Optimising the nitrogen investment - Understanding and minimising N losses while feeding the crop what it needs

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Take home message

- Achieving co-location of water and available N within the soil profile are keys to maximizing efficient use of water and fertiliser N in rainfed grains cropping systems
- Seasonal rainfall (both amount and distribution) is the dominant factor driving fertiliser N use efficiency and environmental losses on clay soils employing these cropping systems
- This makes it difficult to successfully employ fertiliser N management strategies that attempt to manipulate N availability to match individual crop demands in individual seasons
- Increasing the mineralizable soil N pool through enhanced soil organic matter and greater legume frequencies in crop rotations, combined with manipulation of fertiliser rate, timing and mode of application, offer the best opportunities to improve system N use efficiency
- Soil sampling remains an important tool to determine when and how fertiliser N management strategy should change in response to particular events and wetter or drier seasonal conditions.

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 opened to 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) 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, fertiliser N inputs and plant N uptake; and

2. the important processes by which N is lost from the soil N pool to the environment (in the dashed 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.

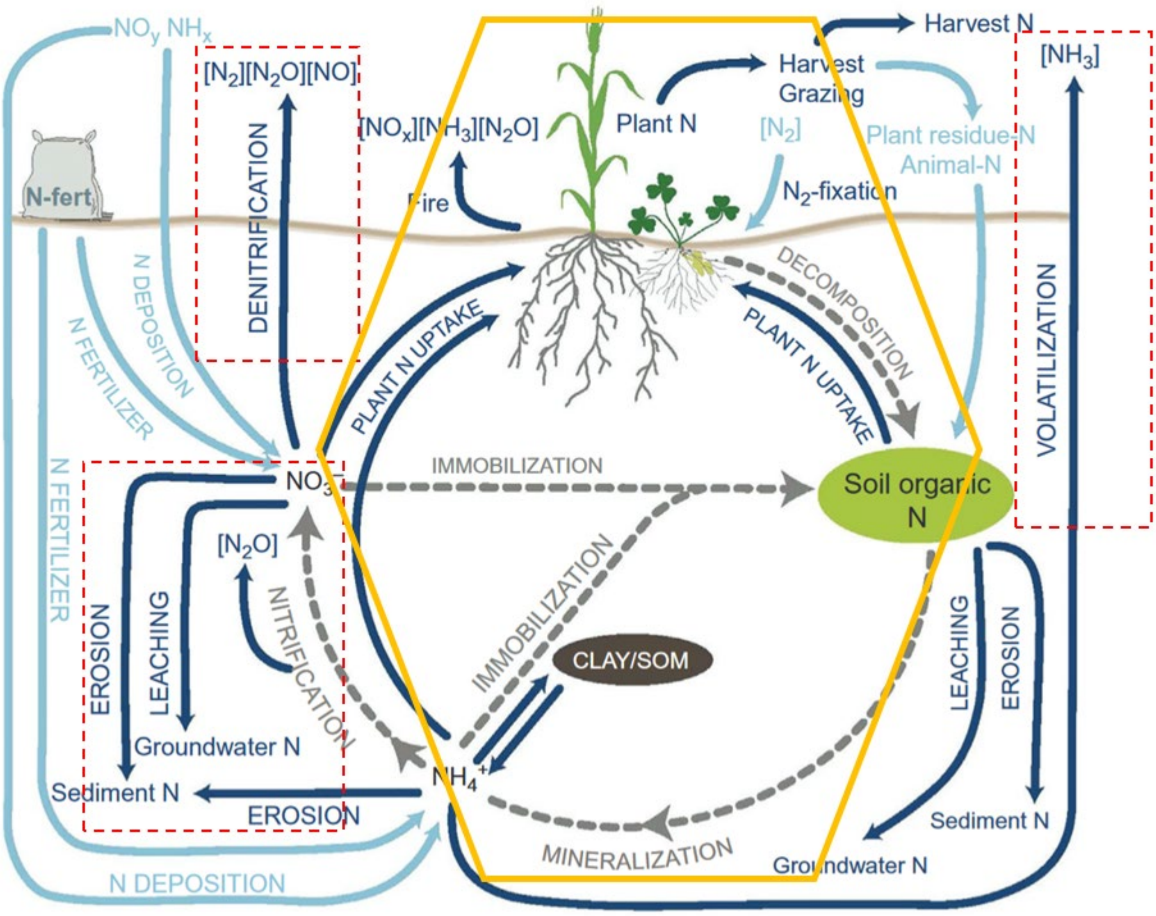

Figure 1. Terrestrial nitrogen (N) cycle showing pathways responsible for the supply and loss of N in soil and plants. Dashed lines indicate soil N transformations. Gases appear in square brackets.
(Reproduced from Barton et al. 2022)

