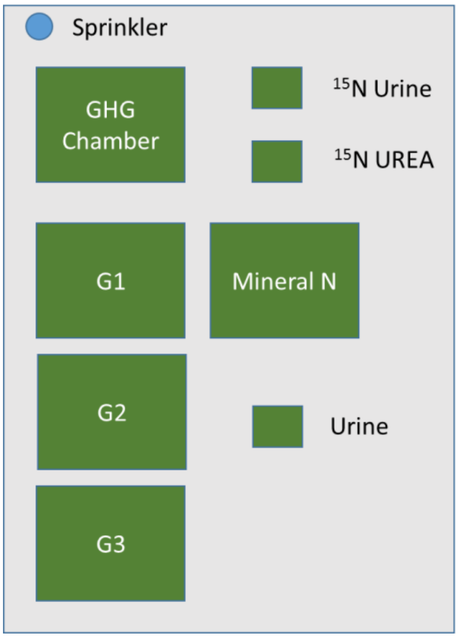


Figure 2 Plot layout for the irrigation trial

The campaign was conducted over three grazing cycles. The experimental layout consisted of the three irrigation treatments with four replicates arranged in a randomised block design. Five large (0.25 m^2) and three small steel frames (0.0484 m^2) were installed in each plot, as shown in Figure 2, covered with a removable rain-exclusion shelter to isolate the effect of irrigation. Before fertiliser application, plots were mowed to grazing height of 5 cm. Fertiliser N was applied in solution at a rate of 2 kg N ha^{-1} day^{-1} with grazing cycles of 20 days. Irrigation was then applied according to the respective treatment. A priming cycle was conducted at each site to establish the treatments and to test the functionality of the irrigation as well as the GHG auto-system. An example of a grazing-cycle timeline is given in **Error! Reference source not found.**.

Irrigations impact on N loss following intense rainfall

A separate follow-up experiment in Casino investigated the effect of LOW and HIGH irrigation frequency on N_2 and N_2O losses in response to a simulated rainfall event in November 2017. HIGH and LOW irrigation frequency was applied following the evapotranspiration replacement model. A rainfall event (100 mm) was simulated ten days after fertiliser application for both irrigation treatments.

Effectiveness of Enhanced Efficiency Fertilisers

A series of experiments were conducted at both core sites to determine if and under what conditions different EEFs are effective. Previous findings suggest the denitrification and volatilisation loss pathways to be the most critical in subtropical dairy pastures and that the nitrification inhibitor DMPP (ENTEC™) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBTT - Green Urea™) show the greatest potential for reducing N losses.

Long-term DMPP

A long-term trial was conducted at Casino to assess different application strategies of DMPP on biomass and pasture N yield. Treatments were applied to the same plots over three years to ensure any long-term effects associated with increased fertiliser immobilisation from the inhibitor (as seen in Friedl *et al.*, 2017a) and was conducted on grazed paddock plots to replicate "real" farm conditions. In year 1 of the trial, DMPP was compared at a 22% reduction (1.5 kg N ha^{-1} day^{-1}) against standard farmer practice (2 kg N ha^{-1} day^{-1}) urea rate.

In years 2 and 3, DMPP was compared against an equivalent urea rate, 25% reduced from the "optimum" N rate to ensure any reduction in N losses was determinable in the biomass response. A second, optimal urea rate was also used to qualify the optimal urea rate and check if the pasture was responsive to additional N. The potential of DMPP to prolong the availability of fertiliser N in the soil, save fertiliser application costs and allow greater flexibly in application frequency was also tested by applying twice as much fertiliser every second grazing. The exact treatments are listed below.

- **Low-Urea:** 26 kg N ha application every grazing (FP) –364 kg N ha-1 yr-1 (14 fertilisations per year)
- **High-Urea**: 35 kg N ha application every grazing (FP) – 490 kg N ha-1 yr-1 (14 fertilisations per year)
- **Urea 2nd**: 70 kg N ha application every 2nd grazing (WP) – 490 kg N ha-1 yr-1 (7 fertilisations per year)
- **Low-DM**PP: 26 kg N ha application every grazing (FP) – 364 kg N ha-1 yr-1 (14 fertilisations per year)
- **DMPP 2nd**: 52 kg N ha application every 2nd grazing (WP) – 364 kg N ha-1 yr-1 (7 fertilisations per year)
- Zero N

DMPP on direct fertilizer and urine N losses

Urine patches represent major inputs of nitrogen, equivalent to up to 1000 kg N ha^{-1}. In intensively grazed dairy systems these can cover over 10% of the paddock area annually and are major point sources of N loss. While substantial research has been conducted on the efficacy of spraying nitrification inhibitors such as DMPP or DCD on patches to slow the nitrification of NH_4^+ to NO_3^-, no research has been conducted examining the effectiveness of inhibitor coated fertilisers on losses. While the addition of more N from the fertiliser would potentially exacerbate denitrification, on a paddock scale the urea is broadcast to patch and non-patch areas irrespectively. Moreover recent research has demonstrated that the inhibitor effect of DMPP coated urea is not just limited to the fertiliser N but also reduces N losses from other sources such as native soil N from mineralisation. It is therefore possible that DMPP can also slow nitrification of urine N in addition to the coated urea.

A trial was conducted at Casino to determine the magnitude of N losses from urine patches fertilised with broadcasted urea following grazing, and if urea coated with the inhibitor DMPP (ENTEC™) could reduce N losses. Farmers typically broadcast urea evenly across paddocks immediately before grazing regardless of urine patch location, however the effect of additional N on losses is largely unknown. Fertiliser was spread as per farmer practice before a 2.5 L urine patch was applied to a 0.25 m^2 area at the rate equivalent to ~750 kg ha^{-1} of N.

Urine was collected over the course of four weeks from dairy cows and kept at 4°C before being evenly mixed for analysis for total N and NH_4^+ and NO_3^- at EAL, Lismore. Bases were installed at one month prior to the addition of urine treatments and run with the urea and DMPP treatments. Treatment application mimicked the typical summer dairy practice in the region where the urea fertilisers were applied prior to every second grazing. In this case the plots were "harvested" to a pasture height of 5 cm, before the equivalent of 56 kg N ha^{-1} (2 kg N day^{-1} based on a 14 day rotation) of urea and ENTEC were applied to the respective micro-plots.

Agronomic importance of NH_3 volatilisation N losses and effectiveness of Green urea

Two trials to determine the agronomic importance of NH_3 volatilisation losses and the potential of the commercial EEF "Green Urea" to reduce losses. Standard urea (U) and urea coated with the urease inhibitor NBTT (GU) were compared over two campaigns at Camden and Casino. To ensure any potential savings in NH_3 were detectable in the harvested biomass, the trial was conducted on a section of the 4-year-old zero N and farmer's practice plots representing extremely N limited and non-N limited soil conditions. Both types of fertiliser were applied at a high (HF), and low (LF) rate to demonstrate that N was indeed limiting and any saving would be detectable in the biomass. Irrigation was applied to optimise the exposure time of the urea granules with at least 8 days between irrigation events. A third delayed urea-only treatment applied fertiliser 10 days (LFT2) after grazing to evaluate the effectiveness of canopy height in reducing losses.

Experimental methodology

Methods applied across different experiments are briefly summarised below.

Pasture productivity

Pasture production was typically monitored over both the annual rye grass and kikuyu growing periods. Grazing was simulated by mowing plots to a height of 5 cm with clippings removed from the plots. The timing of mowing was determined by leaf stage (experimental plots) or farm grazing rotation (paddock plots), with grazing occurring between the two and three-tiller stages (Fulkerson and Donaghy, 2001). Four biomass subsample cuts were bulked ($1 m^2$) from each plot using a 50×50 cm quadrat. Samples were dried at 60 °C for a minimum of 48 h and then weighed to determine dry matter (DM) production. Samples for total N content determination were ground and analysed on a LECO TruMac CNS analyser (MI, USA). From this data, total N removed via plant uptake was calculated and an apparent fertiliser recovery performed. Full details can be found in Mumford *et al.* (2019).

Measuring denitrification losses from intensively managed pastures

Gaseous N losses in the form of N_2 and N_2O were measured using the ^{15}N gas flux method in both laboratory-based trials and the field. This method requires the application of highly enriched ^{15}N fertiliser and analysis of gas samples using Isotope ratio mass spectrometry. Gas samples were analysed at the Isotope facility at QUT's central analytical facility. High temporal resolution N_2O measurements were obtained using fully automated sampling system in Camden and Casino, consisting of 12 pneumatically operated gas-sampling chambers and a gas chromatograph housed in a trailer at each site.

Fertiliser ^{15}N recovery

The use of ^{15}N fertiliser allows tracing applied N fertiliser in the soil plant and atmosphere system and the procedure is described in-depth in Rowlings *et al.* (2016). Using apparent N fertiliser recoveries, the contribution of N fertiliser to a specific N pool is the balance between N recovered in this pool and N recovered in this pool from a zero N fertiliser treatment. This method however neglects the interaction between N fertiliser and mineralisation. The application of ^{15}N fertiliser at the different pasture sites allowed to establish accurate N fertiliser budgets, specifying plant fertiliser N uptake, the contribution of mineralisation to plant N and occurring N losses over several grazing cycles.

Incubations

Incubations to quantify denitrification losses and rates of mineralisation and nitrification were conducted using a triple ^{15}N labelling setup described in detail in Friedl *et al.* (2016). The numerical model n-trace was used to quantify different N transformation and losses.

Results and discussion

Pasture growth in response to N fertiliser application

The cumulative production response to nitrogen application over the two-year N rate trial at Camden was approximately linear (Figure 3) although there is evidence of slight curvilinearity that suggests a marginal decrease in production response as the N rate increases. This is consistent with previous research undertaken at this site that demonstrated that linear pasture production responses occurred even up to high rates of N. The data highlights the potential to grow large quantities of pasture feed under well managed conditions with adequate water supply in sandy soils. There was only a minor decrease in marginal dry matter production with increasing N rate and the DM production rates per unit of N were high.

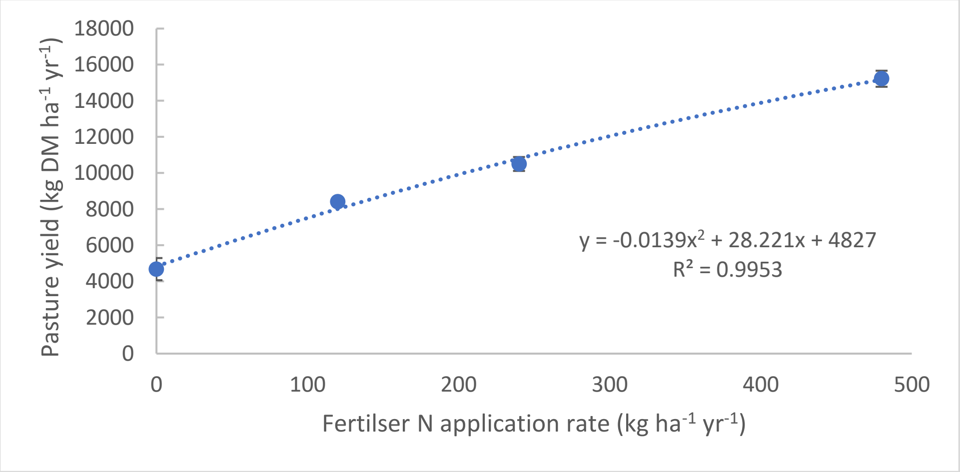


Figure 3 Annual pasture production at Camden in response to increase rates of N fertiliser application.

Similar seasonal responses were observed at Casino, though production in spring 2018 was inhibited by the fast grazing cycle of the farmer necessitated by limited feed and persistently dry conditions (Figure 4). Non-linear responses were observed in all seasons, though this changed between a decrease in biomass with increasing marginal N rates in the Spring ryegrass period of 2017 compared to increasing biomass with marginal N rates in the summer kikuyu period when water was less limiting. The suboptimal irrigation at the Casino trial resulted in lower daily production compared to Camden, which was exasperated in spring 2018 due to the fast grazing cycle. While seasonal responses at both sites showed clear trends, pasture production varied greatly between harvests (Figure 5) depending on climatic conditions during the growth period. Responses to fertiliser application in summer kikuyu at Casino ranged from flat (no response) under dry conditions in late February, low but linear responses under marginal conditions in March to the classic Mitscherlich exponential rise to a maximum response curve under optimal conditions. Overall 90% of maximum yield (Ymax90) was achieved at 23 kg N ha^{-1} application (1.5 kg N ha^{-1} day^{-1}) for kikuyu and 36 kg N ha^{-1} (1.7 kg N ha^{-1} day^{-1}).

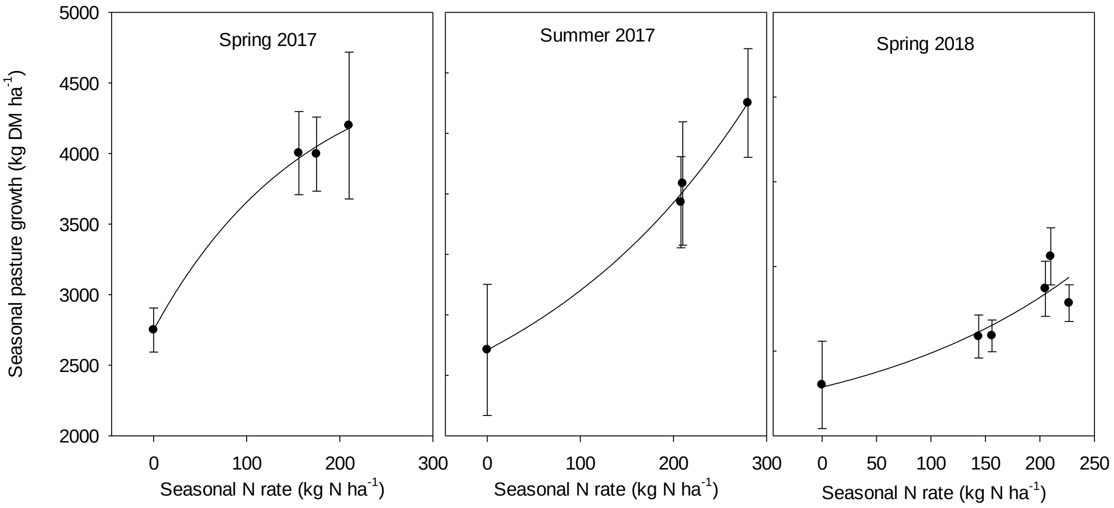


Figure 4 Seasonal cumulative N and inhibitor response at Casino as part of the EEF trial

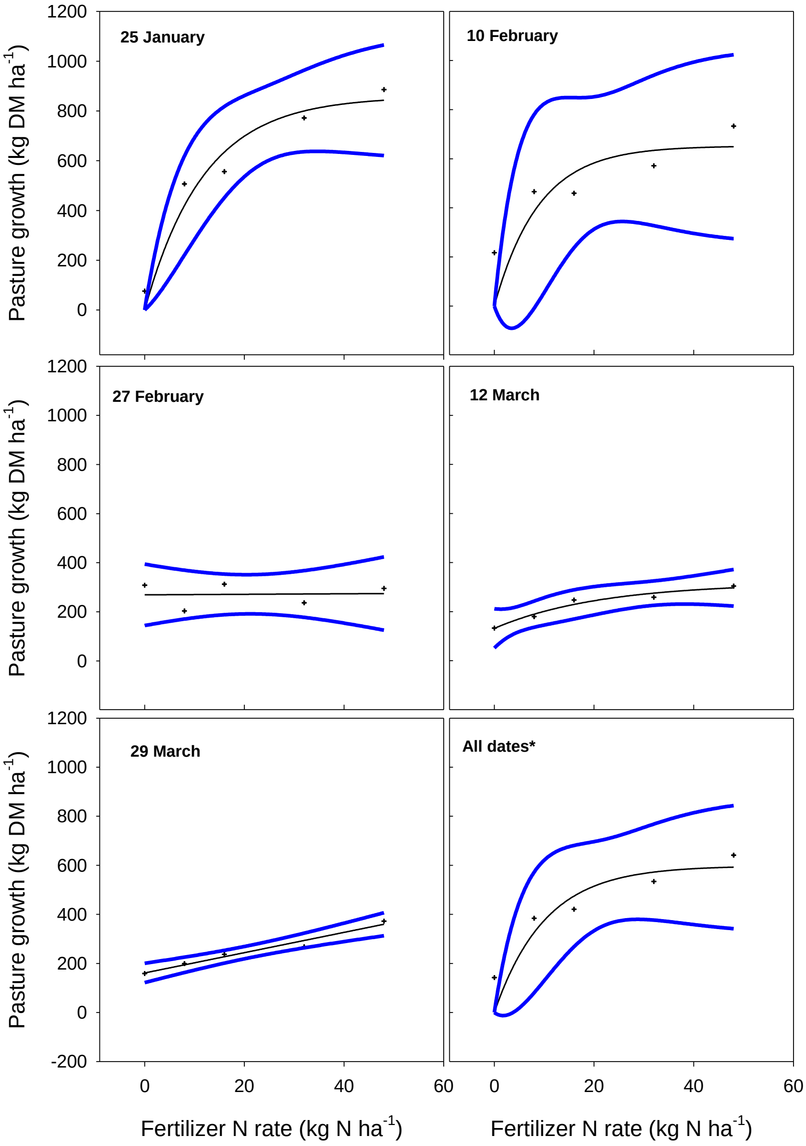


Figure 5 Fertiliser N response to summer kikuyu fertilization at Casino from five harvest dates and the seasonal average.

