Nitrogen strategies and managing losses in the wet and dry tropics: organic vs fertiliser sources of N; denitrification and urease inhibitors – do they have a role; and strategies to mitigate risk in the tropics

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Take home message
- Efficient use of fertiliser N is becoming increasingly important as the reliance on fertiliser N inputs increases, the cost of N fertilisers rise and the impacts of off-site losses of N from fertilisers becomes a greater focus of environmental monitoring.
- Ensuring fertiliser application practices deliver plant-available mineral N at a rate and time that matches crop N demand is the objective of an effective fertiliser management program. To achieve this, understanding the behaviour of different N fertilisers when applied to soils under field conditions is critical.
- Soil water dynamics, driven by both seasonal rainfall and irrigation, will play a major role in determining crop N recovery. Understanding the variation in water dynamics between different soil types and seasonal conditions is critical for the development of effective N management strategies.
- Enhanced efficiency N fertilisers have been shown to reduce the risk of N loss by both gaseous and water-driven loss pathways, but the choice of product and the application strategy will vary with crop, soil type and seasonal conditions.
- Maximizing the proportion of crop N that is derived from in-season mineralisation of soil and residue organic N offers opportunities to reduce fertiliser N demand and N losses. However, a successful strategy will require flexible approaches to crop sequencing and halting the decline in soil organic matter.

Background
The processes that determine the availability, loss and cycling of nitrogen (N) in soils are complex, representing the interactions between management practices, the soil microbial community and seasonal conditions – especially temperature and moisture availability. These processes and interactions are illustrated in the diagram developed by Barton *et al*. (2022) and shown in Figure 1.

The N fertility of a soil is determined by the initial size of the soil N pool (a product of soil type and native vegetation), modified by the net effects of land management that have impacted on that starting condition. In the case of land used for cropping, those management effects will be cumulative soil N inputs (fertilisers, fixed N in legumes, plant and animal residues, atmospheric deposition) minus the cumulative removal of N in harvested produce (forage, grain, meat) and losses of N to the environment. The soil N pool is dominated by N stored in organic matter, which is itself not available for crop N uptake until microbial activity has broken down (‘mineralised’) that organic matter to release ammonium (NH_4) and nitrate (NO_3) N that are taken up by plants. These forms of N (collectively called mineral N) represent a small but critical fraction of the total soil N pool that can increase or decrease quite rapidly in response to prevailing conditions. These mineral N forms are typically found dissolved in soil water or held electrostatically to positively or negatively charged sites on clays and organic matter.

In Figure 1, two of the key parts of the soil N cycle have been highlighted and will be the focus of this paper:

1. the soil-plant N pool itself (within the solid yellow hexagon), where N is cycling between the organic and inorganic fractions under the influence of microbial processes, external N inputs (fertilisers, organic wastes) and plant N uptake; and
2. the key processes by which N is lost from the soil N pool to the environment (in the dashed (red) boxes). It is important to note that except for soil erosion, environmental losses are almost exclusively from the mineral N pool (especially NO_3-N), and so the size of the mineral N pool at times when conditions favour different loss pathways will be critical. We will discuss these pools and processes and the key rate controlling factors, and then move onto discussing how the net effects of these processes, interacting with crop management, can influence crop N uptake and the efficiency of fertiliser N use in cropping systems.

Important considerations for tropical environments compared with temperate environments are the higher temperature (things can happen quickly), and the higher intensity rainfall events that characterise the wet season.