Cycling of N in the soil and availability to plants

The net gain or loss of soil organic matter 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 soil organic matter 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 mineralized to plant available forms [e.g. NH_4^+ and NO_3^-] before agricultural crops can access this stored N. The size of the mineralizable organic N pool and the rate of mineralisation relative to crop demand will determine the ability of this pool to meet crop needs. When the Vertosol soils of northern NSW and Qld were 'new' to cropping, the pool of soil organic matter was high and mineralisation of soil organic matter was able to generate enough surplus mineral N to meet, or exceed, crop N demand. Crops rarely responded to fertiliser N inputs. However, as soil organic matter contents have declined under cropping the pool of mineralizable organic N has declined, microbial mineralisation is increasingly unable to produce enough surplus mineral N to meet crop demand, and 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 a number of 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 labile organic matter and mineral N availability 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 may be sporadic (e.g., after the return of cereal crop residues with low N content), resulting 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. 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., soil moisture), will collectively determine whether that applied N will be actually taken up by plants, and when.

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 in the soil solution. This process is called leaching. In lighter textured soils, especially those with low 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. In other situations (e.g., in soils like the black and grey vertosols on which much of the northern 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 as dinitrogen (N_2) or nitrous oxide (N_2O).

- <u>Ammonia volatilisation</u> 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 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 uncertainly 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 fertilized) 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 (e.g., 2011, and more recently in 2022), 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, measurements of annual N_2O losses at fertilizer N rates delivering maximum yield of 1–2 kg N_2O-N/ha could be indicative of total denitrification losses ranging from negligible to >100 kg N ha^{-1}.

  The use of N fertilizers 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 fertilizer N applied and that recovered in the plant (tops and roots) or remaining in the soil after harvest representing fertilizer N lost to the environment. In soils where fertilizer N has been banded below the soil surface and leaching losses are minimal (such as in the alkaline vertosols), most of the unaccounted-for fertilizer N (20–40% of N applied – Rowlings *et al.* 2022) is presumed to have been lost via denitrification. When cumulative N_2O emissions data are available (such as in 12 of the 18 NANORP sites in Qld and NSW where ^{15}N was used), the ratio of total N lost (from ^{15}N results) to that lost as N_2O can be used to estimate the ratio of N_2 to N_2O for these summer cropping systems. 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.