^{15}N recovery and N response trials

Camden

An additional ^{15}N N rate recovery experiment was conducted during the 2018 rye grass season at Camden to determine the fate of this applied fertiliser, and the effects of the high application rates on NUE. Fertiliser application rates, yields and NUE indicators are presented in Figure 6. Cumulative dry matter yields (7 cuts) ranged from 1.5 to 7.9 Mg DM ha^{-1} for Zero N and 240 kg N ha^{-1} treatments respectively. The cut pasture (>5cm) recorded a fNUE of 27%, 29% and 31% for the 80, 120 and 240 kg N ha^{-1} yr^{-1} fertiliser treatments respectively. Losses were greatest at the highest N rate, increasing from 26% of applied fertiliser N to 33%.

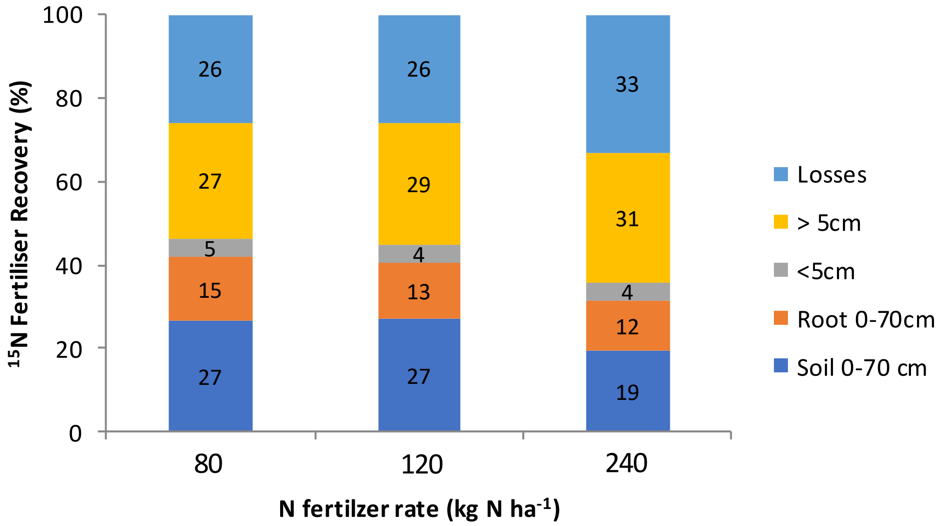


Figure 6 Fate of applied fertiliser at different application rates on a Chromosol at Camden, NSW

Berry

A short term trial in Berry, NSW investigated the pasture yield response and plant NO_3^- content to varying N rates (0, 15, 30, 45, 60, 75, 90 kg N ha^{-1}) in a one off application. This experiment was conducted during the finishing Kikuyu season with cuts in April and May. The results show clearly the typical Mitscherlich response with increasing N rates over two cuts, indicating an optimum application rate between 30 and 45kg N ha^{-1} (Figure 7). Significantly, plant NO_3^- levels increased above the Low risk threshold with N application at 60 an 90 kg N ha^{-1}.

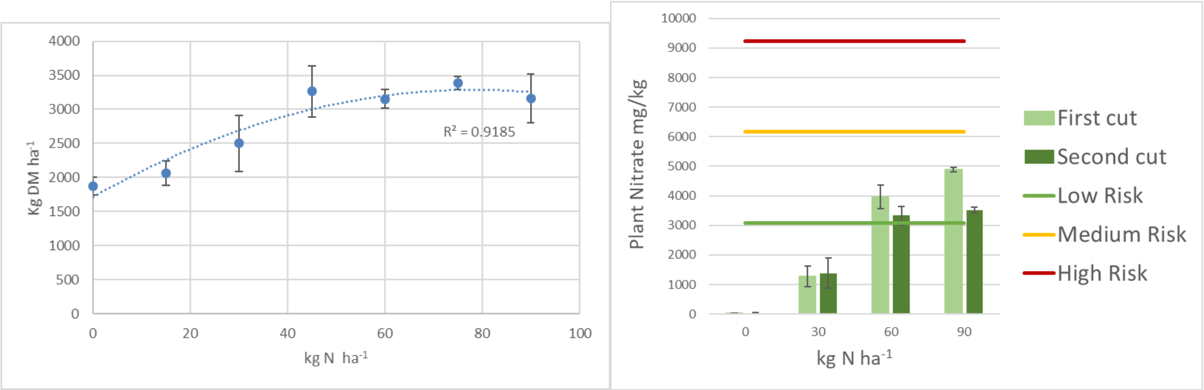


Figure 7 Pasture response to different N application rates and respective plat NO_3^- levels from a two cut pasture trial in Berry, NSW.

Research at the Casino site also demonstrated that plant NO_3^- levels begin to increase exponentially in the leaf above 3.4% total N in kikuyu and 3.8% in ryegrass (Figure 8). Above these thresholds, the plant begins to accumulate NO_3^- because uptake is in excess of the plant's requirements for synthesis of protein. Excessive plant NO_3^- can compromise forage quality with negative consequences for the productivity of dairy cows, as cows require additional energy to excrete excess NO_3^-. Figure 8 shows that in ryegrass plant NO_3^- levels at productive sites such as Casino can be well above the suggested thresholds for forage consumption given in Figure 7, with potential penalties regarding milk production.

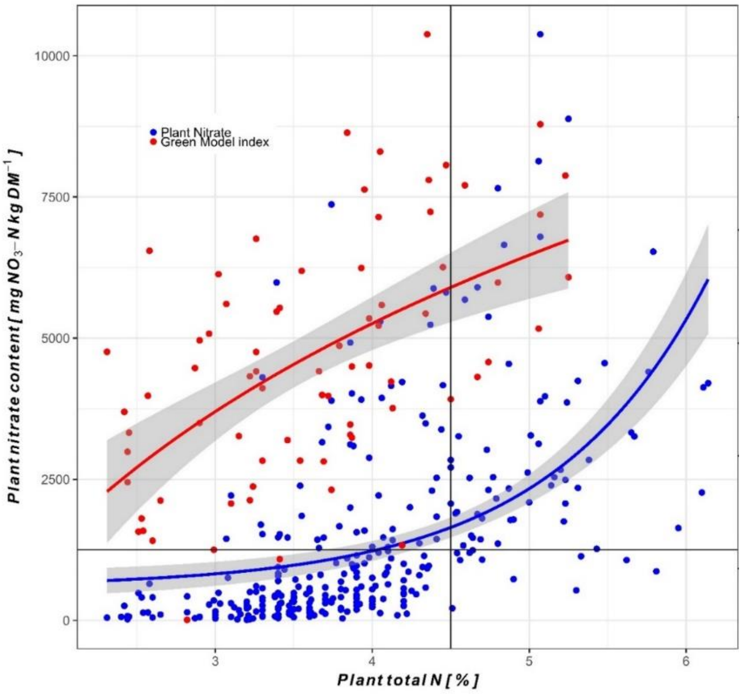


Figure 8 Relationship between total plant N (% N harvest at 3 leaf) and plant nitrate concentrations in ryegrass. NO_3^- begin to increase exponentially in the leaf above 4.5% total N.

Our findings show site specific N response curves in both Kikuyu and rye across different dairy pastures, and link differences in soil type to differences in N response. Our findings regarding **plant NO_3^- accumulation**, in particularly in ryegrass show that a positive response of pasture BM yields to high N fertiliser rates does not necessarily mean a productivity benefit, if the application of N fertiliser results in excessively high plant NO_3^- levels. Future research should investigate the animal's response and adaption to high NO_3^- levels in the biomass, and its potential effects on utilisation and milk production. Nitrification inhibitors as a means to reduce excess NO_3^- in the soil are further discussed in the section on enhanced efficiency fertilisers.

Agronomic and Economic indicators of N fertiliser application

The **marginal response** of pasture production to increasing fertiliser rates and profit maximisation associated with the increased input costs was conducted across the highest, lowest and average N response curves for each season, representing scenarios of optimal, suboptimal and average growing conditions. This follows the **principle of diminishing returns** whereas the input of more and more fertiliser will result in smaller and smaller increases in total output as other factors (i.e. water, sunlight, genetic potential) other than N become limiting. The break-even response can determine how much extra pasture needs to be produced to cover the additional fertiliser input costs and is calculated from the price of the fertiliser input (in this case assuming \$600 kg urea) divided by the value of the biomass produced. Assuming a supplementary feed price of \$250 t^{-1} DM, the marginal fertiliser response or Agronomic Efficiency of Nitrogen (AE$_{N}$) required to breakeven is 5 kg DM/kg N, whereas a \$500 t^{-1} DM feed price will result in a breakeven marginal response of 3 kg DM/kg N.

In the highest response kikuyu on a 14 day grazing cycle (Figure 9), AE$_{N}$ declined from ~44 kg DM/kg N following initial N application (8 kg N ha^{-1}) and dropped below the breakeven point at 2.4 kg N ha^{-1} day^{-1} (33 kg N application^{-1}). By comparison this threshold was reached at 1.0 and 1.9 kg N ha^{-1} day^{-1} (14-26 kg N application^{-1}) in the lowest and average kikuyu seasonal responses respectively. A similar variation in response was seen in the ***annual rye grass*** (Figure 10), with the breakeven point reached at 1.7 kg N day (35 kg N ha^{-1} grazing) on the average seasonal response. If DM feed costs double to \$500 t^{-1} DM, the breakeven rate for rye increases to 2.4 kg N day^{-1}. However, this is only profitable in harvest cycles where an N response is observed. For instance, N application never became profitable in the flat response whereas the AE$_{N}$ never exceeded 0.5 kg DM/kg N. Despite the low yields, the response from the lowest seasonal pasture harvest continued to increase linearly with increasing N rates and was still marginally above the breakeven point (returning 6.1 kg DM/kg N) even at high (>2.5 kg N day^{-1}). However, the profitability of this scenario was very low compared to the other pasture harvests. On average, the marginal revenue (i.e. the return on additional investment) began to become negative at application rates above 1.8 kg N day^{-1} and 1.7 kg N day^{-1} for both the kikuyu and annual rye grass respectively.

Table 2 Average seasonal agronomic N fertiliser response metrics and basic economic analysis for summer kikuyu pasture production at Casino

N fertiliser rate kg ha^{-1}	**Pasture production kg DM ha^{-1}**	**Marginal Pasture production kg DM ha^{-1}**	**Average response to fertiliser N kg DM ha^{-1}/kg N**	**Agronomic efficiency of N fertiliser kg DM ha^{-1}/kg N**	**Harvest return$^{\#}$ \$ ha^{-1}**	**Profit \$ ha^{-1}**	**Marginal revenue \$ ha^{-1}**
Summer kikuyu							
0	142						
8	327	131	41	32.9	\$82	\$71	\$27.7
16	475	60	30	14.9	\$119	\$98	\$9.7
24	542	67	23	8.4	\$136	\$104	\$6.4
32	572	31	18	3.8	\$143	\$102	-\$2.8
40	586	14	15	1.7	\$147	\$95	-\$6.9
48	593	6	12	0.8	\$148	\$86	-\$8.8
56	595	3	11	0.4	\$149	\$76	-\$9.7
Annual ryegrass							
0	304						
5	331	27	49	5.4	\$83	\$76	
15	402	70	41	7.0	\$100	\$81	\$4.6
25	470	68	35	6.8	\$118	\$85	\$4.1
35	537	67	30	6.7	\$134	\$89	\$3.7
45	585	48	23	4.8	\$146	\$88	-\$1.0
55	600	15	18	1.5	\$150	\$79	-\$9.3
65	605	5	15	0.5	\$151	\$67	-\$11.8

*Assuming a fertiliser cost (applied) of \$1.30 kg^{-1}; $^{\#}$ Assuming DM value of \$2.50 kg^{-1}

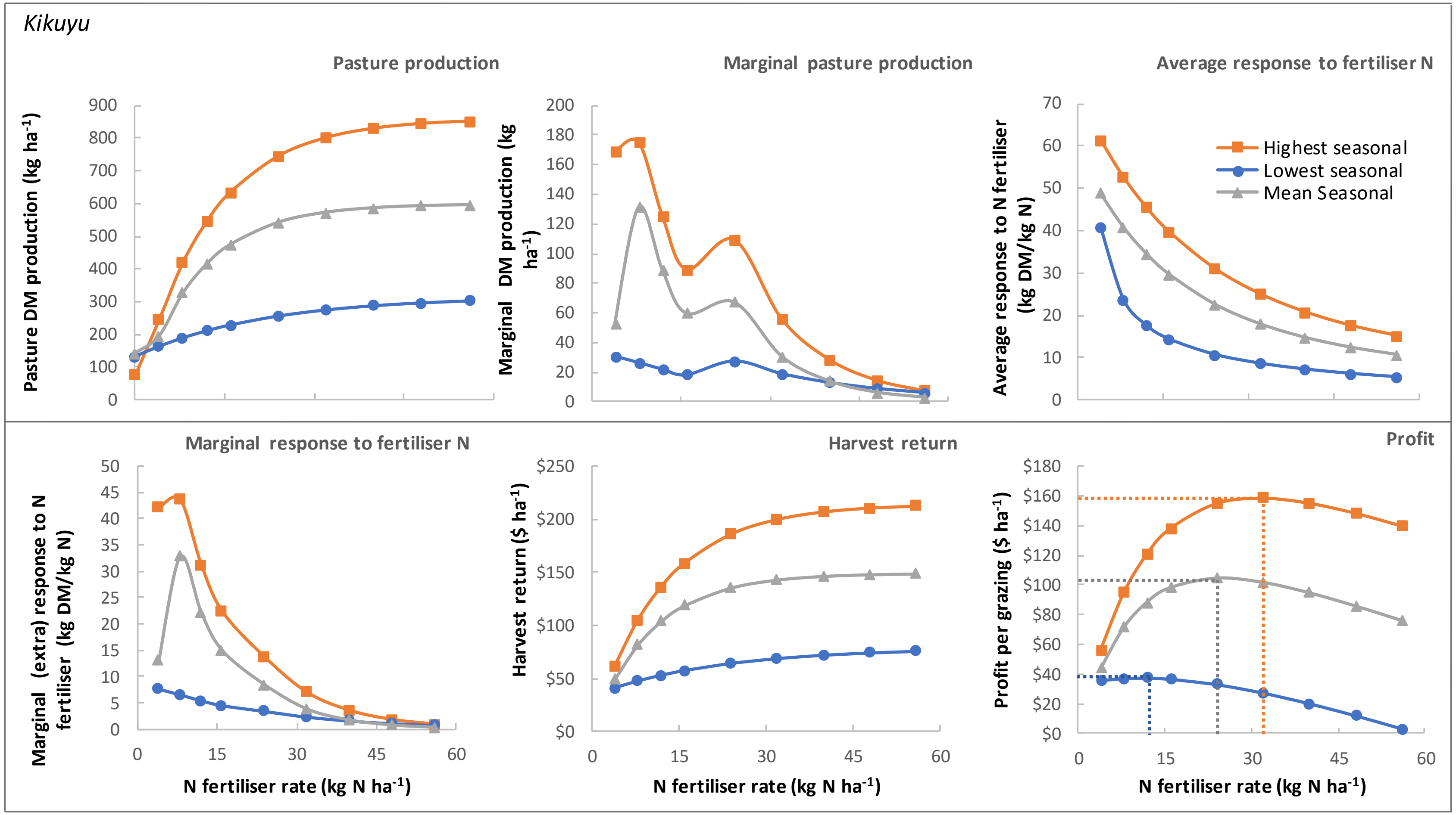


Figure 9 Variability in summer kikuyu pasture production across different grazing cycles (n=5), marginal (extra) pasture production, average response to N fertiliser (DM produced/total N applied), marginal response to N (extra DM/additional N applied), harvest return (assuming a fodder value of $0.25 kg DM), and profit (harvest return minus fertiliser costs (assuming $1.30 kg N fertiliser) in response to increasing fertiliser application rates.