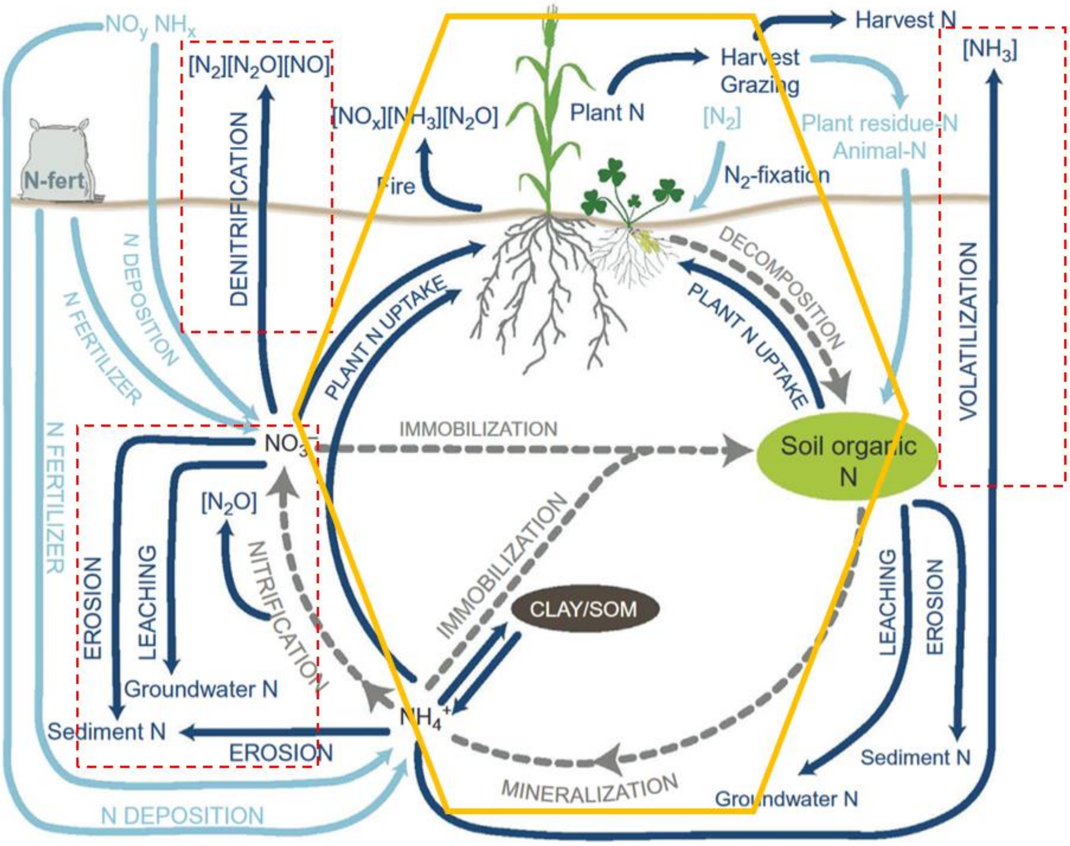

Figure 1. Terrestrial nitrogen (N) cycle showing pathways responsible for the supply and loss of N in soil and plants. Dashed (grey) lines indicate soil N transformations. Gases appear in square brackets. (Reproduced from Barton *et al*. (2022))

Cycling of N in the soil and availability to plants

The net gain or loss of soil organic matter (SOM) is a function of the relative rates of addition of organic inputs (crop residues, manure) and the breakdown/mineralisation of these fresh materials and the resident SOM by microbes that exploit these as sources of nutrients and energy. Soil organic matter acts as a reservoir of organically bound N that must be mineralised to plant available forms [e.g. NH_4^+ and NO_3^-] before agricultural crops can access this stored N. The size of the mineralisable organic N pool and the rate of mineralisation relative to crop demand will determine the ability of this pool to meet crop needs. When soils were 'new' to cropping, the pool of soil organic matter was high and mineralisation of soil organic matter was often able to generate enough surplus mineral N to meet, or exceed, crop N demand. Crops rarely responded to fertiliser N inputs. With longer durations of broadacre cropping, soil organic matter contents have declined, as has the pool of mineralizable organic N, and as a result microbial mineralisation is more often unable to produce enough surplus mineral N (or provide that N fast enough) to meet crop demand. Fertiliser N is increasingly needed to meet the N supply deficit. Application of N fertiliser can rapidly increase the pool of plant-available N, but there are several soil and environmental factors that determine whether that increase will result in more plant N uptake in the short term.