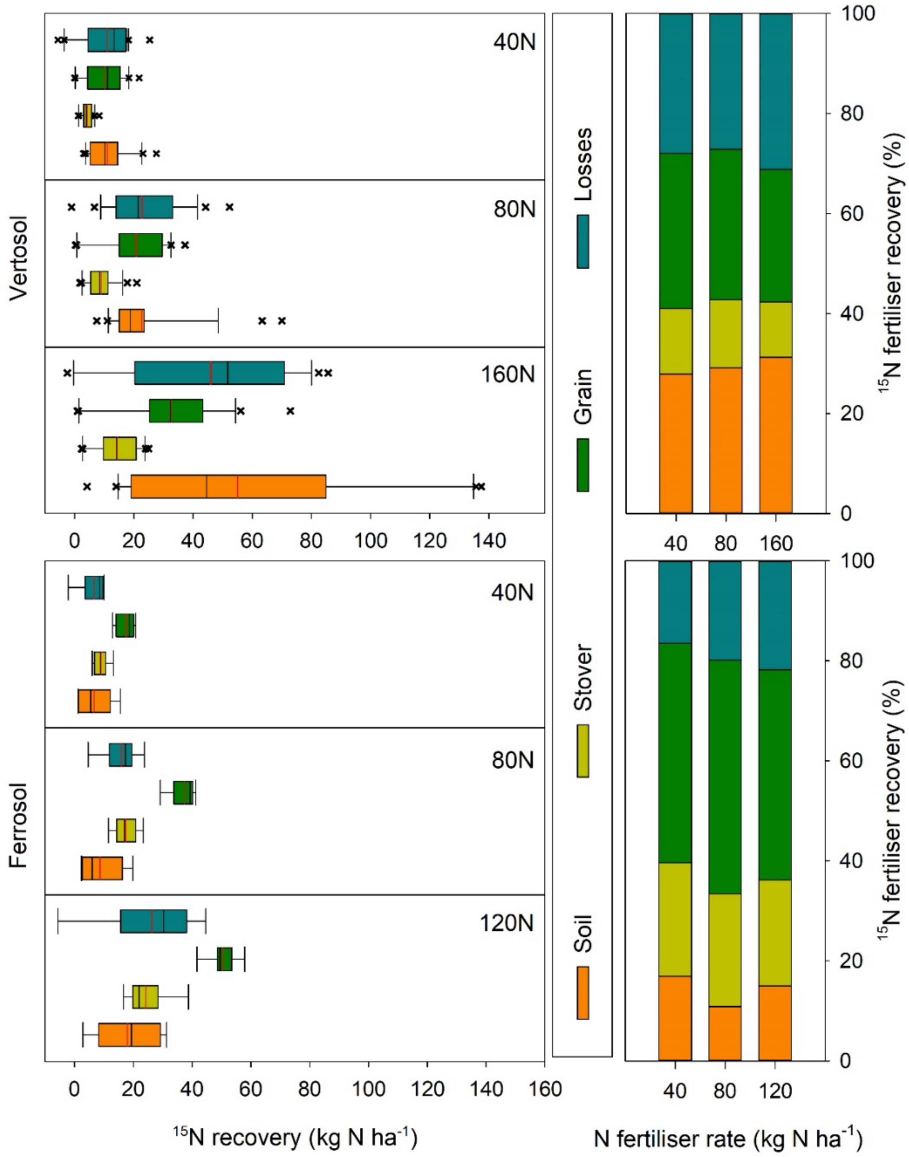

Figure 2. Fate of applied ^{15}N fertiliser, expressed as both kg ^{15}N ha^{-1} recovered and as a percentage of total ^{15}N applied for different N fertiliser rates applied in 4 farmer field sites and in 5 experiments conducted on research stations at Kingaroy (red ferrosol) and Kingsthorpe (black vertosol) from 2012–2014.
(Reproduced from Rowlings *et al* 2022)

Implications for N management and efficient use of fertiliser N

In theory, achieving efficient use of N in our rainfed cropping systems should require the timing and amount of N supply via soil mineralization and N fertilizer addition to be tightly coupled to crop demand, consistent with the '4R' nutrient stewardship concept (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 our warmer climate and with systems that accumulate water during fallows. The combination of moist soil, warm temperatures and stubble/soil organic matter will result in N mineralisation (or immobilisation, depending on N availability) that primarily occur during the fallow, and indeed, production of mineral N (particularly NO_3-N) during the fallow will be essential if we are to achieve the necessary co-location of water and mineral N deeper in the soil profile.

In combination with this, we have the decisions about when and how to apply fertiliser N to top up the available N pool to achieve the water limited yield potential for that growing season. Our current practices are focussed on trying to finesse the 'right' N rate for this purpose, and on delaying our fertiliser application until a cropping decision is certain and seasonal yield indicators (stored soil water and seasonal climate forecasts) are locked in. In many ways, this strategy will effectively ensure the fertiliser recovery in the season of application is limited, unless in season rainfall distributions are favourable, as it limits the likely distribution of fertiliser N to topsoils that are often dry for significant parts of the growing season – especially in winter. Examples of the seasonal variability in the fate of applied N are shown in Figure 3 for summer sorghum.