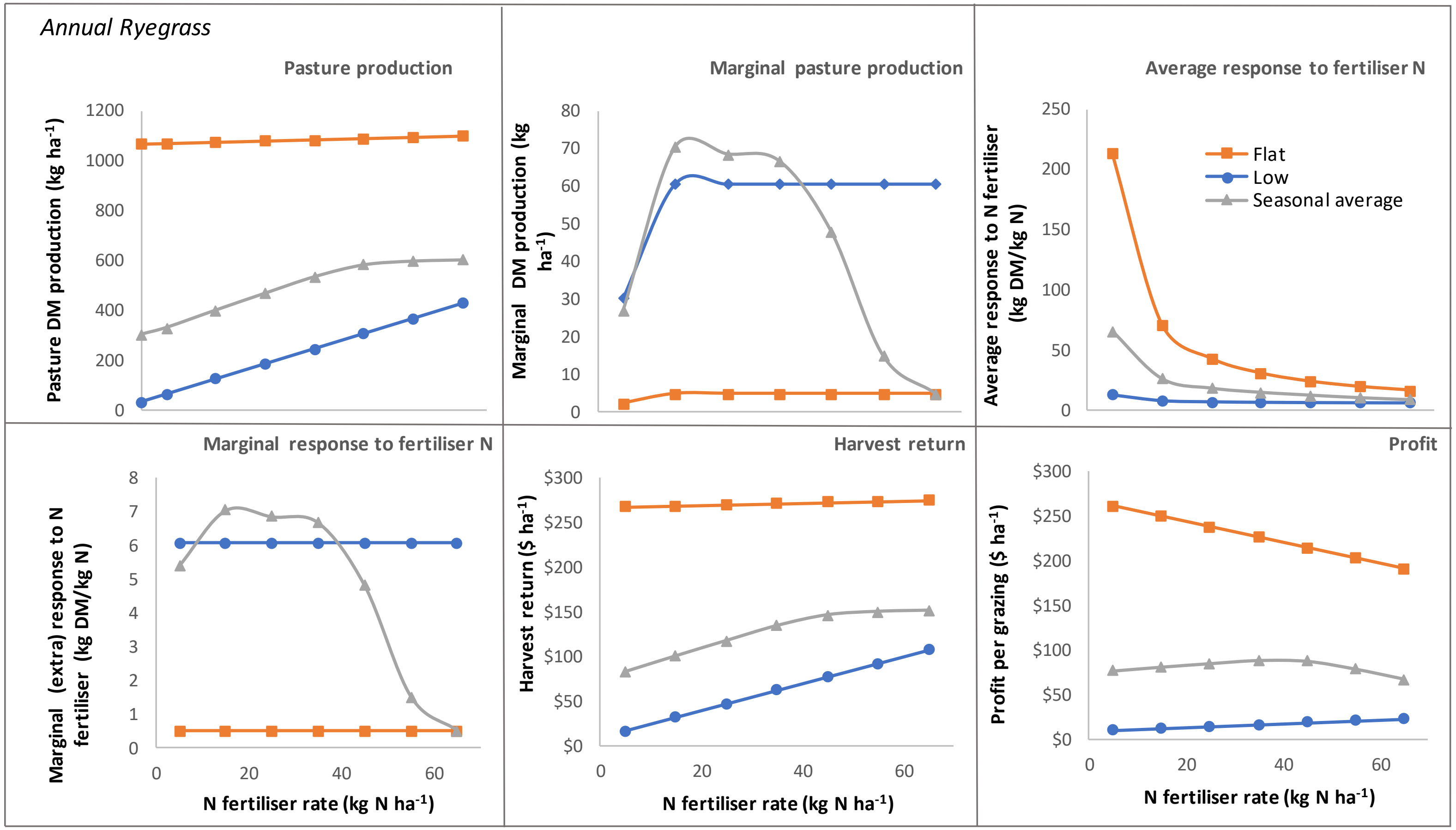


Figure 10 Variability in winter/spring annual ryegrass pasture production across different grazing cycles (n=12), marginal (extra) pasture production, average response to N fertiliser (DM produced/total N applied), marginal response to N (extra DM/additional N applied), harvest return (assuming a fodder value of $0.25 kg DM), and profit (harvest return minus fertiliser costs (assuming $1.30 kg N fertiliser) in response to increasing fertiliser application rates.

The following “basic” feed margin calculation was used as profitability indicator. The pasture cost included establishment of rye grass (Spray, seed and sowing) at $243 ha, N cost at $1.29 kg, P at $4.21 kg, K at $1.24 kg, lime at $0.5 kg and water at $23 ML. The “income” number is based on a simple feed conversion efficiency multiplication factor of 1.2. For example, for every 1 kg of pasture dry matter consumed by a cow, 1 Litre of milk is produced. Annual ryegrass and kikuyu optimum FCE factors are approximately 1.1 and 1.4 respectively. For the purposes of this calculation it’s considered that all additional pasture grown is converted into milk. Farm gate milk price was estimated at $0.50 L.

The additional pasture yield response (at 75% utilisation and minus the control) ranged from 2.38 t ha^{-1} to 8.33 t ha^{-1} (Table 3). A linear pasture yield response is assumed throughout the calculations. The additional feed cost per tonne ranged from $123 t^{-1} to $133 t^{-1}. Wheat is currently trading at $410 t^{-1} (Bega). The calculated feed margin response ranged from $1137 to $3890 ha^{-1}. The calculated feed margin results indicates that the sustainable application of Nitrogen fertilizer is profitable. However, this is dependent on other soil nutrients and water not being limiting.

Table 3 Yield responses and calculated feed margin at Camden under optimal conditions

Metric		**N application rate (kg N ha^{-1} yr^{-1})**			
		0	**120**	**240**	**480**
Annual production costs	($ ha^{-1})	$385	$678	$979	$1493
DM produced total	(t ha^{-1})	3.6	6.7	10.2	14.7
DM produced @75%	(t ha^{-1})	2.7	5.1	7.6	11.0
Agronomic Efficiency of N	(kg ha^{-1}/kg N)		25.8	29.2	18.8
Additional feed cost	($ ha^{-1})		$292	$593	$1107
	$ t^{-1}		$123	$120	$133
Additional milk produced	(litres ha^{-1})		2857	5941	9993
Additional milk value	($ ha^{-1})		$1429	$2970	$4997
Additional feed margin	($ ha^{-1})		$1137	$2378	$3890
	($ t^{-1})		477	480	467
Marginal feed increase	(% ha^{-1})			52	39

- Results show that N application can still be profitable even at high rates under optimal conditions, particularly when feed costs are high (i.e. drought). However a substantial amount of applied N (30-40%) is still lost from the soil-pasture system, more when urine is taken into account. Previous work has shown that as N application increases and marginal DM production reduces, more N is available for N loss processes, decreasing NUE further and impacting the environment. Particularly in annual rye grass there is a risk of high leaf NO_3^- which can have flow on effects to herd health and milk production, as well as substantially increasing the amount of N excreted (and lost) in urine. Luxury N application should therefore be discouraged, and the emphasis for production should be therefore to reduce N losses as opposed to simply applying more fertiliser.

Predicting and accounting for mineralisation in N fertiliser strategies

Soil N supply through mineralisation and pasture PAN demand

The capacity of soil to ***supply*** pasture N requirements through mineralisation was assessed over 26 harvests covering three years and a wide range of climatic conditions. Comparing the zero N treatment to a non-limiting N treatment ("Fully fertilised" - FF) under optimised experimental plot conditions the differentials between plant N demand and the capacity for the soil to supply N was assessed.

On the heavy black clay soil at Casino (4.2% carbon), an estimated 195 kg N ha^{-1} was removed from the zero N plots in the first year. Daily N supply was highest in late January-February following moderate rainfall and high temperatures, exceeding 0.7 kg N day^{-1}, and averaged 0.5 kg N ha^{-1} over the year (Figure 11). This compares well with the estimated 170 kg N ha^{-1} yr^{-1} estimated to be mineralised from a lateritic clay (4.9% carbon) at Gympie (Rowlings *et al.*, 2016). By comparison, the sandy top-soil duplex soil at Camden (2.9% carbon) supplied an average of 100-125 kg N ha^{-1} yr^{-1}, or 0.3-0.35 kg N ha^{-1} day^{-1}, with highest rates >1 kg N day^{-1} in autumn and averaging <0.2 kg N day^{-1} for the remainder of the year.

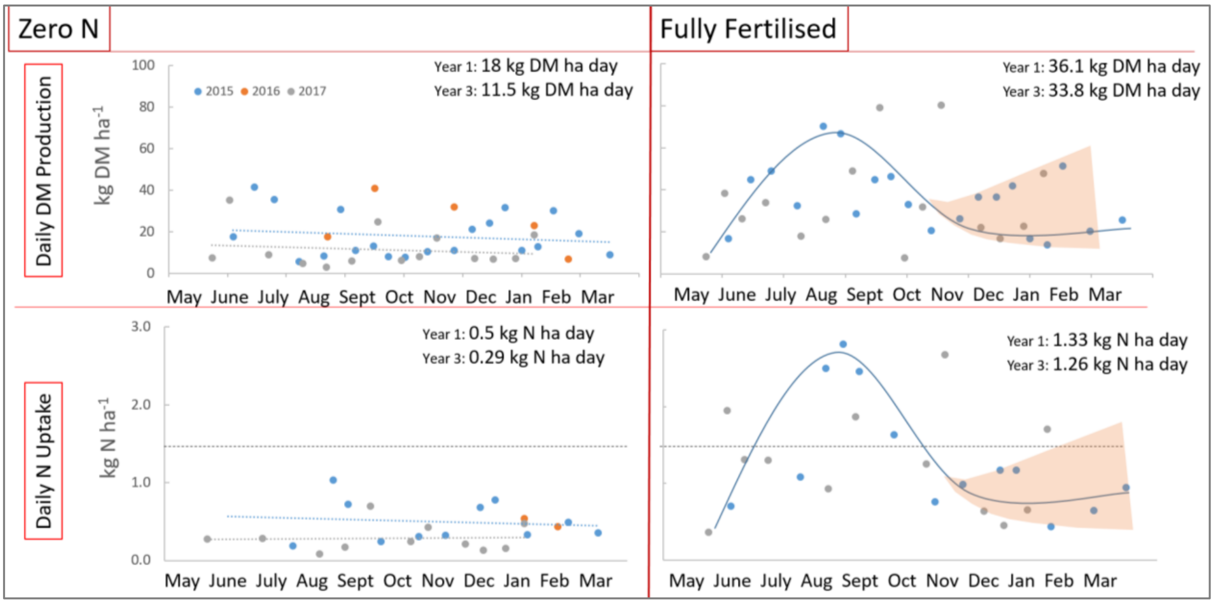


Figure 11 Daily pasture dry matter production at Casino for the Zero N and Fully Fertilised treatments (2015-17) and daily plant N uptake (kg N ha^{-1}) for Zero N and Fully Fertilised treatments at Casino (2015-17). Zero N plots indicate the long-term mineralisation potential (minus new fertiliser N inputs) while Fully fertilised indicates periods of high and low plant demand. Shaded area represesnt the period of highest variability in production.

At both sites, the supply of N removed from the zero N treatments declined in subsequent years. Testing of soil C and N in the top 0-10cm increment indicates that there has been a reduction in these stocks of ~30% at Camden over the 4 years. At Casino, daily N uptake from the zero N treatments decreased to <0.3 kg N day^{-1} (~105 kg N ha^{-1} yr^{-1}) in year three of the trial. The difference between these two years (90 kg N ha^{-1}) represents the "labile" mineralizable N pool which is replenished by applied fertiliser, while ~105 kg N ha^{-1} results from the long-term mineralisation rate (slow turnover pool). This long-term release of N from the "slow" mineralisation pool provides an estimate of how mineralisation N supply may be reduced under an "N mining" scenario where fertiliser inputs are reduced to better utilise the resources in the soil.

Interaction of N fertiliser with soil mineralisation - Camden Chromosol

The ^{15}N recovery rate trial conducted at Camden was also used identify the contribution of mineralisation to pasture N uptake under different N fertiliser application rates. The results indicate that mineralised soil N is the dominant source of N taken up by the plant (Table 4). Rye grass roots are expected to accumulate nitrogen to a depth of 40-50 cm below ground. Based on the total soil N calculated in April 2018 (0-50cm), it was estimated that the total percentage of soil N supplied to the >5cm biomass ranged from 0.45 (Zero N) to 1.78% (480 kg N ha^{-1}) over the period from July to December 2018. There was an increasing linear relationship between soil N supplied to the cut pasture and fertiliser N application. Figure 12 shows a notable increase in the N being supplied from the soil going into spring. It is generally expected that when soil temperatures starts increasing that soil N mineralisation increases.

Table 4 Total nitrogen and fertilizer derived (15N labelled) nitrogen removed in the pasture biomass, actual fertilizer recoveries and estimated nitrogen supply from mineralization from a Ryegrass dairy pasture at Camden, NSW. July to Dec 2018

N fertiliser applied (kg N yr^{-1})	0	80	120	240
Number pasture harvests	7	7	7	7
Pasture yield (kg DM ha^{-1})	1481	3829	5129	7493
TN %	2	2	2	3
CP %	11	13	14	16
TN plant biomass (kg ha^{-1})	27	80	112	188
^{15}N biomass (kg ha^{-1})	0	23	40	77
Non-^{15}N biomass (kg ha^{-1})	27	57	71	111
fNUE (%)		28	34	32
NDiff plant (%)		28	36	41
NDiff soil (%)	100	72	64	59
Soil TN 0-50cm (kg ha^{-1})	6150	6499	5964	6454
% of Soil N in >5cm biomass	0.44	0.88	1.20	1.72

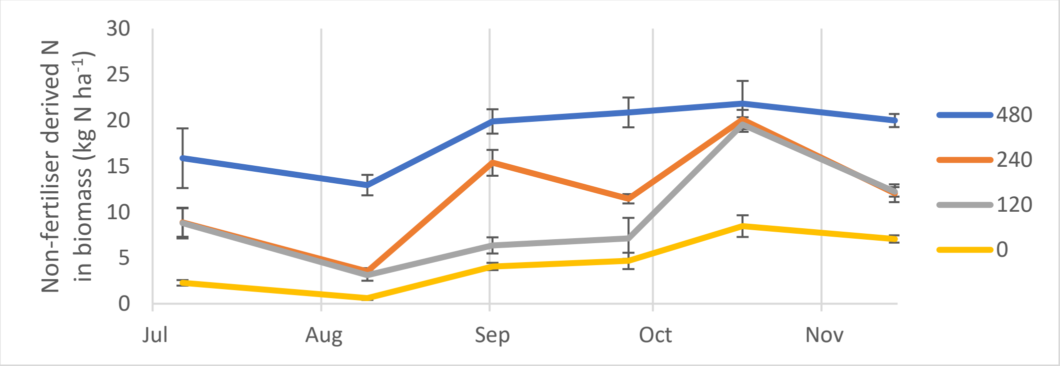


Figure 12 Non-fertilizer (^{15}N) N recovered in the ryegrass biomass (>5cm) from July to November at Camden.

Timing of N fertiliser application to match plant demand

Plant demand for N for fertiliser was assessed by examining the variability in maximum production under non-limiting conditions (adequate N + irrigation). At Casino, 414 kg N was applied to the fully fertilised (FF) plots resulting in 380 kg N being removed with an apparent recovery of 66% in 2017 and 56% in 2015. Total biomass dry matter (DM) production in the FF averaged 36.1 and 33.8 kg DM ha day^{-1} in 2015 and 2017 respectively compared to 18 and 11.5 kg DM ha day^{-1} respectively for the zero N (Figure 11). Highest production of up to 70-80 kg DM ha day^{-1} occurred between October and December which represents the peak of the rye grass and early kikuyu however even during this period production was extremely variable with growth rates falling below 30 kg ha^{-1} day^{-1} over a number of harvests. Similar dynamics were observed at Camden

Figure 13 emphasises the key periods where fertiliser demand is high, and soil N supply through mineralisation is low. This peaks at over 60 kg DM ha^{-1} more being produced in the fertilised plots compared to the Zero N plots during the spring (August to November) when rye production conditions are optimal. Early in the season there is little response to additional fertiliser N whereas in the late summer and autumn the variability in both plant fertiliser demand and fertiliser efficiency increases due to the random and sporadic large rain events (leading to both large mineralisation of N but also large losses). The higher fertiliser efficiency associated with year three compared to year one is an indication of the depletion of the mineralisable N pool and subsequent increased reliance on fertiliser N.