Soils in which there is a reduced pool of mineralizable organic matter and mineral N availability, or where large quantities of high carbon (C):low N crop residues (e.g. maize residues, or a sugar cane trash blanket) have been returned to the soil, can result in conditions where the microbial community can be a net consumer of mineral N (e.g., from fertiliser applications) rather than the source of a mineral N surplus. This microbial competition for mineral N can result in short term immobilisation of mineral N in organic matter and microbial biomass that is typically reversed over longer time frames. However, these shorter-term dynamics can be particularly important in terms of meeting the mineral N requirements of a crop at critical crop growth stages (floral initiation in cereals, tillering and subsequent tiller/stalk retention in sugarcane). The timing of fertiliser N application relative to the demand for N by the plant, combined with the relative rates of N immobilisation and mineralisation and the environmental conditions that influence the rates of microbial processes and environmental losses (e.g., from irrigation or rainfall), will collectively determine whether that applied N will be taken up by plants, and when. The interaction between rainfall or irrigation after fertiliser application and the soil characteristics that determine rates of water infiltration and drainage will ultimately determine the risks of poor N recovery by the target crop.

Losses of N to the environment

Essentially, nitrogen can be lost from cropping soils via downwards, sidewards or upwards movement. Nitrate N primarily moves down into the soil profile with soil water infiltration, with the rate and depth of movement a function of the rate of movement of the wetting front and the concentration of NO_3-N in the soil solution. This process is called leaching. In lighter textured soils and in well-structured red volcanic soils, which typically have lower water holding capacities, wetting fronts and associated leaching of NO_3-N can be rapid and extend below the depth of the crop root zone. In this case, leaching can result in loss of plant available N and depending on the connectivity of that deep water infiltration with drainage lines or water tables, can result in negative effects on environmental water quality. When those environmental losses impact on natural resources like freshwater lakes or the Great Barrier Reef lagoon, the implications of leaching losses are particularly visible and problematic. In other situations (e.g., in black and grey cracking clays on which much of the northern rainfed grains cropping industry is based), this leaching of N is unlikely to penetrate beyond the depth of crop root access and is a critical success factor for cropping systems that rely on stored soil water rather than in-season rainfall. Crops extracting stored soil water during dry periods need access to N (and other nutrients) to continue to produce dry matter and grain.

Sideways movement can occur rapidly through erosion of topsoil rich in organic matter during intense rainfall events, or more slowly through lateral subsoil movement of nitrate-N in soil water. The widespread adoption of minimum or no tillage and the associated maintenance of surface cover in grains cropping, combined with the relatively dry seasonal conditions, means lateral N losses are typically minor.

Gaseous N losses to the atmosphere are of much greater significance and can occur through two main pathways viz. volatilisation of ammonia or denitrification of nitrate-N as dinitrogen (N_2) or nitrous oxide (N_2O).