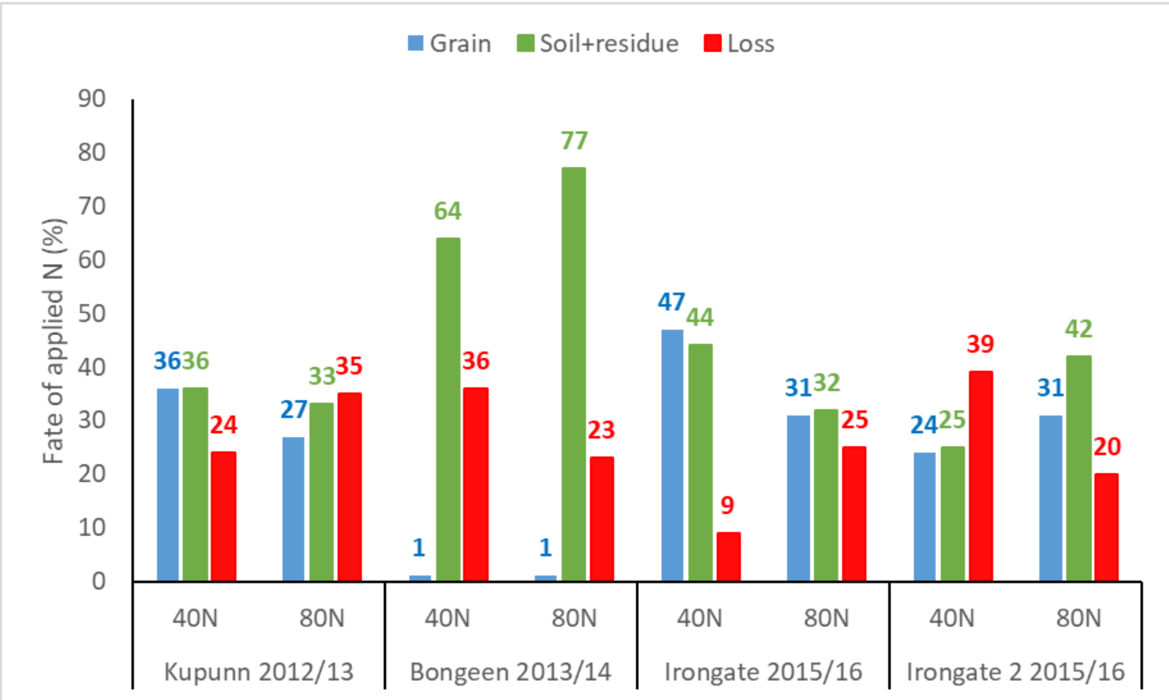

Figure 3. Percentages of fertiliser N either removed in sorghum grain, lost to the environment (presumably via denitrification) or carried forward to the following cropping seasons in soil and crop residue. Data were from sorghum crops grown on vertosols in commercial fields on the Darling Downs from 2012–2015.

(Bell *et al* 2015)

Considerations for improving management of soil and fertiliser N

Some important principles to improve fertiliser nitrogen use efficiency (NUE) in northern cropping systems are:

- Fertilise the soil and not just the crop – this recognises that building a bank of labile N in the soil profile, both in organic and inorganic forms, is important to achieve water limited yield potentials. The current decline in soil organic matter and mineralizable N has resulted in less fallow N mineralisation and a greater reliance on fertiliser N to meet crop demand. Systems are now characterised by longer periods of immobilisation of N while crop residues with low N concentrations are broken down, and this is resulting in slower recharge of subsoil mineral N. Maximising the return of residues, improving the N content of residues through increasing legume frequency, and improving overall soil nutrient availability will help to maximise the building of soil organic matter and help fallow N recharge.

- Be more flexible with timing of fertiliser N application – this is particularly relevant in situations where profiles have been depleted of mineral N, much as they have been over the last 18 months. Combinations of wetter seasonal conditions, high crop yields and widespread denitrification losses have further increased the reliance on fertiliser N to meet current crop demands, so ensuring at least some of that N is distributed with water in deeper profile layers will be very important. This can be achieved by applying a proportion of the fertiliser N when soils are dry early in the fallow period, to ensure the wetting front moves nitrate N into deeper soil layers as the profile refills. While more research is needed to quantify the net benefits of early application, important considerations are likely to be: the extent to which immobilisation of N may delay nitrate leaching early in the fallow (e.g., with high cereal stubble loads); and the relative denitrification risk of early application with differing amounts and distributions of moisture in the soil profile.
- Consider the implications of different N formulations and application methods. There has been considerable recent focus on the relative merits of in-soil banding v top dressing in terms of crop N responses, with the results generally inconclusive and apparent crop recoveries from both application methods similarly poor (Daniel et al. 2019). We should not forget there are also considerations in choosing the right product (e.g., granules v liquids; enhanced efficiency fertilisers v conventional products). When N fertiliser is banded, there is little evidence of either coated or stabilised N fertilisers producing improved fertiliser N recovery by crops in rainfed systems. This is thought to be because these technologies either slow the formation, or release, of NO_3 into the soil solution, and so delay the movement of N into deeper soil layers that are accessible during drier periods (Dang et al. 2021). In the case of top-dressed N, there may be advantages in the use of urease inhibitors to coat urea granules (e.g., NBPT in products like Green Urea NV®) to reduce the risk of volatilisation losses – especially when stubble loads prevent direct soil-granule contact. However, the protection window for these products is short (e.g., <7–10 days) in field environments (Janke et al. 2020).