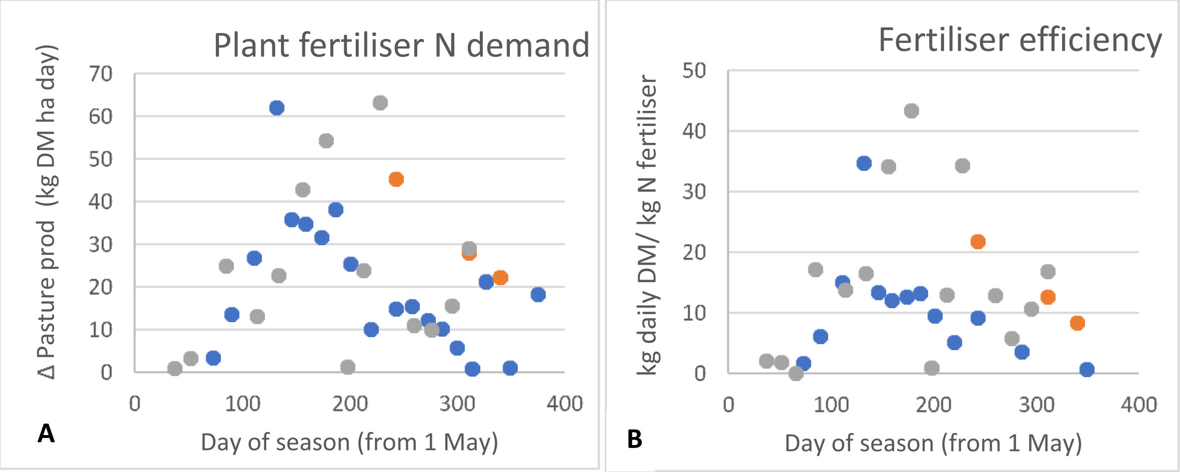


Figure 13 Response of fertiliser to pasture DM production as ***A****) Plant fertiliser N demand calculated by subtracting (Δ) pasture production in the Zero N plots from the Fully Fertilised plots, and* ***B****) Fertiliser efficiency calculated as the Δ pasture production per unit of N fertiliser applied.*

Biomass collected from the long-term Zero N and FF plots allows for plant demand for N, and the capacity of the soil to supply that N, to be determined. Highest yields from the FP occur during early spring when temperature conditions for the ryegrass pastures are optimum, and lowest in the late autumn immediately following rye sowing.

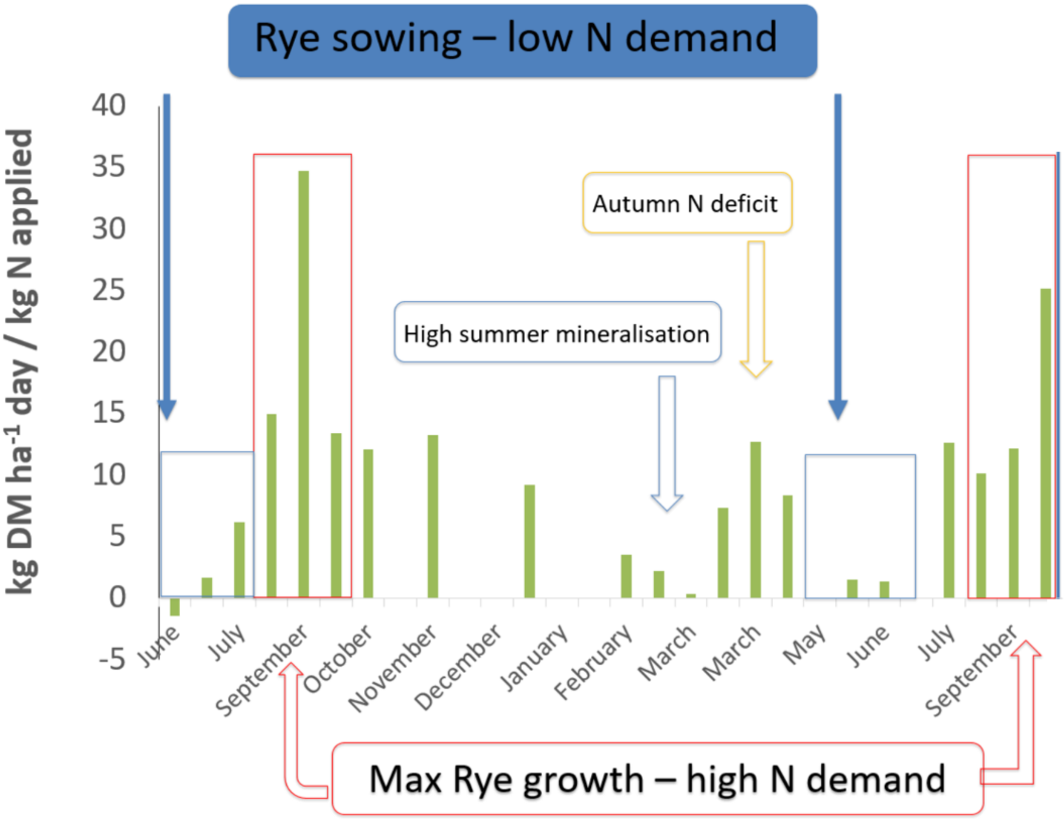


Figure 14 Pasture N demand as expressed as kg dry matter per kg N applied from June 2016 to September 2017 at Casino, NSW. N demand was calculated by subtracting the zero N plot biomass from the fully fertilised farmer practice treatment.

By contrast, N supply to the plants (Zero N plots) is lowest in the winter/spring due to low soil temperatures and highest in the summer. Subtracting the Zero N from the FP and dividing by the amount of FP fertiliser applied allows for the "fertiliser N demand" of the pasture system to be calculated (Figure 14). The highest response to added fertiliser occurs in September/October when rye demand is high, and soil N supply is low, whereas in the summer fertiliser demand is low due to adequate supply from soil mineralisation.

Potential to optimise irrigation to reduce N losses

The response of N turnover and N losses via denitrification from three differently textured pasture soils to different soil moisture levels

Developing the experimental rationale for the irrigation trial

Bulk soil was collected from three different dairy pasture sites in Casino (NSW), Gympie and Kerry (Qld). The soil was fertilised, wetted to four different soil moisture levels (40, 60, 80 and 95% water-filled pore space (WFPS) and mineralisation, nitrification and gaseous N loss in the form of N_2 and N_2O was measured over two days.

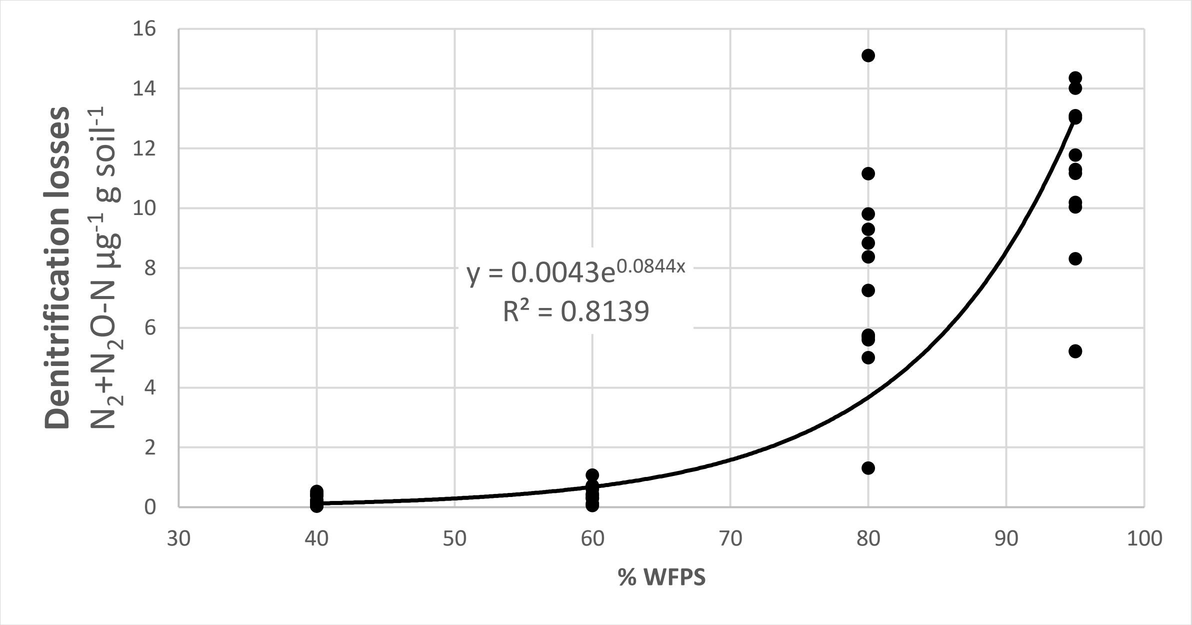
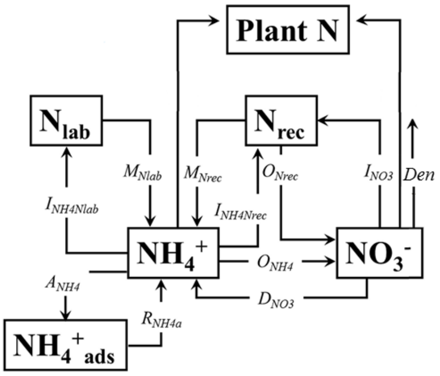


Figure 15 Denitrification losses (N_2+N_2O-N µg^{-1} g soil,$^-$ equivalent to N kg^{-1} ha^-) across different soil water contents from three intensively managed dairy pasture soils in Gympie and Kerry (Qld), and Casino (NSW) over a two day incubation period.

The response of denitrification (N_{2+} N_2O) is shown in Figure 15. Between 40 and 60% WFPS, only small amounts of N are emitted as N_{2+} N_2O. Above 60% WFPS, which roughly equals field capacity across sites, N_{2+} N_2O losses increase exponentially, showing high variability at both 80 and 90% WFPS. These results suggest that significant N losses in the form of N_2 and N_2O can be expected, if soil moisture levels exceed 60% WFPS, with highest N losses between 80 and 100% WFPS.

Nitrogen availability is critical for pasture yield and quality. The high N turnover in pasture soils however can lead to periods of excess N in the soil, prone for loss via denitrification. We combined the use of ^{15}N fertiliser with a numerical ^{15}N tracing model in an incubation study, to get an insight into the processes affecting plant available N (PAN) at four different soil moisture levels across 3 different dairy soils. The model considers four main N pools: NO_3^-, NH_4^+, a labile N pool (N_{lab}) and a more recalcitrant e.g. less available N pool (N_{rec}). A fifth pool, the $NH_4^+{}_{ads}$ pool specifies NH_4^+ adsorbed to clay (Figure 5). The model splits N production and consumption into ten N transformations quantifying the production of soil mineral N (mineralisation and nitrification) and the consumption of soil mineral N (immobilisation and denitrification) (Figure 16). As such, the model gives a comprehensive insight into N turnover in dairy soils, providing a robust base to forecast PAN.

Results shown in Figure 17 demonstrate the response of N turnover to different soil moisture levels. The high mineralisation and nitrification rates show the high N turnover in subtropical pasture soils and are consistent with high net nitrification rates from the same soils after rainfall events (Friedl *et al.*, 2017). The differences in overall mineralisation correspond with labile C availability in the soils, and identify the loam from the dairy pasture in Gympie as the most productive in terms of N supply into the soil mineral N pools. N consumption across soils is however proportional to N production rates, dominated by immobilisation into the labile, e.g rapidly turned over NH_4^+ pool. The balance between N immobilisation and remineralisation determines the N turnover in these pasture soils, and therefore the fate of N fertiliser in the system. Mineralisation and nitrification rates are summarised in Figure 18 for Gympie. With increasing soil moisture, mineralisation of organic N slightly increases. The dominant process however is nitrification, increasing drastically with soil moisture up to 80% WFPS and decreases when the soil reaches saturation. Nitrification converts NH_4^+, which is plant available and well bound to the generally negatively charged soil matrix to NO_3^-, which is easily lost via leaching, runoff and denitrification. Our findings show that large spikes in soil water content increase the supply of N into the NO_3^- pool with an exponential increasing risk of N loss via denitrification.



	Transformation
O_{NH4}	Oxidation of NH_4^+ to NO_3^- - Nitrification
O_{Nrec}	Oxidation of N_{rec} to NO_3^- - Nitrification
I_{NO3}	Immobilisation of NO_3^- to N_{rec}
D_{NO3}	Dissimilatory NO_3^- reduction to NH_4^+
M_{Nrec}	Mineralisation of N_{rec} to NH_4^+
M_{Nlab}	Mineralisation of N_{lab} to NH_4^+
$I_{NH4Nlab}$	Immobilisation of NH_4^+ to N_{lab}
$I_{NH4Nrec}$	Immobilisation of NH_4^+ to N_{rec}
R_{NH4a}	Release of adsorbed NH_4^+ to NH_4^+
A_{NH4}	Adsorption of adsorbed NH_4^+ to NH_4^+
Den	Denitrification

Figure 16 ^{15}N tracing model for the analysis of N gross transformations in three different textured pasture soils with the respective N transformations

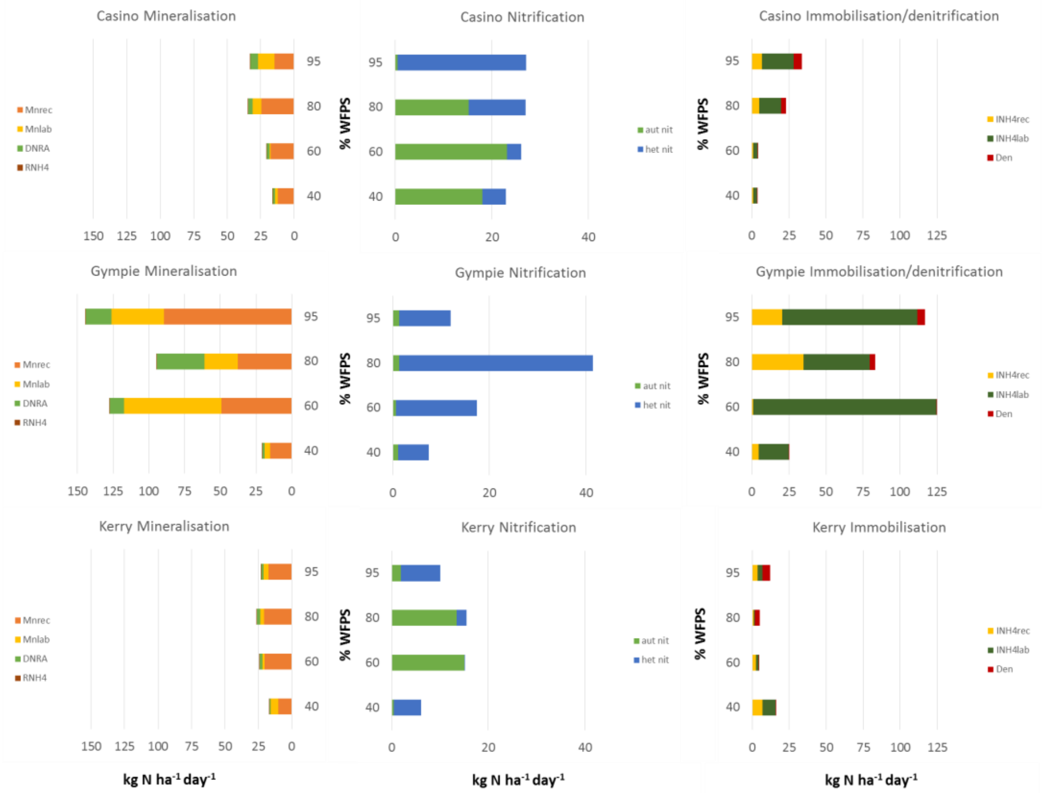


Figure 17 Nitrogen production and consumption in three different textured pasture soils with the respective N transformations

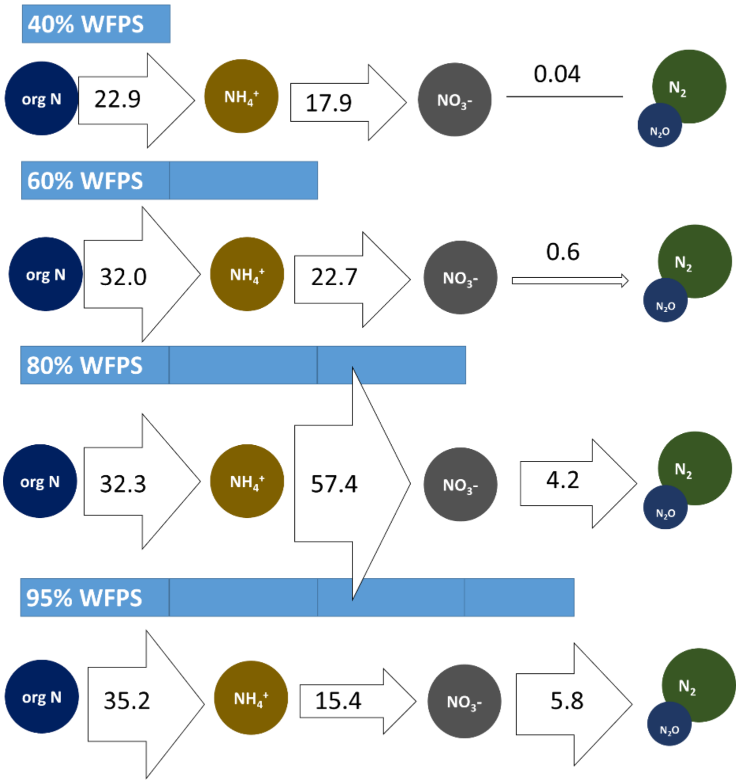


Figure 18 Mineralisation, nitrification and denitrification in response to soil water content from in an intensively managed pasture soil from Gympie (Qld)

Denitrification losses from three different dairy pastures in response to intensive rainfall

Figure 19 shows pooled $N_2 + N_2O$ data from field trials across different soil moisture levels from three intensively managed dairy pastures in southern Qld and northern NSW. The experimental setup included the simulation of a large rainfall event of (200 mm). Emissions of N_2 and N_2O show a drastic increase with WFPS, with peak losses of up to 8 kg N ha^{-1} day^{-1}. The highest N losses (up to 28 kg of N over 21 days) were observed from pastures where intense rainfall led to prolonged periods of saturation in the first 10 cm of the soil profile.