- Ammonia volatilisation is a process that primarily occurs when urea or ammoniacal N fertiliser (DAP, MAP or UAN) is broadcast onto the soil surface without incorporation, or if shallow fertiliser bands are not covered with soil and left exposed to the air. Losses typically occur soon after fertiliser is applied to soil, with a range of factors influencing the actual amount of N lost. Simple models such as the one published by Fillery and Khimashia (2015) use a maximum potential loss figure (65% of applied N when urea is applied to moist soil) that is discounted according to factors such as clay content, soil pH, fertiliser rate, rainfall in the week after application, presence of a crop canopy and the placement of the fertiliser. This model was reasonably effective at predicting volatilisation losses from top-dressed urea fertiliser applied on vertosol soils in northern NSW (Schwenke *et al*., 2014). In those studies, losses averaged 11% (5–19%) of applied N when urea was broadcast onto the surface of fallow paddocks, 5% (3–8%) when applied in a growing wheat crop (mostly when soils were dry), and as much as 27% when applied to pasture. In the latter situation, there had been little rain after spreading to wash the urea into the soil. This resulted in a significant proportion of the urea being suspended on the pasture thatch rather than in direct contact with soil particles, greatly increasing the risk of volatilisation loss. Wind-speed after fertiliser application was a critical factor determining the amount of N lost over time in all studies.
- Schwenke (2021) recently concluded that ammonia (NH_3) volatilisation loss will be low when urea is broadcast onto dry, clay soil under non-humid, non-windy conditions followed within a few days of application by sufficient rainfall to move the urea/ammonium into the soil. In contrast, NH_3 loss will be higher when urea is applied to wet soil followed by dry, windy conditions with little or no follow-up rainfall. However, while recent laboratory studies suggest that risks of volatilisation loss may be greater on lighter textured soils with lower clay contents, there is real uncertainty extrapolating the losses from the NSW field studies to other soil types and climatic conditions.
- Nitrate denitrification losses can be large but require the simultaneous occurrence of low soil oxygen availability (e.g., when soil is waterlogged for an extended period, or in wet soils with a high level of microbial activity), high soil NO_3-N concentration (soon after soils have been fertilised) and readily available (labile) carbon to support an active microbial community. Clearly these set of circumstances do not coincide every year, but when they do, denitrification losses can be high. Rates of loss are typically higher when soils are warmer in spring and summer rather than late autumn and winter.
- Unlike ammonia volatilisation, it is more difficult to quantify total N losses due to denitrification. This is because variable proportions of those losses can occur as N_2 or as N_2O. While direct measurement of N_2O losses under field conditions is possible, losses as N_2 are far harder to quantify due to the high background atmospheric N_2 concentrations (~78% of the atmosphere).

There are reports in the literature of the ratio of losses as N_2:N_2O being anything from 1:1 to 70:1, depending on soil and environmental conditions. To put this uncertainty into perspective, at fertiliser N rates delivering maximum yield, measurements of annual N_2O losses of 1–2 kg N_2O-N/ha could be indicative of total denitrification losses, ranging from negligible to >100 kg N/ha. Direct measurement of these N_2 and N_2O losses is being undertaken in the project "Predicting nitrogen cycling and losses in Australian cropping systems - augmenting measurements to enhance modelling" (UOQ2204-010RTX). An example of the data collected from research conducted at Gatton in a sorghum crop last summer (2023/24) showed N_2O losses to be only 5–10% of total denitrification losses for the growing season. While most losses occurred in the month following fertiliser N application, the N_2O losses were recorded in a series of discrete pulses related to rainfall events, while the N_2 losses were dominated by a single major waterlogging event in late January. During this event, the rapid loss of N_2 was linked to the occurrence of depleted soil oxygen in the microbially active top 10cm of the soil profile.

The use of N fertilisers labelled with the stable ^{15}N isotope allows the fate of applied N to be studied in detail (e.g., Figure 2), with the difference between fertiliser N applied and that recovered in the plant (tops and roots) or remaining in the soil after harvest an indicator of the fertiliser N lost to the environment. In soils where fertiliser N has been banded below the soil surface and leaching losses are minimal (such as in the alkaline vertosols), most of the unaccounted-for fertiliser N (20–40% of N applied – Rowlings *et al.*, 2022) is presumed to have been lost via denitrification.