  With conventional fertilisers, comparisons between fluid and granular formulations are confounded by the different products that are typically used (e.g., urea-ammonium-nitrate (UAN) liquids *cf*. urea granules), and use is typically governed by convenience rather than performance. When fertiliser is sub-surface banded, use of products like UAN may limit the chemical changes in the band area and allow N to move deeper into the profile from early season rainfall events. Conversely, the more rapid conversion of UAN to NO_3-N may increase denitrification risks when wet conditions occur. Clearly the seasonal conditions will affect the impact of these formulation choices, and so developing principles for such variable conditions will be challenging.

  Similarly, the relative effectiveness of topdressing v subsurface banding will also vary. The delays in formation of NO_3-N that occur in concentrated N bands can be a benefit in situations where in-crop rainfall is an important yield determinant (mid-row banding in southern systems with winter rainfall) but can cause delays in movement of N into deeper soil layers and contribute to stranding of N in dry topsoils unless banding is done early in the fallow. Topdressing, particularly during a fallow, can overcome some of these issues and provide a greater volume of soil enrichment, but this application method also maximises the interaction with the microbial community, and can result in similar delays in N movement due to immobilisation. The relative benefits of each strategy will therefore change with the amount and type of crop residue, the timing of N application and subsequent rainfall.
- Soil sampling as a guide to fertiliser N management strategies – the to's and fro's of soil sampling to determine fertiliser N requirement have been discussed extensively over recent updates, but mainly in the context of trying to determine the 'right' rate in situations with unreliable seasonal rainfall forecasts. Hopefully this discussion has shown that while fertiliser responsiveness will vary in response to crop sequences, seasonal conditions etc, so will the fertiliser application

strategy required to give the best chance of meeting crop demand. Soil sampling to periodically check the performance of your fertiliser N strategy, or to determine the impact of an unusual set of seasonal conditions (like the recent wet seasons from 2020–2023), will be essential to determine when and how future N management should change. For example, the current extremely low soil mineral N, especially in the subsoil, will indicate problems meeting crop N demand from fertilisers unless seasonal conditions are exceptional. Fertiliser strategies will need to focus more heavily on timing and placement of fertiliser N, and perhaps cause a rotational shift to a higher legume intensity in coming seasons. Once profile mineral N returns to more normal amounts and distribution, a more conventional approach can be adopted.

Current research to develop better guidelines for N decision support

The focus of current fertiliser N research nationally is to improve our understanding of the fate of applied N fertiliser in grains cropping systems with investment by GRDC in project : Predicting nitrogen cycling and losses in Australian cropping systems - augmenting measurements to enhance modelling" – UOQ2204-010RTX. This involves studying N transformations and how these vary in different soils, climatic conditions and cropping sequences, and what this means for crop N demand, fertiliser use efficiency and environmental losses. There are a total of 15 experimental sites established across the country, with ^{15}N labelled urea fertiliser used to track the fate of applied fertiliser across up to 3 consecutive growing seasons. Soils and crop residues from these sites are being provided to undertake more fundamental studies under controlled conditions, to better quantify the key processes involved in soil and crop N dynamics. Detailed monitoring of denitrification and volatilisation losses are being undertaken in the field and controlled conditions. Collectively, the data generated in this intensive research program 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.

An additional DAWE-funded project in Qld (Project 4-H4T03F0: Understanding impacts of contrasting cropping systems on soil organic matter and the dynamics of soil water and nitrogen in rainfed cropping systems on vertosols in northeast Australia) runs in parallel with this work. It is using ^{15}N-labelled fertilisers applied at different times during the fallow to track the leaching, crop recovery and environmental losses of fertiliser N in vertosol soils. It is collaborating with the GRDC farming systems sites at Pampas and Mungindi to explore these dynamics under contrasting crop sequences, with information also to be utilised to test the ability of crop models to predict these dynamics, and ultimately to evaluate contrasting fertiliser N strategies.

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