In contrast, well-drained soils with lower C content lost less than 5 kg N under the same conditions, highlighting the importance of soil type to identify the risk of N loss from pasture soils (Table 6). The response of denitrification in the field confirms the observed relationship with WFPS under controlled conditions. This relationship between soil moisture, N supply into the soil mineral N pools and associated losses of N shows the potential to manage N turnover and losses more effectively by minimising the variation of soil moisture via irrigation.

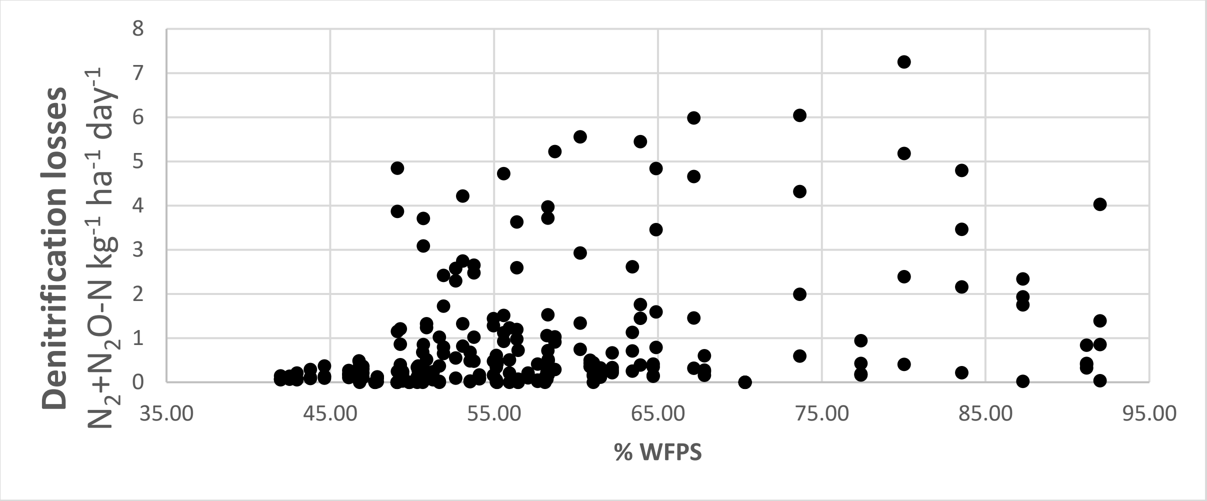


Figure 19 Denitrification losses (N_2+N_2O-N kg^{-1} ha^{-1} day^{-1}) different soil water contents from three intensively managed dairy pastures in Gympie and Kerry (Qld), and Casino (NSW).

The irrigation trials were set up to provide optimal water supply for plant growth by replacing the estimated evapotranspiration over a grazing cycle, while maximising soil aeration, i.e. minimising the saturation of the soil. Irrigation was applied in one event, split into two events or split into four events. (LOW Frequency + High Rate, MEDIUM Frequency + Medium Rate, HIGH Frequency + Low Rate).

Effect of irrigation scheduling on annual pasture yield and nitrous oxide emissions

This trial used emissions of N_2O as an indicator for gaseous N loss as affected by different irrigation frequencies. Highest cumulative N_2O losses of 5.9±0.5 kg N ha^{-1} were measured from the LOW-Frequency treatment, which was significantly higher than the MEDIUM and HIGH-Frequency treatments with 3.2.±0.2 kg ha^{-1} and 3.8±0.5 kg ha^{-1}, respectively. Emission factors ranged between 0.49% and 1.17% for MEDIUM-Frequency and LOW-Frequency treatments respectively. Despite significant differences in N losses, much of this variance was not directly related to individual irrigation events but to a treatment legacy seen during succeeding high rainfall events. These high losses from the LOW-Frequency treatment have been attributed to the effect of severe drying of the soil profile between irrigation events; suggesting a future focus of research on wetting and drying cycles rather than absolute soil moisture contents.

Despite the significant reduction in N_2O losses by the HIGH and MEDIUM treatment, these N savings did not translate into a benefit to pasture production and NUE as was hypothesised. Over the ten month measurement period, the difference between the irrigation treatments was less than a tonne of DM. However, large differences were seen in the efficiency metrics, especially that of N_2O intensity, the combined metric of N_2O intensity per unit of irrigation water use efficiency (WUE) and the irrigation related electricity costs of each treatment (Table 5). N_2O intensity in the LOW treatment was found to be 0.46 kg N_2O kg^{-1} DM, 35% greater than HIGH and 41% more than MEDIUM. When combined with irrigation WUE, the benefit of the MEDIUM and HIGH as irrigation strategies became even more pronounced, with the HIGH and MEDIUM treatments producing less than half the N_2O per kilogram of DM for each millimeter of irrigation applied. The HIGH treatment was the most cost effective in terms of electricity required for the pumping of irrigation. Despite no difference in annual DM production between the HIGH, MEDIUM and LOW treatments, each tonne of DM in the MEDIUM and LOW cost $10 and $14 more to produce per hectare. The second most cost effective treatment accounting for electricity prices was the farmers practice treatment which cost $7 more per hectare to produce a tonne of DM. All fertilised treatments were significantly more efficient producers of pasture DM than the non fertilized treatment, which required between $17 and $31 more electricity for irrigation than the other treatments (Mumford *et al.*, 2019).

Table 5 Summary of, pasture yield and N removal, N_2O emissions, Emission Factors (EF) and treatment intensity metrics an irrigated dairy pasture in Casino, Australia. The standard error is given in parentheses; the statistical significance is denoted by subscript letters

	High-Frequency	**Medium-Frequency**	**Low-Frequency**
Biomass yield (t DM ha^{-1})	$13.2\ (0.3)_a$	12.5 (0.3)	$12.6\ (0.5)_a$
Total N yield (kg ha^{-1})	$437.2\ (20.1)_a$	$411.7\ (13.3)_a$	$410.1\ (13.2)_a$
Daily biomass yield (kg DM ha^{-1} d^{-1})	$38\ (1.3)_a$	$37.6\ (0.9)_a$	$37.3\ (1.5)_a$
Total N_2O loss (g N ha^{-1})	$3790\ (417)_a$	$3282\ (232)_a$	$5855\ (534)_b$
Emission Factor	0.62 (0.12)	0.49 (0.05)	1.17 (0.14)
Irrigation Water Use Efficiency (kg DM mm^{-1})	44.8	29.6	25
N_2O intensity (kg N_2O kg DM^{-1})	0.29	0.26	0.46
N_2O intensity per unit of Irrigation Water Use Efficiency (kg N_2O kg DM^{-1} mm^{-1})	0.08	0.11	0.23

The reduction in N_2O losses demonstrated here raised the question if overall denitrification losses – N_2 plus N_2O - would be affected by irrigation frequencies. This research question was investigated in the following experiment.

Denitrification losses from intensively managed dairy pastures in response to different irrigation frequencies.

The impact of irrigation on soil water content was confirmed in both Camden and Casino. Soil aeration was calculated as soil gas diffusivity (*Dp/D0*), and an example of the temporal variation of this parameter for MEDIUM and LOW frequency in Casino is shown in Figure 20. Soil aeration remained higher in the HIGH treatment, falling only below the threshold for anaerobic conditions when irrigation was applied. In contrast, the LOW treatment showed a drop in soil aeration upon irrigation, with a steady subsequent increase.

Denitrification losses at both sites ranged from 1 to 5 kg N ha^{-1} over 20 days from the fertilised pasture plots. These losses are considerably lower than the 20-28 kg ha^{-1} observed over 21 days in Gympie and Casino, respectively, when a large rainfall event of 200 mm was simulated. The application of the LOW frequency irrigation increased soil WFPS to >80% (Figure 20), but soil WFPS decreased rapidly below 70%. The low N_2 and N_2O losses at both sites demonstrate that accounting for the evapotranspiration rate limits denitrification losses from intensively managed pastures. Losses from the Urine patches were higher than those from the fertilised plots, with up to 28 kg of N lost via denitrification over 60 days. These losses were significantly higher in Casino compared to Camden, but accounted for only up to 3.5% of the applied urine N (Table 6). Less than 10 % of the urine was recovered in plant biomass and soil, suggesting that ammonia volatilisation, lateral translocation, plant uptake and leaching led to loss of urine N from the soil.

Table 6 Denitrification losses after intense rainfall and under three different irrigation frequencies from fertilised pasture and from urine patches in Camden and Casino, NSW.

Site	Season	Days	Nitrogen	Treatment	N_2	N_2O	N_2+N_2O
Casino	Rye/October	21	Urea-N fertiliser (36.8 kg N ha^{-1})	Irrigation 20 mm + 200 mm of rainfall	21.97 ± 4.65	0.09 ± 0.03	22.07 ± 4.66
Gympie	Rye/October	21	Urea-N fertiliser (36.8 kg N ha^{-1})	Irrigation 20 mm + 200 mm of rainfall	28.45 ± 6.78	0.68 ± 0.21	29.12 ± 6.81
Kerry	Rye/October	21	Urea-N fertiliser (36.8 kg N ha^{-1})	Irrigation 20 mm + 200 mm of rainfall	3.99 ± 0.76	0.13 ± 0.02	4.12 ± 0.76
Casino	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	HIGH irrigation frequency	4.97 ± 0.89	0.21 ± 0.03	5.18 ± 0.87
Casino	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	MEDIUM irrigation frequency	0.92 ± 0.10	0.28 ± 0.05	1.20 ± 0.09
Casino	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	LOW irrigation frequency	4.50 ± 0.66	0.72 ± 0.25	5.22 ± 0.76
Casino	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1}) + Urine*	HIGH irrigation frequency	28.34 ± 3.18	1.91 ± 0.26	30.28 ± 3.48
Casino	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1}) + Urine*	LOW irrigation frequency	27.91± 5.56	2.81 ± 0.22	30.74 ± 5.75
Casino	Rye/November	15	Urea-N fertiliser (30 kg N ha^{-1})	HIGH irrigation frequency + rainfall of 100 mm	5.55 ± 0.91	1.75 ± 0.60	7.30 ± 1.48
Casino	Rye/November	15	Urea-N fertiliser (30 kg N ha^{-1})	LOW irrigation frequency + rainfall of 100 mm	6.32 ± 0.64	2.27 ± 0.75	8.59 ± 1.33
Camden	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	HIGH irrigation frequency	4.31 ± 0.58	0.04 ± 0.01	4.35 ± 0.58
Camden	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	MEDIUM irrigation frequency	2.32 ± 0.52	0.07 ± 0.03	2.39 ± 0.55
Camden	Rye/August	20	Urea-N fertiliser (40 kg N ha^{-1})	LOW irrigation frequency	3.03 ± 0.82	0.09 ± 0.03	3.12 ± 0.84
Camden	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1}) + Urine*	HIGH irrigation frequency	17.78 ± 2.28	0.59 ± 0.13	18.39 ± 2.42
Camden	Rye/August - September	60	Urea-N fertiliser (120 kg N ha^{-1}) + Urine*	LOW irrigation frequency	12.71 ± 1.88	0.32 ± 0.06	13.05 ± 1.95

* Urine was applied at an equivalent rate of 800 kg N ha^{-1}

For the fertiliser only plots, the irrigation frequency had no significant effect on overall denitrification losses, and there was no significant difference between Casino and Camden. Importantly, MEDIUM and HIGH frequency irrigation reduced N_2O losses in Casino. This is a reduction of environmental harmful N losses from dairy pastures. The magnitude of this reduction is however not agronomically significant. As other rural industries such as MLA move towards carbon-neutral production, reducing emissions of the GHG gas N_2O is likely to become more important also in dairy systems. Marketing of carbon-neutral products frames the term "More profit for N" differently, making a reduction of the GHG footprint of a farming system also an economically interesting option. These findings are however site/soil specific, showing that further research is needed to evaluate on which soil type a reduction of N_2O can be achieved by increasing the irrigation frequency.

- Improved N management on dairy farms should aim to adjust irrigation by replacing the evapotranspiration rate to limit denitrification losses (N_2+N_2O) triggered by irrigation. However, our results do not show a reduction of overall denitrification (N_2+N_2O) by increasing the irrigation frequency from LOW to HIGH. The reduction of N_2O in the MEDIUM and HIGH treatment observed in Casino indicates a viable option to reduce environmental harmful N losses from these pastures, requiring further research.

Impact of different irrigation frequencies on denitrification losses triggered by a rainfall event

The research question of this study was if increased irrigation frequency could increase the resilience of a dairy pasture to denitrification losses after a simulated rainfall event. We hypothesised that the priming of the plots over the winter/rye season by the different irrigation frequencies would show a legacy effect on denitrification losses, (a) reducing overall N loss from the pasture soil and (b) shifting the N_2:N_2O ratio towards N_2, thereby limiting losses of environmentally harmful N. Figure 6 shows the response of soil aeration, soil WFPS, and N_2 and N_2O emissions from the HIGH and LOW frequency irrigation treatment. After fertilisation, denitrification losses responded to the treatments, with higher emissions for LOW compared to HIGH. Subsequent N_2 and N_2O emissions from LOW decreased, which is consistent with increasing soil aeration as shown in Figure 6. With every HIGH irrigation event, N_2 and N_2O emissions increased. By day nine after N fertiliser application, cumulative N_2 and N_2O emissions from HIGH broke even with those from the LOW treatment at 2 kg N ha^{-1}. The simulated rainfall triggered peak emissions from both, with no significant differences in overall N loss between treatments. However, the relative change in the N_2:N_2O ratio showed a shift from N_2O to N_2.

These findings show that the constant irrigation in HIGH frequency treatment did not reduce overall N losses, but led to constant stimulation of denitrification, resulting in the same N losses as in the LOW treatment after three irrigation events. The experiment confirmed however the expected legacy effect regarding the N_2:N_2O ratio, suggesting increased irrigation frequency as a means to reduce N_2O.

- At this point, the differing results between sites do not allow a general recommendation regarding irrigation frequencies aimed at reduced overall denitrification loss from pastures. Based on the data available, we can not confirm a reduction of N_2 + N_2O losses by increasing the irrigation frequency. Considering the ^{15}N recovery shown in Figure 21 and Figure 22, denitrification is likely not the only process responsible for N loss observed in the experiment, as evidenced by the increasing N losses from HIGH to LOW irrigation frequency. Other pathways of loss such as runoff and leaching need to be investigated by future research to evaluate the full effect of these irrigation strategies on N loss and mitigation.