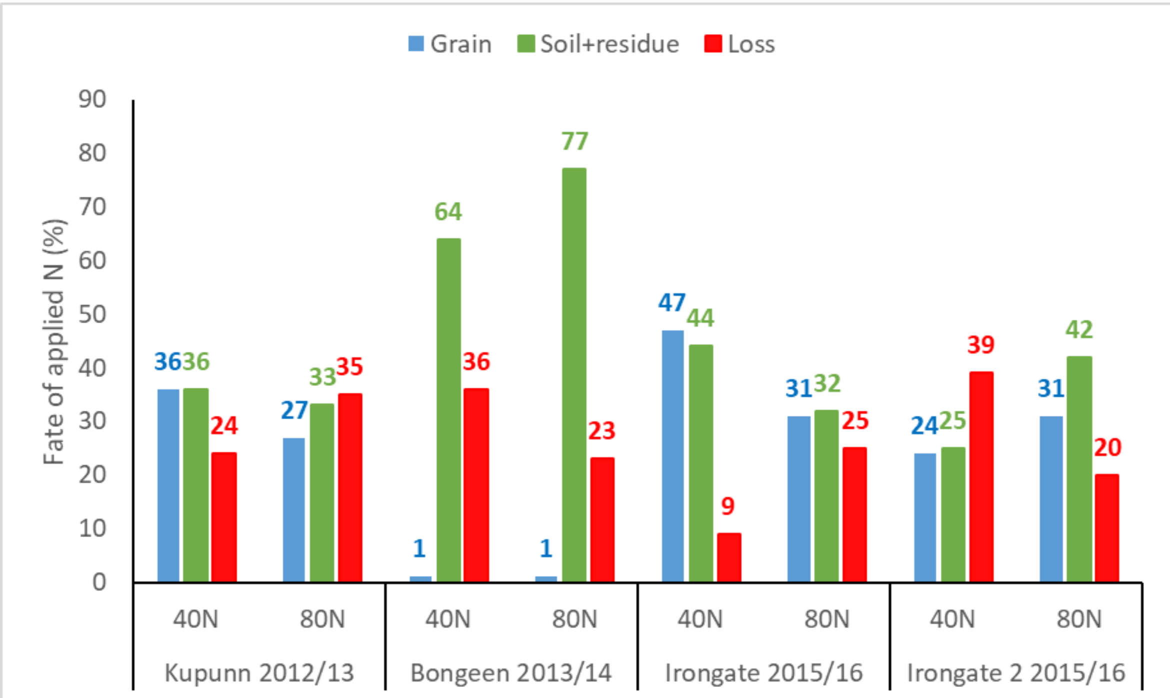

Figure 2. Percentages of fertiliser N either removed in sorghum grain, lost to the environment or carried forward to the following cropping seasons in soil and crop residue. Data were from sorghum crops grown on vertosols in commercial fields on the Darling Downs from 2012–2015 (Bell *et al*., 2015).

There have been studies using isotopically labelled N fertilisers to quantify fertiliser N recovery in sugarcane ratoon crops. Some of these were specifically focussed on the volatilisation losses of N top-dressed onto trash blankets in the early days of adoption of green cane trash blanketing, but those of Vallis *et al.* (1996) (at a variety of southern sites from Childers in Qld south to Broadwater and Harwood in northern NSW), Prasertsak *et al.* (2002) (sites near Innisfail) and Meier *et al.* (2006) (sites near Babinda) either placed N below the trash (Meier *et al.*

(2006)) or used sub-surface banding typical of current industry practice. More recently, a study by Takeda *et al.,* (2022) reported ^{15}N recoveries in soil and plant biomass from fertiliser banded into hills after a burnt cane harvest in the Burdekin, or stool-split after a green cane harvest at Mackay (Figure 3).

Fertiliser N uptake by ratoon crops in the year of application ranged from as little as 4–5% at Babinda (Meier *et al.,* 2006) to 30–35% at Childers (Vallis *et al.,* 1996), with the findings of Takeda *et al.,* (2022) at Mackay (16–21%) and the Burdekin (26%) intermediate, and unresponsive to rates of applied N. The earlier studies reported an additional 20–25% of applied N in soil and roots at the end of the crop year, with similar findings in the Takeda *et al.,* (2022) study. Collectively, these studies report apparent losses of applied fertiliser N of 40–60% in the year of application – notably higher than that recorded in the dryland grains industry in Figure 2. Clearly our tropical and subtropical cropping industries have room for improvement in terms of the use efficiency of applied N fertilisers, with environmental considerations (greenhouse gas emissions, reef water quality) increasing the focus on industry fertiliser management practices.

