# A systems approach to nitrogen management

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**GRDC codes**

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**Take home messages**

- Crops obtain their N supply from mineralisation of organic material, spared fertiliser N from previous seasons and fertiliser applied in the year of sowing. While fertiliser is vital to crop productivity, only 20-40% of the crop N requirement is met by fertiliser applied in the year of sowing.
- Crops typically take up 20-50% of the N applied in a given season, however long term studies indicate that they continue to access fertiliser N in subsequent years. It is estimated that this value increases to around 66% over the long term.
- Aim to maintain soil fertility and maximise profits by using N fertiliser to achieve a neutral or small positive N balance. N Banks, Yield Prophet® and variable rate N fertiliser application based on protein maps are effective ways of achieving this.
- Don't be overly concerned about poor NUE and response to fertiliser N in the year of application. Manage to minimise losses (4Rs) and unused N will make an important contribution to soil fertility.
- Monitor soil N fertility by either soil testing for total soil N or organic C or calculating an N balance for each paddock over your crop sequence.
- N isn't always the limit to yield – what other constraints might you have that would be more cost effective to alleviate?

**Background**

Nitrogen (N) deficiency is the single biggest cause of the gap between water limited potential yield and farm yield in non-legume grain crops in Australia (Hochman and Horan, 2018). Recent shifts to continuous cropping with low legume intensity mean crops are highly reliant on fertiliser N to achieve water limited yields. Due to Australia's variable rainfall and thus variable water limited potential yields, it is difficult to match fertiliser N to anticipated crop yields, and many crops are under-fertilised and nitrogen (N) deficient. Wheat or barley grain protein less than 11.5% is a good indication of N deficiency. Under-fertilising not only reduces crop yield, but also causes crops to mine soil organic derived nitrogen, which runs-down soil organic matter, emitting carbon dioxide to the atmosphere and increasing reliance on fertiliser N for future production.

In 2022, urea tripled in price compared to previous years. Grain prices also increased meaning that optimal N rates haven't changed all that much, but the total cost of N fertiliser inputs and value at risk has increased markedly. It is now more important than ever to make sure that N fertiliser is being used effectively and environmental losses are avoided as much as possible.

In the past, much research and extension emphasis has been placed on maximising nitrogen fertiliser use efficiency in the year of application. This overlooks the fact that in continuous cropping systems, fertiliser not used in the year of application contributes to maintaining soil organic matter and thus soil fertility. We argue that to effectively close yield gaps, a longer-term systems approach to N fertiliser management is needed where losses are minimised, but it is recognised that applications of N fertiliser are as much about maintaining soil N fertility as they are about meeting the N requirement of the crop in year of application.

**Nitrogen in cropping systems**

Most N in cropping systems is stored in soil organic matter that cannot easily be taken up by plants or lost to the environment. There are usually tonnes per hectare of soil organic N in most cropping soils, and this forms the basis of soil fertility. N becomes readily available to plants when it is mineralised by microbes from organic matter into mineral form (Figure 1). Mineral and organic N together are referred to as total soil N. Nitrate ($NO_3$) and ammonium ($NH_4$) are the most stable forms of mineral N in the soil, and the forms most readily taken up by plants. These are the compounds that are typically measured in soil N tests as a measure of instantaneous plant available N.


**Figure 1.** A twin chamber measuring bottle provides a good analogy for soil N – most N in the soil is in organic form (bottom chamber), but crops mainly take up N in mineral form (top chamber). N moves between organic and mineral form via mineralisation and immobilisation. N can be added to

or lost from the soil in both organic and mineral form. To achieve N balance the units leaving the soil via the green arrows needs to be equal to the units entering the soil via the blue arrows.

Mineral nitrogen moves back into the organic pool when it is **immobilised** by microbes or taken up by plants. Immobilisation occurs when soil microbes breaking down carbon-rich molecules in plant residues or other dead microbes for energy, take-up mineral N to form proteins in their cellular structures. When these organisms die, their rapid decomposition can be prevented by association with soil mineral particles or aggregates, and this forms the basis of soil organic matter. Very fine particles of decomposed plant material protected from rapid decomposition by soil aggregates are the other important component of soil organic matter. Nitrogen is also present mostly in organic form in living plants, and in plant residues on the soil surface which form the feedstock for soil organic matter production.

The major inputs (tens to hundreds of kg/ha) of N into cropping systems are from legume fixation of atmospheric N and addition of synthetic N fertiliser or organic wastes e.g. manures, composts, biosolids etc. (Figure 2). There are smaller amounts (ones to tens of kg/ha) provided through rainwater and dust deposition, and fixation of atmospheric N by free-living (non-rhizobial) bacteria.