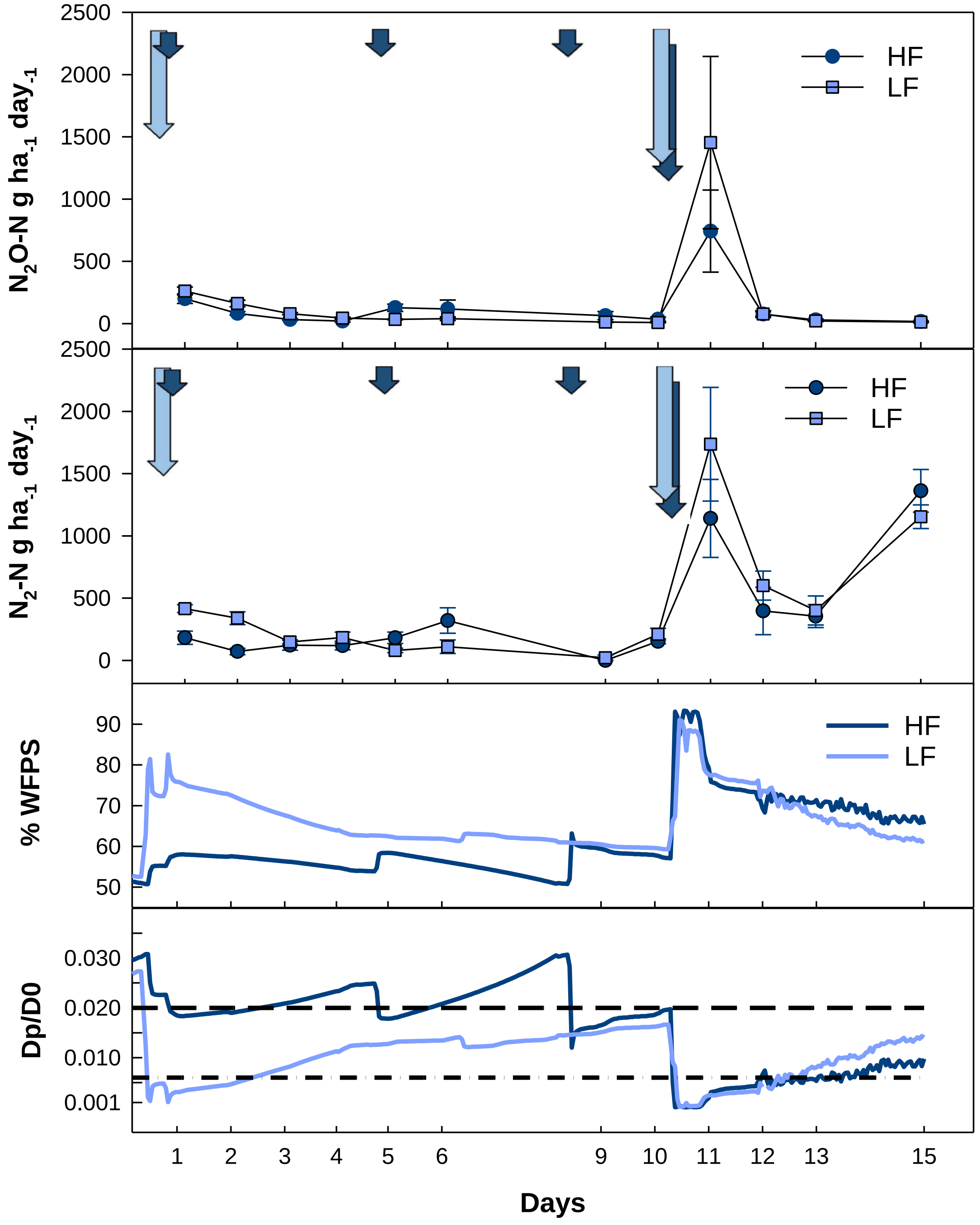


Figure 20 Emissions of N_2 and N_2O from an intensively managed pasture in northern NSW, Casino under two different irrigation frequencies: Low frequency (LF) applying the estimated evapotranspiration of 15 days at once and high frequency (HF), applying the estimated evapotranspiration rate split in four applications. The arrows represent the relative magnitude of irrigation and the simulated rainfall vent at day 10. Soil water-filled pore space and respective soil gas diffusivity (Dp/D0) are shown below

Investigating the short and mid-term fate of applied N fertiliser on intensively manage pastures

In intensively managed dairy systems, plant available N will critically depend on the immobilisation and remineralisation of applied N fertiliser. In particular in soils with high organic matter and therefore high microbial activity, a significant amount of N fertiliser can be immobilised by microbes, with remineralisation cycles determining when the N fertiliser will become available for both plant uptake and/or loss pathways. Importantly, fertilizer N immobilisation is not an N loss from the system, only reducing short term N fertilizer availability and apparent NUE. The pulse of re-mineralisation in response to increased soil moisture (Figure 15) highlights the potential impact of irrigation on N remobilisation as well as N loss. This experiment therefore determined the fate of applied ^{15}N fertiliser subject to three different irrigation frequencies over three grazing cycles in the ryegrass season. At both sites, urea was applied at a rate of 40 kg N per ha^{-1} before each grazing cycle. Only the first application was ^{15}N urea, enabling to trace the fate of the applied N over the following grazing cycles. A complete ^{15}N recovery after each grazing cycle allowed to investigate (a) the contribution of fertiliser N to plant N yield, (b) remobilisation of immobilised N and (c) the amount of N fertiliser lost.

Pasture biomass yield (>5cm) increased in both Camden and Casino over the three grazing cycles, with Biomass yields over 20 days ranging from 1000 to 2000 and 550 to 1400 kg BM ha^{-1}. This temporal pattern reflects both increasing temperatures and the time from ryegrass establishment. The differences between sites however suggest Casino as the more productive site over the winter season. The results of the ^{15}N recoveries are shown in

Figure 21 and

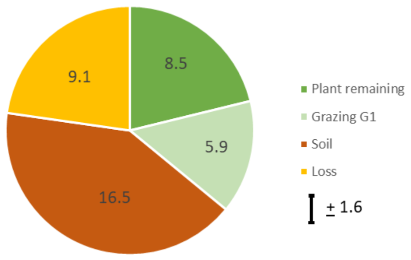
Figure 22, for Camden and Casino, respectively.

In Camden, fertiliser ^{15}N uptake into the plant BM > 5cm ranged from 5.9 to 7.1 kg ha^{-1} in the first harvest after ^{15}N application. The contribution of ^{15}N fertiliser to plant N uptake decreased over the following grazing cycles, with 1.9 to 2.5 kg N recovered at the end of the third cycle. At the same time, both the ^{15}N fertiliser recovery in soil and plant BM <5cm decreased by around 50%, suggesting N supply plant N uptake into plant BM > 5cm from these N pools. Significantly, 20% of the applied 40 kg N ha^{-1} were lost in the first grazing cycle, with no significant impact of irrigation frequency. Up to 20% of N were lost in the second grazing cycle, but no further losses were observed in the third cycle.

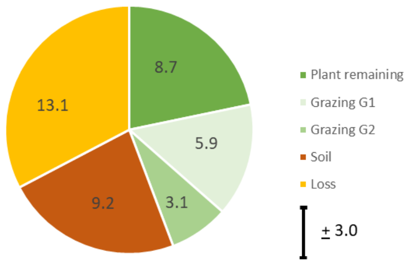
In Casino, fertiliser ^{15}N uptake into the plant BM > 5cm ranged from 9 to 12 kg N ha^{-1} in the first harvest after ^{15}N application, exceeding uptake rates from Camden by more than 50%. Similar to Camden, the contribution of ^{15}N fertiliser to plant N uptake decreased, with 1.9 to 2.8 kg N recovered at the end of the third cycle. The ^{15}N recovery in the soil shows little to no change over the three grazing cycles, with 25-35% of applied N fertiliser recovered. In contrast, the ^{15}N fertiliser recovered in the plant BM<5cm decreased across treatments by 30-40%. These findings indicate that the ^{15}N uptake in the plant BM >5cm in grazing cycle 2 and 3 in Casino was driven by the translocation of N within the plant rather than by N uptake from the soil. The stable pool of fertiliser N in the soil indicates that mid-term remineralisation is unlikely in such high carbon pasture soils under the conditions of the experiment. Losses of N ranged from 2.8 to 4.8 kg N ha^{-1} and were smaller in Casino compared to those in Camden. Losses of N occurred only in the first grazing cycle, denoting tight N cycling in Casino. In contrast to Camden, losses of N were negatively correlated with irrigation frequency, showing the highest N losses in the LOW frequency treatment.

- Our finding highlight the differences between the two intensively managed pasture sites, showing higher fertiliser N uptake, but also higher N immobilisation for the more productive Vertosol in Casino. Irrigation had no impact on remineralisation. Differences in remineralisation between soil types are critical and need to be considered for improved pasture N management. In soils with lower organic C such as Camden (type a), N losses and fN uptake is likely to occur gradually over grazing cycles, decreasing from the time of fertiliser application. In soils with higher organic C (type b), fN immobilised in the soil is a very stable pool, and is unlikely to be mineralised, unless drastic changes in soil conditions such as large rainfall events trigger remineralisation of fN. Our findings indicate that N management of type a soils needs to target constant loss of N, while for type b soils, N management needs to focus in particular on above average rainfall events.

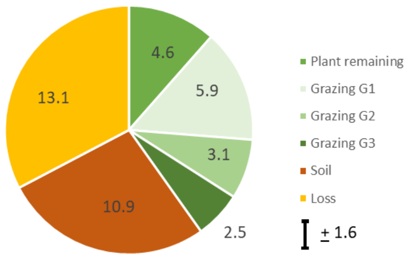
High irrigation frequency



Grazing cycle 1

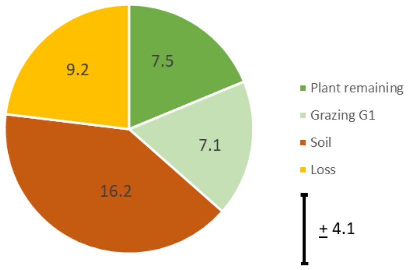


Grazing cycle 2

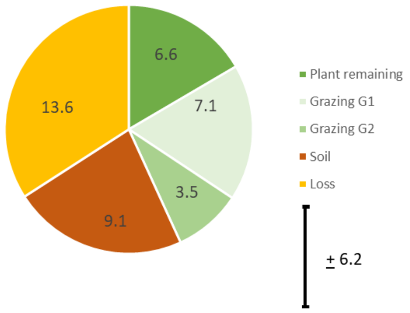


Grazing cycle 3

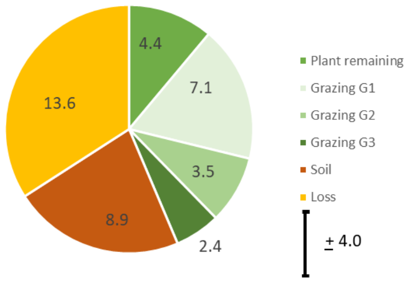
Medium irrigation frequency



Grazing cycle 1

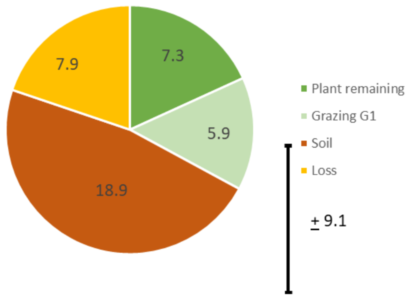


Grazing cycle 2

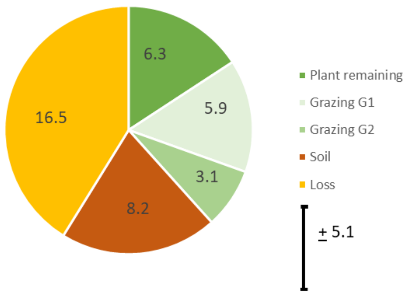


Grazing cycle 3

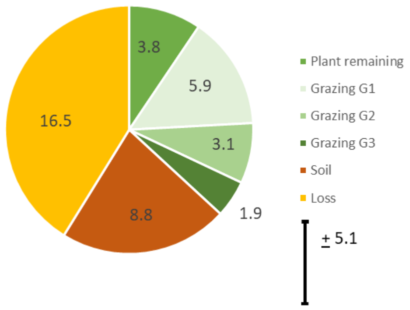
Low irrigation frequency



Grazing cycle 1



Grazing cycle 2



Grazing cycle 3

Figure 21 Fate of N fertiliser (kg N ha^{-1}) over three grazing cycles under different irrigation frequencies in ryegrass in Camden, NSW. The black bar represents the relative magnitude of the standard deviation of the overall fertiliser N recovery.

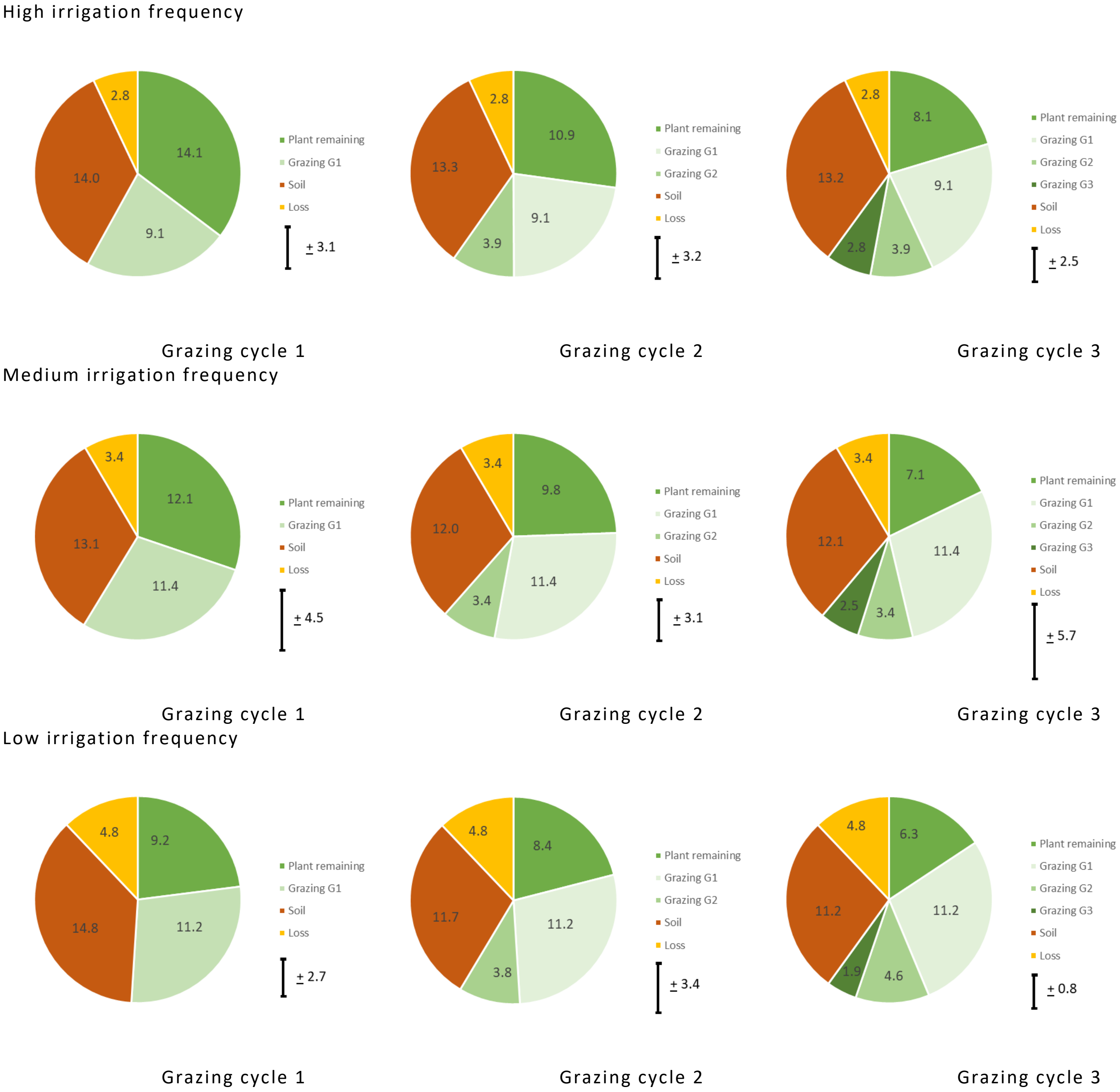


Figure 22 Fate of N fertiliser (kg N ha^{-1}) over three grazing cycles under different irrigation frequencies in ryegrass in Casino, NSW. The black bar represents the relative magnitude of the standard deviation of the overall fertiliser N recovery.