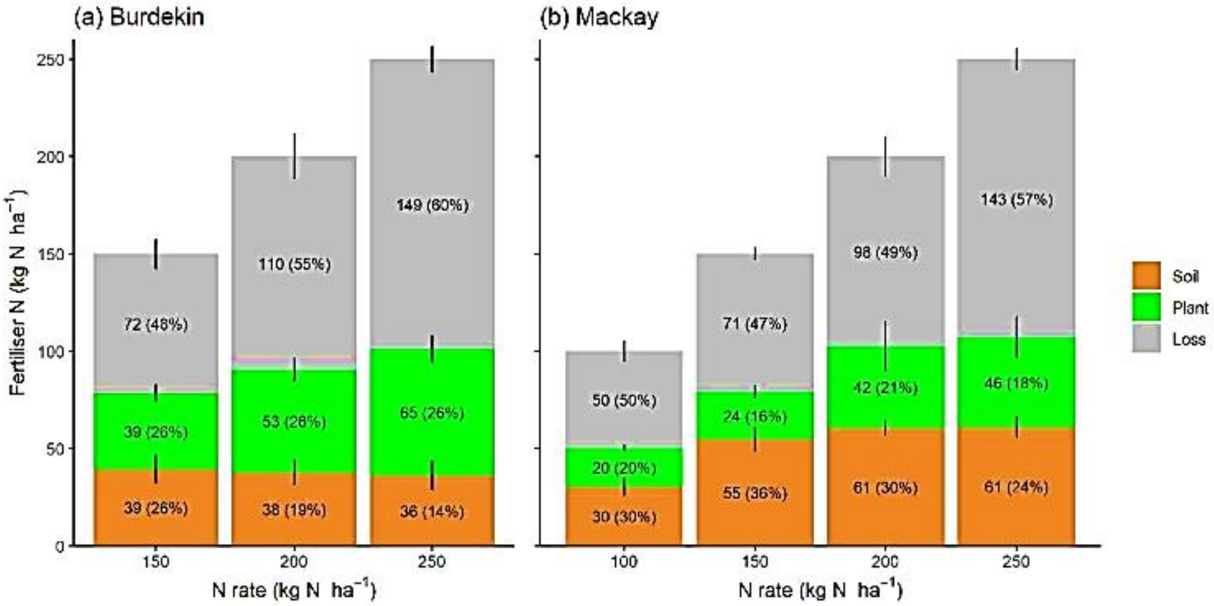

Figure 3. Fertiliser N recoveries in the soil and plant and fertiliser N loss in the 100N, 150N, 200N and 250N treatments at sites in (a) the Burdekin and (b) Mackay. The error bars indicate standard errors and the percentages in the columns are proportions of fertiliser N to the applied N rate. This figure is reproduced from Takeda *et al.,* (2022)

Implications for N management and efficient use of fertiliser N

In theory, achieving efficient use of N requires the timing and amount of N supply, via mineralisation of residues, organic amendments (manures, mill mud) or soil organic matter and N fertiliser addition, to be tightly coupled to crop demand (Bruulsema *et al.,* 2009). This should ensure minimal loss of surplus reactive N into the environment. Whilst fine in theory, achieving this synchrony presents challenges in irrigated production systems and hotter climates, particularly during the monsoonal wet season. The combination of moist soil, high temperatures, trash blankets and organic amendments will result in N mineralisation (or immobilisation, depending on N availability) that occurs at rates and times not consistent with peak N demand by the crop. While fertiliser application can limit the impacts of this asynchrony on crop N supply, the resulting loss of reactive N can be substantial.

Determining the most appropriate N management strategy for a given situation requires a clear understanding of crop N demand (both timing and quantity), the moisture environment during the fertilisation and crop uptake period (determining active zones of root and microbial activity) and the soil characteristics that determine the rate of infiltration and drainage of rain or irrigation. Soils that drain freely are more likely to leach N into deep layers, and possibly out of the root zone, while soils that drain slowly or have impermeable subsoils can create prolonged periods of waterlogging and denitrification loss. In both cases, the form of N required to underpin leaching or denitrification losses is nitrate-N.