The major outputs of N from cropping systems are through export of grain, hay or removal of crop residues (sometimes referred to as N off-take), as well as burning and environmental losses due to denitrification, volatilisation, leaching, run off and erosion.

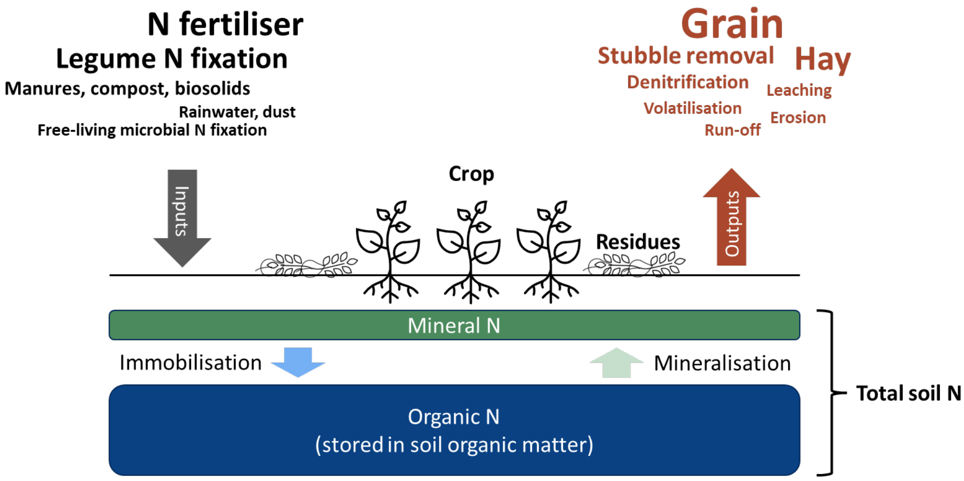


**Figure 2.** Nitrogen pools, inputs and outputs in grain cropping systems

**Soil is the most important source of N to crops**

On average, grain crops derive only 20-40% of their N requirement from fertiliser applied during their life cycle, with the remainder being taken up from the soil (Gardner and Drinkwater, 2009; Wallace et al., 2022). Soil sources of N are thus the most important source of N to a crop, and include;

1. Mineral N accumulated prior to sowing, which comes from various sources, including;
    a. N that mineralises out of soil organic matter or plant residues during the summer fallow
    b. Mineral N from various sources not used by previous crops ('spared' N)
2. N that mineralises from soil organic matter or plant residues while the crop is growing (in-crop mineralisation).

Rates of net mineralisation (mineralisation minus immobilisation) are determined by soil temperature and water availability, amount of soil organic matter, and amount and C:N ratio of plant residues. Decomposition of plant residues with C:N ratio of 25:1 or less will usually result in net mineralisation, but at C:N ratios above this, net immobilisation is likely (cereal straw typically has a C:N ratio of 80:1).

In any given year, it is difficult to compensate for poor soil N fertility (low mineral N and soil organic matter) with high rates of N fertiliser because it is difficult to get more than 20-50% of total crop N uptake from fertiliser N. To support high yields, it is essential that soil N fertility is maintained.

**How can N fertility be maintained?**

Over the long term, N fertility in cropping systems is maintained by ensuring that N inputs either equal or exceed N outputs in grain and losses. That is, the cropping system needs to have a neutral or positive N balance. When outputs exceed inputs, N balance of the system is negative, and plant and microbial growth become strongly N limited. As N mineralises out of the organic pool to be taken up by crops and exported in grain, it is not replaced, and soil organic N declines over time. This is referred to as 'mining' of soil organic N, and long fallowing is one of the most effective ways to achieve this. Because of the fixed ratio of C:N in soil organic matter, soil organic carbon also declines during periods of N mining as C is respired into the atmosphere as $CO_2$. Eventually soil organic matter will reach an equilibrium set be the low fertility where the ability of the soil to provide mineral N to crops (and support yield) is greatly diminished, forcing greater reliance on fertiliser N inputs to support yield. In many continuously cropped soils estimates indicate negative N balance resulting in the average N mineralisation potential of soils halving every 23 (+/- 12) years (Angus and Grace 2017).