Potential of Enhanced Efficiency Fertilisers to improve NUE and pasture productivity

Agronomic response to NH_3 volatilisation and potential of urease inhibitors

Previous research undertaken at Camden over two years failed to illustrate any significant yield benefits from the use of either DMPP or NBPT. Two trials to determine the agronomic importance of NH_3 volatilisation losses and the potential of the commercial EEF "Green Urea" to reduce losses. Standard urea (U) and urea coated with the urease inhibitor NBPT (GU) were compared over two campaigns at Camden and Casino. To ensure any potential savings in NH_3 were detectable in the harvested biomass, the trial was conducted on a section of the 4-year-old zero N and farmer's practice plots representing extremely N limited and non-N limited soil conditions. Both types of fertiliser were applied at a high (HF), and low (LF) rate to demonstrate that N was indeed limiting and any saving would be detectable in the biomass. Irrigation was applied to optimise the exposure time of the urea granules with at least 8 days between irrigation events. A third delayed urea-only treatment applied fertiliser 10 days (LFT2) after grazing to evaluate the effectiveness of canopy height in reducing losses.

While climatic conditions were not severe during the duration of the trial, they represent the range of conditions that farmers would reasonably be expected to apply urea. Results indicated a clear response to N but no difference in either biomass production, pasture N content, or mineral N content using the inhibitor at either site. The clear N response between the low fertiliser history plots and the high plots suggests N was indeed limiting to growth and any subsequent improvement in NUE from using the inhibitor would be evident in the biomass response. This suggests that under typical winter-spring growing conditions when the majority of fertiliser is applied, the risk of N loss through volatilisation is minimal. The delayed treatment showed a substantial reduction in biomass compared to the comparable N rate where N was applied immediately after grazing suggesting the timing of application impacts substantially on yields.

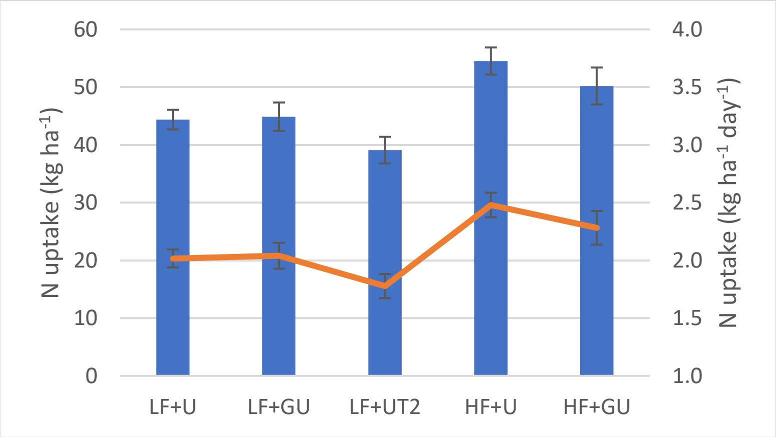


Figure 23 Total (blue bars) and daily (red line) plant N uptake for the final harvest period (3 October 2018- 25 October 2018) of the winter/spring volatilisation trial for the low-fertiliser urea (LFU), low-fertiliser green urea (LFGU), urea delayed application (LFUT2) and the high fertiliser urea and green urea (HFU and HFGU respectively).

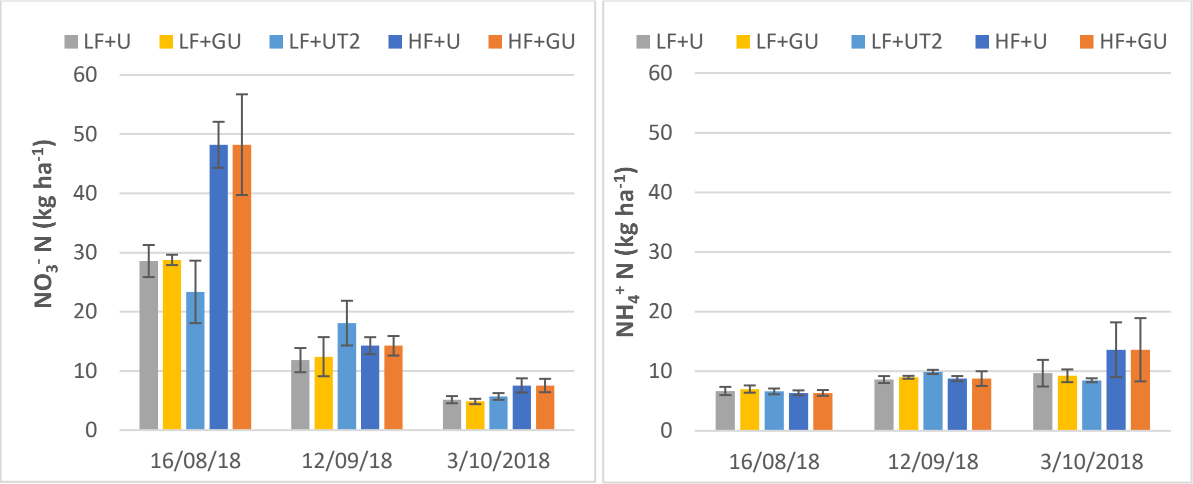


Figure 24 Soil mineral N content (NO_3^- and NH_4^+) taken on day 0, and prior to each subsequent fertiliser event during the winter/spring volatilisation trial for the low-fertiliser urea (LFU), low-fertiliser green urea (LFGU), urea delayed application (LFUT2) and the high fertiliser urea and green urea (HFU and HFGU respectively).

Effect of DMPP on direct fertilizer and urine N losses

Urine patches represent major inputs of nitrogen, equivalent to up to 1000 kg N ha^{-1}. In intensively grazed dairy systems these can cover over 10% of the paddock area annually and are major point sources of N loss. While substantial research has been conducted on the efficacy of spraying nitrification inhibitors such as DMPP or DCD on patches to slow the nitrification of NH_4^+ to NO_3^-, no research has been conducted examining the effectiveness of inhibitor coated fertilisers on losses. While the addition of more N from the fertiliser would potentially exacerbate denitrification, on a paddock scale the urea is broadcast to patch and non-patch areas irrespectively. Moreover recent research has demonstrated that the inhibitor effect of DMPP coated urea is not just limited to the fertiliser N but also reduces N losses from other sources such as native soil N from mineralisation. It is therefore possible that DMPP can also slow nitrification of urine N in addition to the coated urea.

A trial was conducted at Casino to determine the magnitude of N losses from urine patches fertilised with broadcasted urea following grazing, and if urea coated with the inhibitor DMPP (ENTEC®) could reduce N losses. Farmers typically broadcast urea evenly across paddocks immediately before grazing regardless of urine patch location, however the effect of additional N on losses is largely unknown. Fertiliser was spread as per farmer practice before a 2.5 L urine patch was applied to a 0.25 m^2 area at the rate equivalent to ~750 kg ha^{-1} of N.

Urine was collected over the course of four weeks from dairy cows and kept at 4°C before being evenly mixed for analysis for total N and NH_4^+ and NO_3^- at EAL, Lismore. Bases were installed at one month prior to the addition of urine treatments and run with the urea and DMPP treatments. Treatment application mimicked the typical summer dairy practice in the region where the urea fertilisers were applied prior to every second grazing. In this case the plots were "harvested" to a pasture height of 5 cm, before the equivalent of 56 kg N ha^{-1} (2 kg N day^{-1} based on a 14 day rotation) of urea and ENTEC were applied to the respective micro-plots.

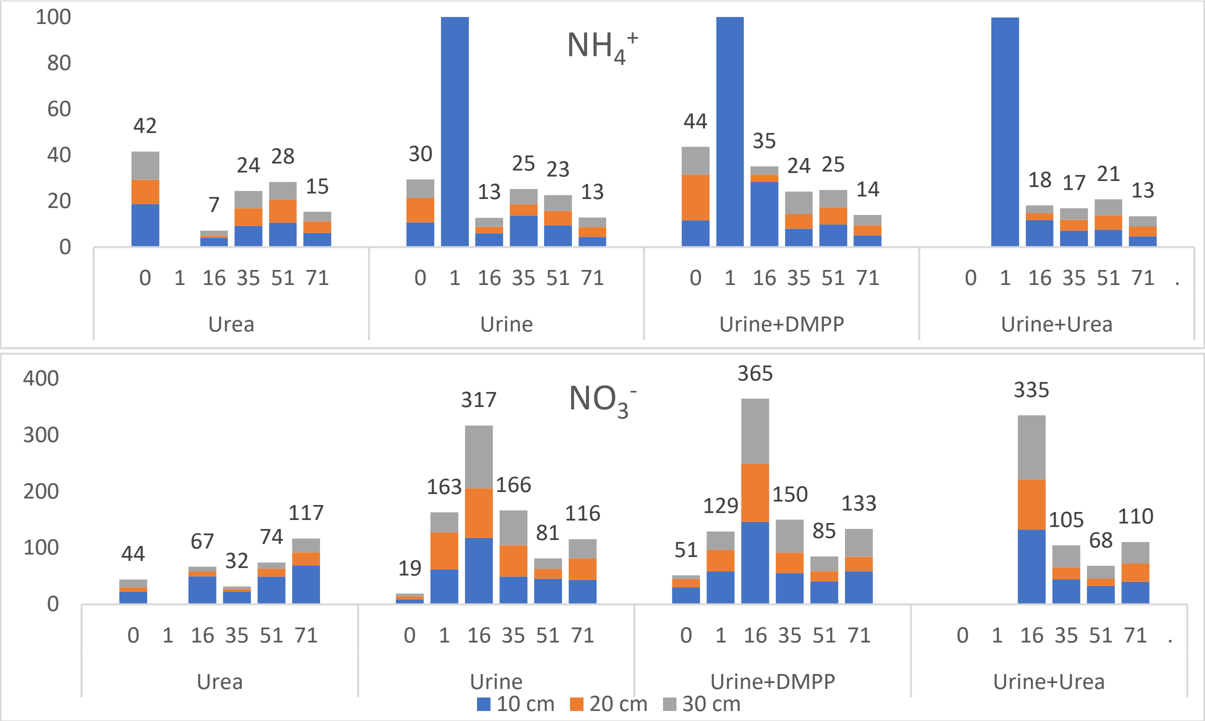


Figure 25 Soil (0-30 cm) ammonium (NH_4^+) and nitrate (NO_3^-) concentrations from urea fertiliser only, urine patch only, and combined with urea and DMPP at Camden, NSW.

Results show an expected spike in soil NH_4^+ contents one day following application, but only minimal difference from the urea only control from subsequent events as most of the applied N was nitrified to NO_3^- by day 16 (Figure 25). The DMPP treatment increased total mineral N at day 16 marginally but not significantly. Nitrification was also evident immediately following application with a quadrupling of soil NO_3^- within 24 hours of application. This resulted in the immediate production of N_2O, which increased further following an irrigation event two days later. Diurnal variation in N_2O over the first two week (Figure 26) were huge, increasing over 5-fold from the lowest (during the day) to the highest (at night). The exact mechanism here is still to be determined.

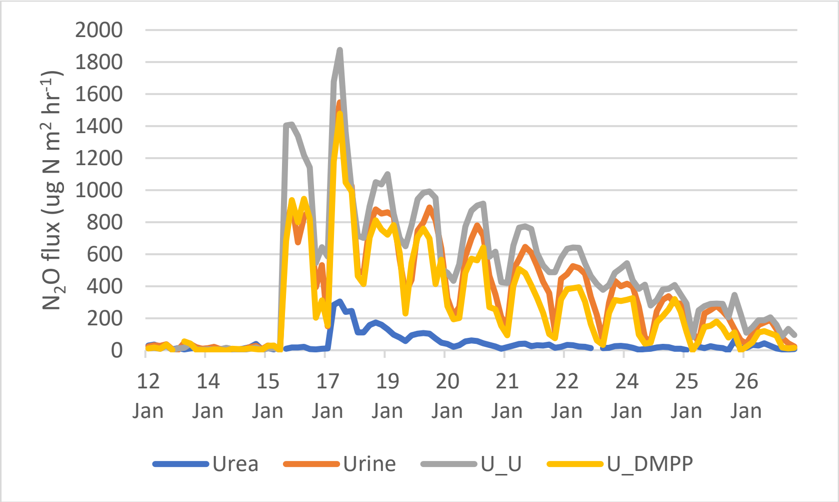


Figure 26 Diurnal N_2O emissions following the application of fertiliser and urine treatments on the 15 January at Camden, NSW.

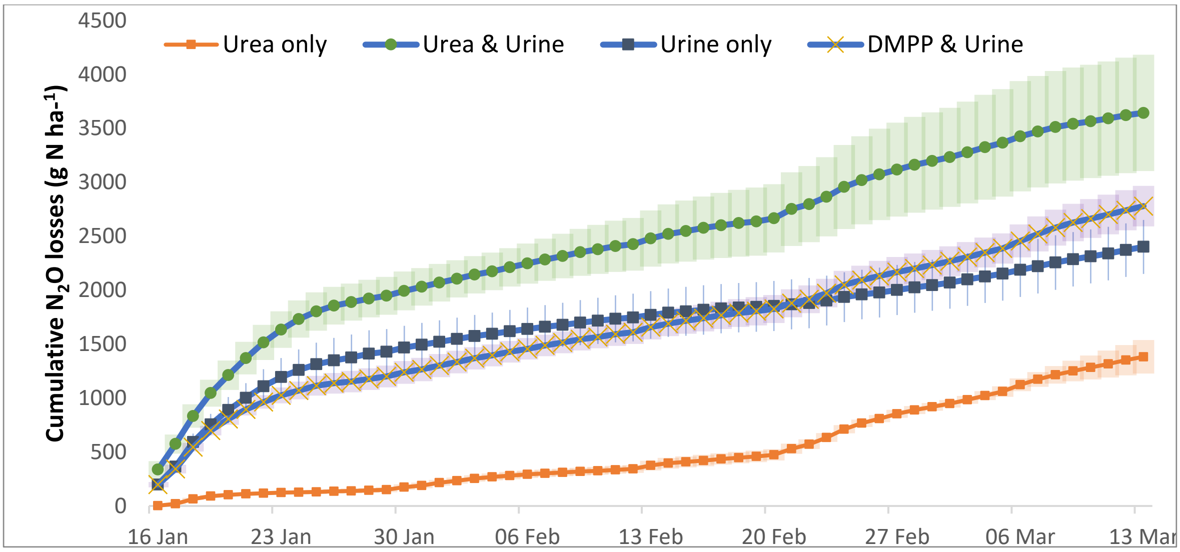


Figure 27 Cumulative N_2O emissions following the application of fertiliser and urine treatments on the 15 January at Casino, NSW.

Total N_2O-N losses over the experiment totalled less than 4 kg N ha^{-1}, extremely low considering the 750 kg N applied (Figure 27). The combination of fertiliser urea on top of the urine patch increased losses by over 50%. The combination of DMPP and urine reduced N_2O emissions by 24%, with the majority of this reduction occurring within the first week after urine application.

The cumulative yield post the application of the different fertiliser formulations showed no statistically significant difference between the green urea and normal urea treatments. Although there is a visual indication of an increased yield under DMPP, the large standard deviation of each treatment precludes detection of significant differences.

Potential for DMPP to increase pasture yields following long-term application

The longitudinal DMPP trial demonstrated the effectiveness of using the nitrification inhibitor DMPP to increase yields and agronomic efficiency of N fertiliser (AE_N) at both reduced and comparable application rates to urea. In year one of the study, no significant difference was discernible between the DMPP and the urea treatments in both the annual ryegrass and kikuyu, despite a 22% reduction in the DMPP application (Figure 28).

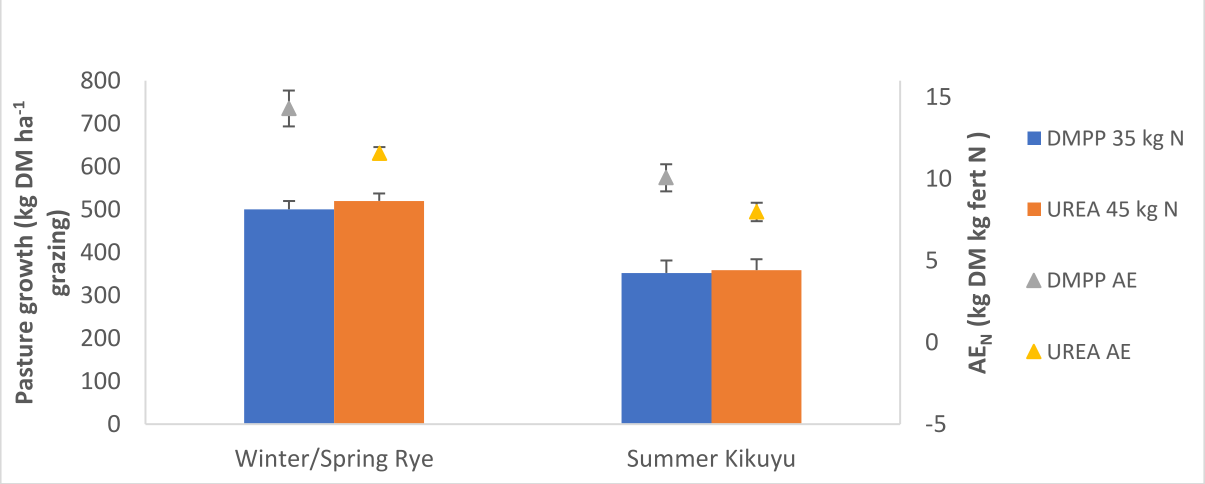


Figure 28 Pasture growth (kg DM ha-1 grazing-1) and agronomic efficiency of N (AE_N) for the application of urea and DMPP coated urea in the 2016-17 annual ryegrass/kikuyu

The lower N application rate (35 kg N ha^{-1} grazing) compared to the urea (45 kg N ha^{-1}) resulted in an improvement in AE_N, the amount of biomass produced per unit of applied N, by 24% and 26 % for the ryegrass and kikuyu respectively.