During the dry season in northern Australia, careful management of soil moisture using best practice irrigation management can limit leaching and denitrification loss, but this is far more difficult during the monsoonal wet season. There is one exception to this generalisation, and that lies with flood-irrigated systems and shallow fertiliser N placement. In this situation, water moves laterally from the furrow into the hill/bed, with the hill/bed topsoil wet from underneath as water is sorbed up into dry topsoil layers. This upwards movement of water can also move nitrate-N with it to the soil surface if the N has been placed in the upper half of the hill/bed (e.g. with stool split applications in sugarcane), where intense microbial activity can exacerbate denitrification loss risks.

The other loss risk pathway does not involve nitrate-N moving in soil water, but rather is a direct chemical reaction that can result in the gaseous loss of ammonia from the soil surface by volatilisation. In this case, there is a requirement for mineralising N fertiliser to have minimal soil contact and be exposed to the atmosphere (e.g. urea top dressed onto lighter soils or trash with limited follow-up rain, or fertiliser bands applied in a stool-splitting operation that leaves the furrow open to the atmosphere). In these situations, the high ammonium N concentrations that result from urea hydrolysis and the associated pH increase, especially where there is no clay to hold the ammonium and/or buffer the pH increase, can result in large and quite rapid N loss. Placing fertiliser N into, rather than on top of, soil is the safest way to minimise this loss pathway, but we are seeing more surface applications and a resulting increase in volatilisation risk in dryland grains systems for practical reasons relating to the logistical and labour considerations of covering large areas quickly.

Can fertiliser technology help to minimize N loss risk?

Enhanced efficiency fertiliser (EEF) technology (i.e., inhibitors and controlled-release products) are potential tools for improving nitrogen use efficiency (NUE) in cropping environments. However, the effective use of EEFs is dependent on understanding how they work and choosing the right product to suit the soil and water environment and the N loss risk that you are trying to mitigate. There is currently a poor understanding of how these technologies behave in soil and how this translates to agronomic outcomes in the field in contrasting environments, particularly as most EEF products have been developed and tested in temperate environments where they are broadcast or incorporated with conventional tillage. The grains industry is currently addressing this knowledge gap via a major national research project that focusses on EEF use in dryland production systems (UOM2404-007RTX), with much of the Qld research being undertaken under irrigated and dryland conditions at UQ Gatton campus and building on previous work reported in Dang *et al.,* (2021) and Martinez *et al.,* (2021).

There has been an extensive field research program evaluating the potential benefits of EEF use in the sugar industry, especially from Mackay north, which showed that EEF use can reduce fertiliser N loss and enhance crop N recovery, allowing reduced N rates to be used to balance the additional cost of the fertiliser N products (Connellan *et al.,* 2022). This extensive program, conducted over 60 sites and 3 consecutive crop seasons, concluded the greatest benefits from EEF use were when significant rainfall and/or flood irrigation occurs shortly after fertiliser application, and this was confirmed in subsequent modelling studies (Verburg *et al.,* 2022).

Considerations for improving management of soil and fertiliser N

Some important principles to improve fertiliser NUE in subtropical and tropical cropping systems are:

- Understand crop N requirement and the rate of fertiliser N to meet that demand – crops with extended periods of N uptake (e.g. over a 6–7-month period in sugarcane, compared to a little over 2 months in maize) require an extended period of high N availability in soil. Split N applications would be suited to these longer season crops, although limited field access due to crop height suggests that a combination of split applications and EEF use would prove most effective at maximizing fertiliser N recovery. These extended periods of crop N demand also provide plenty of opportunities for mineralisation of N from residues and soil organic matter to contribute to crop N uptake, so any determination of fertiliser application rates will need to build in appropriate discounts that will vary with crop type and likely in-season mineralisation.
- Understand the limitations of soil sampling to guide fertiliser N inputs – in dryland grains systems in NE Australia, accumulation of water and mineralised N during fallow periods are critical to cropping success. In those situations, soil tests in the period leading up to fertiliser application and sowing provides very useful information that can result in the reduction of fertiliser N rates. However, when fallow periods are limited and the quantities of high C:N residues returned are substantial, preplant soil tests to determine fertiliser N requirement provide little useful information. This can be particularly relevant when establishing a crop shortly after harvest of a legume rotation crop, as profile mineral N is typically depleted and mineralisation of the low C:N legume residues has yet to occur. In this instance, soil sampling prior to side dressing (some 3–4 months after legume termination) would provide more useful information to guide fertiliser N inputs, if laboratory turnaround times are sufficiently short.
- It is also worth remembering that soil mineral N (especially nitrate-N) can 'disappear' very quickly in response to irrigations and/or heavy rain, so relying too much on profile mineral N to contribute to crop N uptake over coming months can be problematic, and other risk management strategies may need to be implemented to ensure crops have access to adequate N.
- Understand the water dynamics for the soil and seasonal conditions in which you are applying fertiliser – the soil response to water inputs (irrigation or rainfall) will have a dominant role in the movement and potential loss of N from the cropping system. Understanding those dynamics (e.g. free draining in red volcanic or sandy soils of the Atherton Tableland and in the alluvial soils in the Burdekin delta, compared to the heavy clays of the Burdekin River Irrigation Area) will allow a more informed choice of the fertiliser N application strategy and product to minimise the risks of N loss. This understanding becomes increasingly important as control over soil water dynamics diminishes (e.g. during the monsoonal wet season). Good examples of this are in the research reported by Bell *et al.,* (2019), Dowie *et al.,* (2019) and Connellan *et al.,* (2022), where the benefits of using EEF products, and the type of EEF product that produced the greatest benefits, changed between locations and with soil type within a location in the sugar industry.
- As mentioned previously, understanding the impact of different irrigation methods (flood v overhead) on water and N movement is also important to determine the likely fate of N in the soil profile and recovery by the target crop.
- Ensure the suite of N management practices is suited to the target crop/site/season – In the dryland grains industry there is considerable interest in moving away from subsurface banding to

top dressed fertiliser N applications (sometimes with products that delay urea hydrolysis and volatilisation risk) during the fallow prior to planting, but this is driven more by logistical considerations than any perceived increase in NUE. Concentrated bands of urea-N applied below the soil surface have been the benchmark for most row crops (e.g. sugarcane, cotton and maize), with this strategy avoiding N loss by volatilisation – as long as those bands are well covered by soil (e.g. by 5cm or more). Concentrated subsurface urea bands provide some protection from early season leaching or denitrification losses, with the band environment ensuring a delayed formation of nitrate-N (particularly in heavy clays – Janke *et al.,* 2020). However, in more freely draining soils and in longer season crops like sugarcane, this protection is not enough to cover the N uptake period. In these instances, use of split applications, nitrification inhibitors or slowed release of urea in EEF products or blends can provide additional protection. Important considerations here are the species preference for N uptake (most tropical grass species prefer N in the ammonium form, while crops like cotton prefer nitrate-N) and the management system capacity to ensure N that is less able to leach into deeper profile layers does not get stranded in dry topsoils for extended parts of the growing season – as can occur in dryland grains systems (Dang *et al.,* 2021).

Current research to develop better guidelines for N decision support

The focus of current fertiliser N research nationally is to improve understanding of the fate of applied N fertiliser, particularly in grains cropping systems. A range of GRDC investments are active in this space, with the focus on improving fertiliser NUE and reducing emissions of greenhouse gases like N_2O. The data generated in these intensive research programs will be used to validate and improve our ability to accurately simulate N dynamics in grains cropping systems nationally, with this improved capability to be used to improve decision support systems for fertiliser N management.

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