In continuous cropping systems, N fertility can only be maintained by inclusion of grain or forage legumes in the crop rotation and/or addition of sufficient N fertiliser or manure to compensate for N exported in grain or lost to the environment. Only 20-50% of applied fertiliser (and less of manure) is used by crops in the year of application, and the remainder is either carried over in the soil as 'spared' mineral N, immobilised into soil organic matter or lost to the environment through stubble burning, volatilisation, run-off, leaching or denitrification.

Cropping systems with an overly positive N balance are at risk of accumulating mineral N and suffering higher N losses although running a positive N balance may be necessary to build fertility in paddocks in which soil organic matter is depleted. Building fertility is likely to be more cost effective and less prone to losses if it is achieved by adding organic sources of N e.g. by growing legume pastures or brown manure crops, or applying manures or other organic wastes, rather than adding excessive amounts of synthetic N fertiliser.

Use of decision support tools such as Yield Prophet®, Nitrogen Banks and variable rate application of N fertiliser based on protein or N removal maps are both effective and can guide N fertiliser management to ensure that crop N balance is neutral.

Five years of data from the Birchip Cropping Group (BCG) and University of Melbourne long term N management experiment at Curyo in NW Victoria (Hunt et al., 2022) has shown that fertiliser N management strategies which run a neutral to slightly positive N balance (N Bank 125 kg N/h, Yield Prophet 50%) are also the most profitable (Figure 3) and that profit begins to decline at an N balance of ±50 kg N/ha from neutral. Profitability also declines above a marginal nitrogen use efficiency (NUE) of ~20 kg/kg (Figure 4), illustrating that NUE is not the best indicator of overall system performance.

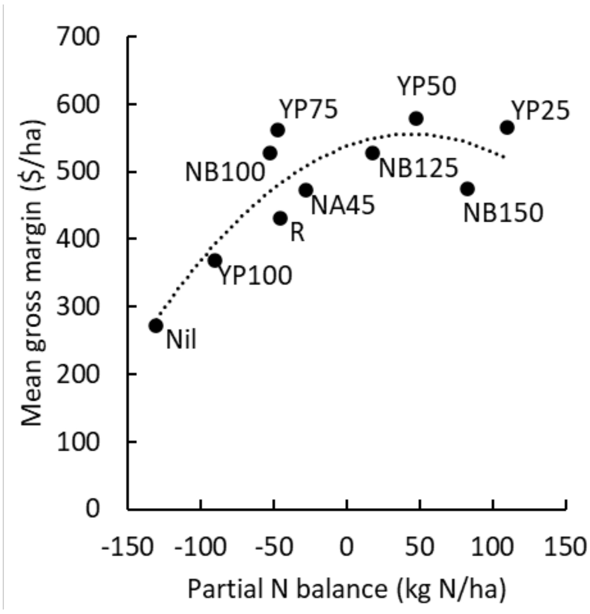


**Figure 3.** The relationship between partial N balance (N applied as fertiliser - N exported in grain) and mean gross margin ($R^2$=0.74). Results are averaged from 2018-2022, but costs and prices from 2022 were used to calculate gross margin, including urea at $1400/t. YP=Yield Prophet at different probabilities indicated by following number, NB = N Banks at different target levels indicated by following number, R= replacement and NA45 = national average application 45 kg N/ha.

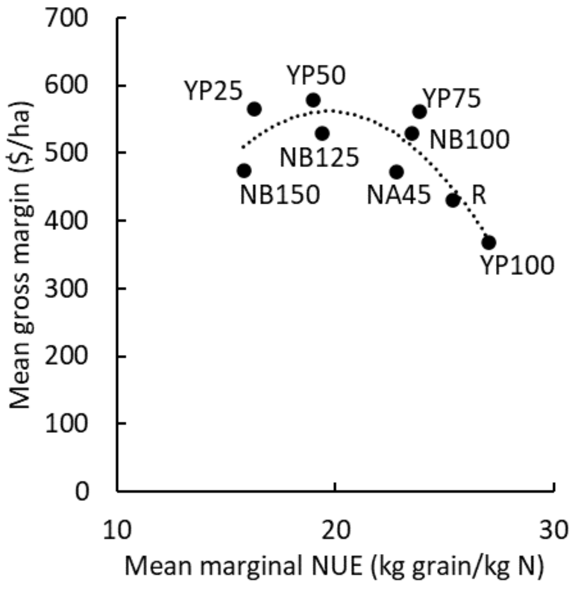


**Figure 4.** The relationship between mean marginal NUE (kg grain produced per kg of fertiliser N applied relative to Nil control) and gross margin ($R^2$=0.69). Results are averaged from 2018-2022, but costs and prices from 2022 were used to calculate gross margin, including urea at $1400/t. YP=Yield Prophet at different probabilities indicated by following number, NB = N Banks at different target levels indicated by following number, R= replacement and NA45 = national average application 45 kg N/ha.