The effectiveness of repeated application of DMPP was further validated over the subsequent two years in the paddock plots under real farm conditions on the heavy clay soil at Casino. Direct comparison of DMPP and urea at the reduced rate showed a clear production advantage of the inhibitor, with an average increase for the 2017 and 2018 ryegrass of 15% per grazing, or an additional 71 kg DM ha^{-1} grazing^{-1}. This effect was further enhanced in the third ryegrass season of trial (2018) when 156 kg ha^{-1} of N applied as DMPP produced an additional 856 kg DM ha^{-1}, an **increase of over 70%** compared to the equivalent N rate as urea only.

This variation in the effectiveness of the inhibitor to increase yields, and the variation between grazing cycles in DM production to N fertiliser rate in general can largely be explained by the amount of precipitation (rainfall + irrigation) received over the interval. Figure 29 shows the influence of grazing interval and precipitation on pasture response to N, also accounting for temperature and grazing interval length. The strongest responses to applied urea N occurred under wet (>120 mm) periods, particularly in the kikuyu when adequate soil moisture allowed applied N to be fully utilised by the plants. DMPP also had the strongest effect during these wet periods at the highest N rates, though potentially limited the conversion of NH_4^+ mineralised from the soil organic matter to the more plant available NO_3^- at the lower application rates.

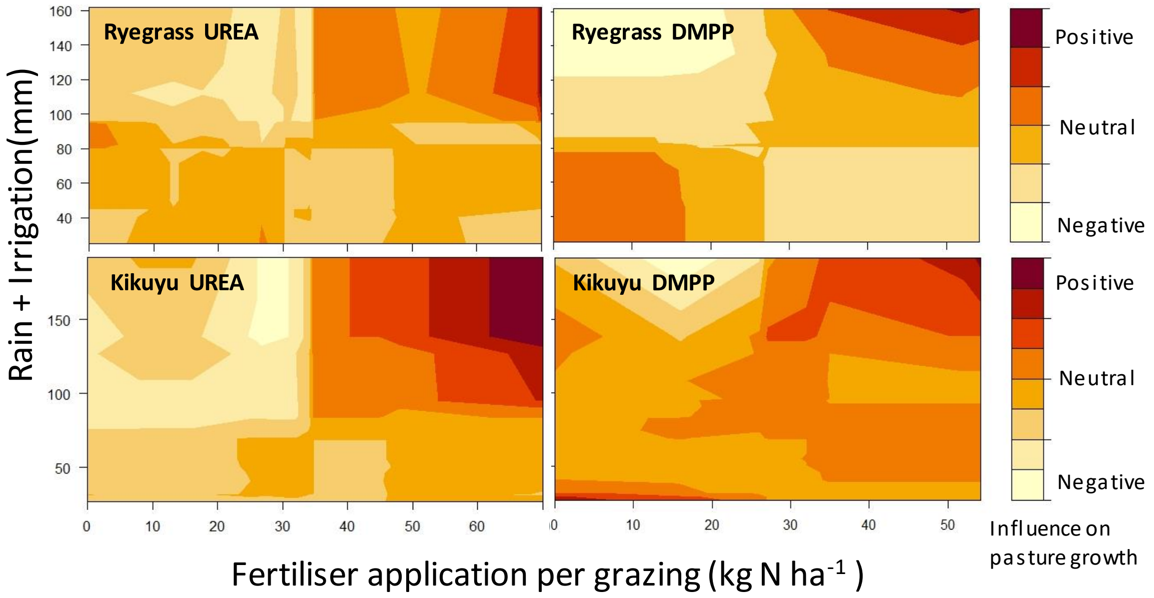


Figure 29 Influence of rainfall and irrigation on biomass productivity response to fertiliser N application rate for both standard UREA and DMPP coated urea in winter/spring Rye and summer Kikuyu at Casino

Overall, in ryegrass DMPP had the greatest effectiveness at the application rate of 20-30 kg N ha^{-1} application, with limited benefit observed at the higher rates where the retention of N in the soil-plant system has less impact on yield (Figure 30). The inhibitor also increased DM yield to a lesser extent in the kikuyu, though the response was less consistent and did not vary with N rate. This is most likely due to the importance non-fertiliser derived N from mineralisation has during this season, with DMPP having been shown to also inhibit N losses of organic matter derived N (Friedl *et al.*, 2017).

Applying fertiliser every second harvest had only a minor effect on yields on the biomass immediately following N application, but resulted in a 29-51% yield penalty on 40% of the subsequent cuts where fertiliser was skipped. Applying DMPP every second application suffered the same yield penalties as the skipped applications of standard urea.

Even at the higher price premium for the DMPP fertiliser, the **increase in harvest return** from additional pasture growth far **outweighed the additional cost** (Figure 31). However, due to the plateauing nature of pasture growth to N inputs as other factors such as moisture, sunlight, temperature, other nutrients, grazing interval and genetic potential become growth limiting factors, the additional expense of the product meant profit and marginal profit declined rapidly once application rate surpassed the optimal. The additional price of the inhibitor product increased the breakeven point for increasing AE_N from 5 kg DM/ kg N to 6 and 7 for the 15% and 30% price premiums respectively, which AE_N fell below at 37 kg N ha^{-1}. Subsequently, increasing the N rate from 35 to 45 kg N ha^{-1} (1.7 to 2.1 kg N day^{-1}), decreased the marginal profit from +$14.4 kg of additional N to -$16.9. As such it is recommended as a **rule of thumb that DMPP application always be applied at a 15-30% reduction in N rate**, effectively maintaining fertiliser expenditure but increasing yields and reducing environmental losses.

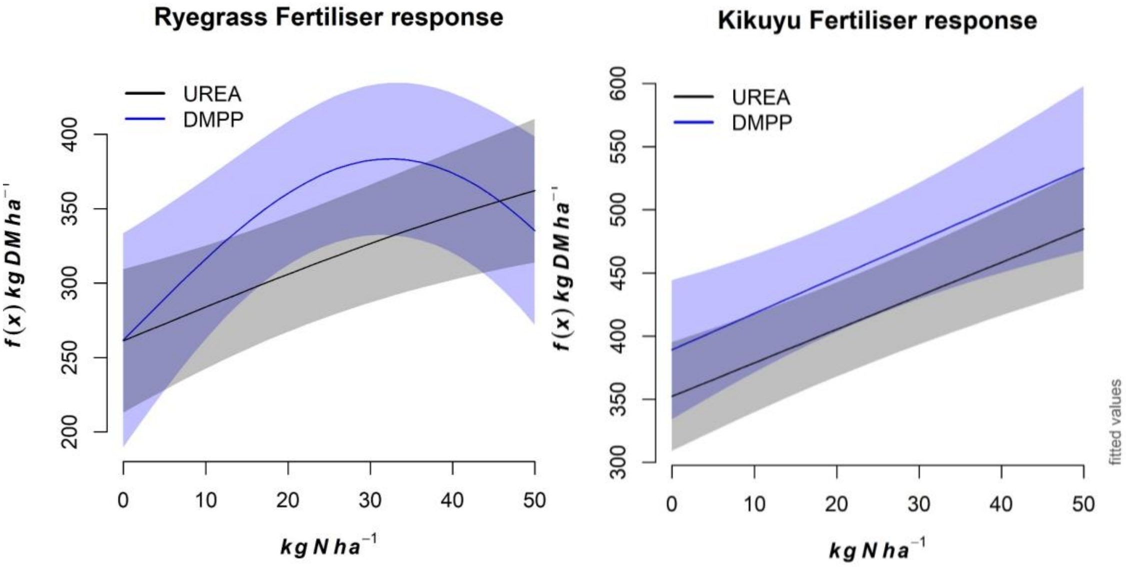


Figure 30 Pasture biomass response (kg DM ha-1) for standard UREA and DMPP coated urea to increasing N fertiliser application rates (kg N ha^{-1} $grazing^{-1}$) in winter/spring Rye and summer Kikuyu at Casino.

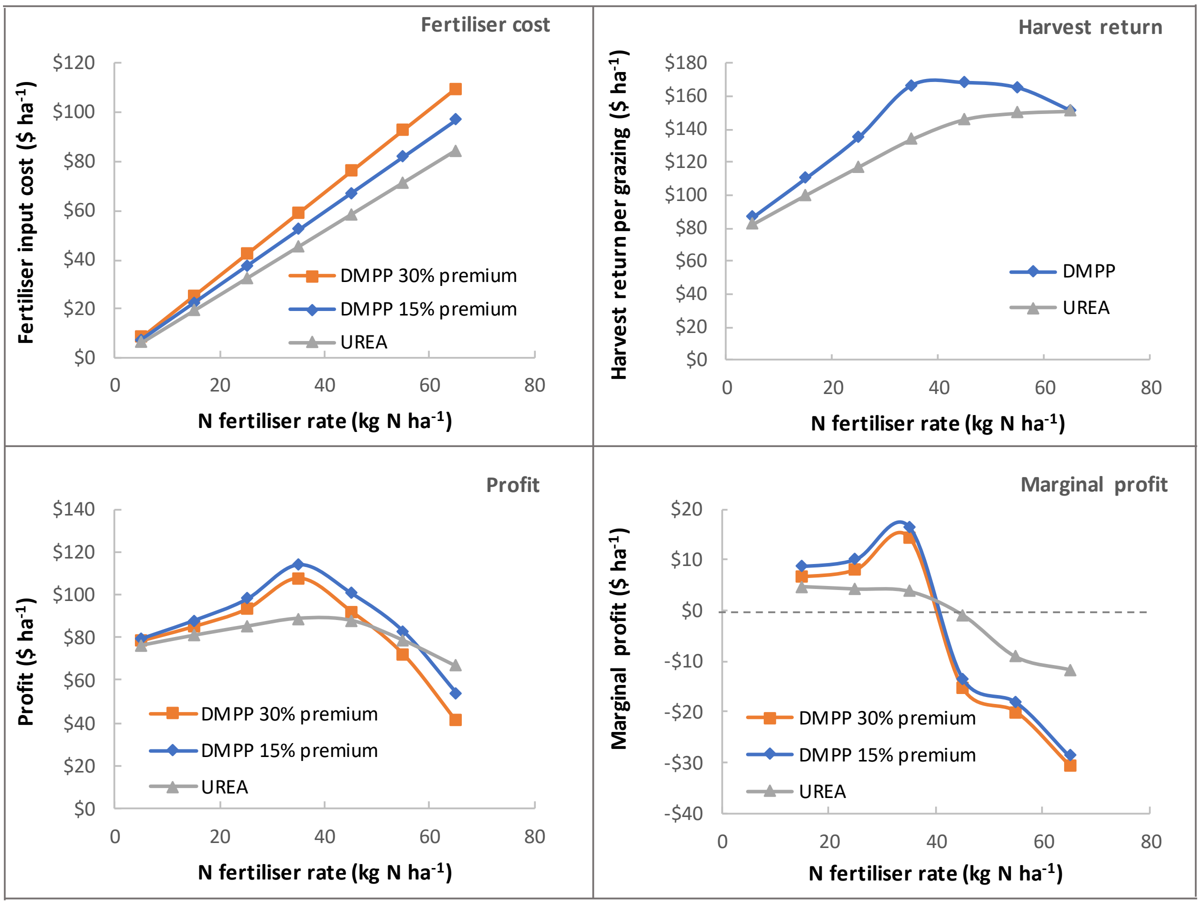


Figure 31 Economic indicators of applying DMPP versus Urea fertiliser in annual ryegrass at Casino. DMPP 15 and 30% premium represents a price of $1.50 and $1.70/ kg N respectively compared to $1.30 for urea.

Previous studies have shown a mixed response to the nitrification inhibitor DMPP (ENTEC™) in subtropical dairy pastures, ranging from no effect at all on biomass and N losses at Camden (Dougherty et al., 2016), to decreasing denitrification losses at Casino by 70% (Friedl *et al.*, 2017), and increasing yields by 30 % at Gympie(Rowlings *et al.*, 2016). There are a number of possible reasons for these discrepancies, including climatic conditions, length of study and inappropriate experimental design (i.e. not applying at a suboptimal rate (Rose *et al.*, 2018), although it's likely that soil type is a also major contributing factor. As a substantial proportion of the effectiveness of DMPP appears to be the inhibition of mineralised N from the soil organic matter, soils with higher carbon contents and subsequently higher mineralizable N supply should benefit the most. However, more research is needed running N rate by inhibitor trials across a range of dairy soils to fully evaluate the effectiveness of DMPP as a means to increase farm profitability.

Conclusion

Due to the high potential of N losses in subtropical dairy production systems, profitability from N fertiliser should be focussed on trying to match plant demand within the short-medium term (1-3 grazing cycles) as opposed to broad seasonal rules of thumb. The precision of these applications, and the room for error, is lower sandier soils with less carbon (i.e. Camden), which react rapidly to N fertilisation in a predictable and manageable manner, with the majority of N being available for plant uptake shortly after application. The heavier, higher carbon clay soils however absorb (immobilise) a significant greater proportion of applied N particularly under high-growth conditions, which is then released (mineralised) under warm and wet conditions when it can be prone to loss. The success of enhanced efficiency fertilisers appears directly tied to this fertiliser N interaction with the organic matter, and have greater potential in the clayeyer soils. As such their use should be used in conjunction with more strategic N management during the different growing seasons, and ensuring adequate soil moisture is available to optimise plant N utilisation.

References

Dougherty, W., Collins, D., Van Zwieten, L., Rowlings, D., 2016. Nitrification (DMPP) and urease (NBPT) inhibitors had no effect on pasture yield, nitrous oxide emissions nor nitrate leaching under irrigation in a hot-dry climate. Soil Research.

Friedl, J., Scheer, C., Rowlings, D.W., Mumford, M.T., Grace, P.R., 2017. The nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) reduces N_2 emissions from intensively managed pastures in subtropical Australia. Soil Biology and Biochemistry 108, 55-64.

Friedl, J., Scheer, C., Rowlings, D.W., Trappe, J., Grace, P., 2016. Nitrogen turnover and N_2: N_2O partitioning from agricultural soils–a simplified incubation assay. International Nitrogen Initiative Conference, "Solutions to improve nitrogen use efficiency for the world", Melbourne, pp. Retrieved from http://www.ini2016.com/conference-proceedings-2012.

Isbell, R., 2016. The Australian soil classification. CSIRO publishing.

Isbell, R.F., 1997. The Australian Soil Classification. CSIRO Publishing, Melbourne, Victoria.
Koci, J., Nelson, P., 2016. Tropical dairy pasture yield and nitrogen cycling: Effect of urea application rate and a nitrification inhibitor (DMPP). Crop and Pasture Science.

Mumford, M., Rowlings, D., Scheer, C., De Rosa, D., Grace, P., 2019. Effect of irrigation scheduling on nitrous oxide emissions in intensively managed pastures. Agriculture, Ecosystems & Environment 272, 126-134.

Rose, T.J., Wood, R.H., Rose, M.T., Van Zwieten, L.J.A., ecosystems, environment, 2018. A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. 252, 69-73.

Rowlings, D.W., Scheer, C., Liu, S., Grace, P.R., 2016. Annual nitrogen dynamics and urea fertilizer recoveries from a dairy pasture using ^{15}N; effect of nitrification inhibitor DMPP and reduced application rates. Agriculture, Ecosystems & Environment 216, 216-225.

Soil Survey Staff, 1999. Soil taxonomy: A basic system of classification for making and interpreting soil surveys. U.S Government Printing Office, Washington D.C.