## Avoiding nitrogen losses

While the benefits of minimising loss of N to the environment are clear, implementing reliable management strategies to achieve this under conditions of uncertainty (seasons and yield potential, input prices, commodity prices) is more complicated. Nonetheless, understanding the risk factors that contribute to N loss can help to inform management for maintaining soil N reserves.

Previous studies across a range of grain crops grown in Australia indicate that on average, 22% to 28% of fertiliser N applied is unaccounted for and presumably lost from the farming system by harvest (Angus and Grace, 2017; Barton et al. 2022). However, losses can vary significantly, typically ranging from 5-50%. Rates of N loss are highly correlated with soil water supply – either too much or not enough can influence N cycling, availability to the crop and the processes that lead to loss. Measurements of NUE across a range of environments in Victoria have shown that highest losses occur under wet conditions in either high rainfall (7-93%) or irrigated conditions (31-54%). Conversely, measurements from lower rainfall (< 450 mm annually) environments show typical losses of 5-42% (Wallace et al., 2022).

Under wet soil conditions, potential loss processes include denitrification (where nitrate is reduced to di-nitrogen, nitrous oxide and nitrogen oxide under waterlogged conditions) and leaching or runoff (where soluble nitrate moves through or across the soil with the flow of water). These processes attract significant research and policy interest due to their relevance as a potent greenhouse gas (nitrous oxide), potential pollutant of waterways (nitrate leaching or runoff) and a cause of soil acidification (nitrate leaching). Under dryland conditions in most Australian grain growing regions, significant deep leaching events are rare. However, the potential for extended periods of waterlogging, leading to anaerobic soil conditions causing denitrification may result in large rates of N loss. Unfortunately, field-based assessments of total denitrification are currently limited as accurate measurements are difficult. However, research supported by GRDC and their partners continues in this area to help better inform the N cycle and likely losses (Barton et al., 2022).

Where soil conditions following N fertiliser surface application are relatively dry, the risk of losing N to ammonia volatilisation increases. Volatilisation occurs where water supply is sufficient to cause dissolution of fertilisers such as urea (a heavy dew can begin this process) but is insufficient to wash the N into the soil profile. Where N is maintained near the soil surface as ammonium, it can be subject to loss as ammonia gas. High soil pH, surface application of fertiliser, high temperatures, windy conditions and minimal ground cover are some of the key factors influencing the amount of N lost through this pathway. Measured losses due to volatilisation in Australian cropping systems range significantly. Analysis by Schwenke (2021) suggested a median of 8.1%, ranging from 0-29% for in-crop, surface application of urea.

Minimising loss of applied N centres around controlling levels of excess mineral N in the soil, particularly at times when conditions are conducive to loss (see above). Ideally this means more fertiliser N being taken up by the crop. If this can't be achieved, then maintaining this N in the soil, ideally in tied-up organic forms for future cropping cycles is preferred. To achieve this, fertiliser decision making can be guided by the 4Rs principle: right rate, right time, right product, right place.

Right Rate: Under Australian conditions, determining the 'right rate' of application is a first order priority. Variable rainfall, fertiliser prices and uncertainty relating to N response make for a difficult annualised based decision, although this uncertainty can be removed if N decisions are made across a longer-term horizon. While year to year variables often dominate thinking about N rate, consideration should be given to a broader view that considers multiple years, for example in a review covering long term trials in Europe and the USA average crop N recovery increased from 43.8% in the first year of to 66% in the long term (Vonk et al. 2022). If removal of N exceeds total inputs, soil fertility is in decline and this needs to be replaced in one form or another. Where possible N rate should target partial N balance.

Right time: Achieving the 'right time' for application relates to understanding crop demand patterns and their relationship with N availability as well as the probability of receiving adequate rainfall between N application and anthesis in wheat. Previous studies show that crop uptake of applied N is directly related to crop growth rate at the time of application (Limaux et al., 1999) and the amount of rainfall received after N application (Armstrong et al 2021). As a result, delaying application until the commencement of stem elongation in cereals (DC30/31) can help to increase crop uptake of applied N and reduce loss (Figure 5). Other factors are also important and one of these considerations is rainfall between the post N application and anthesis period in wheat. Calculating the probability of receiving greater than 70 mm of rainfall in this window is an important consideration in improving N uptake (Armstrong et al 2021) – particularly in low rainfall environments. The right time therefore considers two main stage-gates – the first is the timing of stem elongation in wheat and the second is ensuring a high probability of greater than 70 mm between N application and anthesis based on historic rainfall records. In Figure 5 below, results from years with wet winters and modest springs (2012 and 2013) lead to reduced loss where N application was delayed. However, in a dry year (2014) these differences were limited.

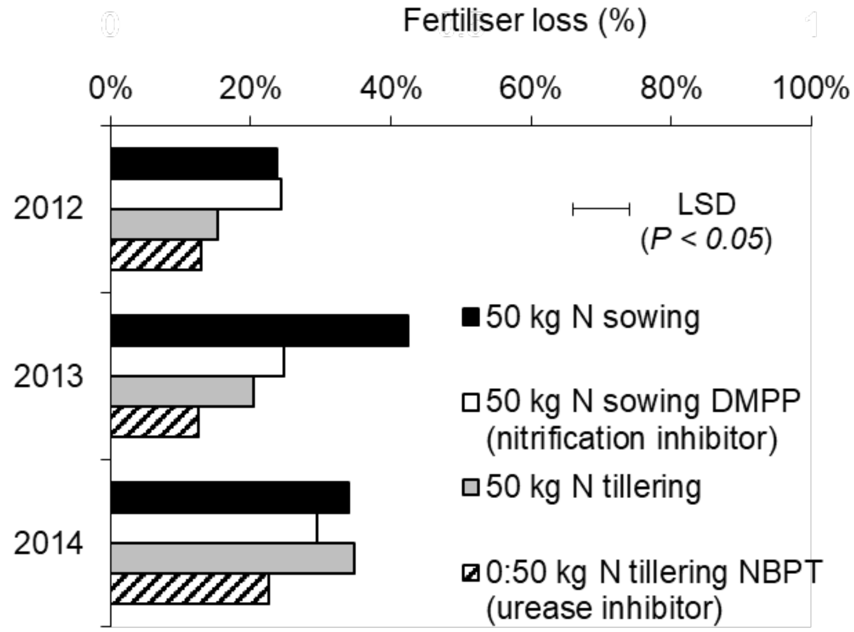


**Figure 5.** Proportion of fertiliser N lost (not recovered in either plant material or soil) between the time of application and harvest for urea applied to wheat in the Victorian Wimmera (2012-2014). All treatments applied at 50 kg N/ha with sowing treatments banded below the seed and tillering treatments top-dressed. Treatments include inhibitor treated urea at each application time. Seasonal conditions were characterised by wet winters and modest spring rainfall in 2012 and 2013 and dry conditions throughout in 2014 (Wallace et al., 2020).

Right product: In most situations, urea is the preferred product based on economic considerations and logistics of application in broadacre cropping. Where N application during high-risk periods is unavoidable (e.g. very wet or drying conditions), the use of enhanced efficiency fertilisers (EEF's) offers an opportunity to mitigate a proportion of the N losses. EEF's cover a wide range of fertiliser products that are designed to control the cycling of applied N. Nitrification inhibitors such as DMPP slow the conversion of ammonium to nitrate, helping to control N loss associated with denitrification, leaching or runoff where conditions are conducive (see data from 2013, Figure 5). Nitrification inhibitors could however exacerbate ammonia losses if applied in the incorrect circumstance – for example on drying, high pH soils, hence the importance of understanding the likely N loss pathway. Conversely, if N is applied during dry conditions, urease inhibitor treated urea can slow the conversion of urea to ammonium, reducing the risk of volatilisation (2014, Figure 5). In sandy soils where nitrate leaching is possible, improved NUE could be provided by either nitrification inhibitors or urease inhibitors by slowing the release of nitrate. Of course, the use of EEF's is contingent on an economic response to offset their associated price premium through either increased yield or grain quality, increased retention of N for future seasons or reduced rate of application.

Right place: In many circumstances spreading urea on the soil surface is the lowest cost option for N application, however other options do exist. Achieving the 'right placement' of applied N can help to reduce loss and retain more N in the crop or soil. Similar to the timing of fertiliser application, if the product is placed into areas of the soil where conditions are conducive to a particular process, it can be prone to loss. Incorporation or sub-surface banding of urea to reduce the risk of ammonia volatilisation during dry conditions is one example of how improvements can be achieved (Rochette et al., 2014). Trials conducted in Victoria have shown that mid-row banding of urea during the growing season rather than topdressing can increase crop uptake of applied N from an average of 40% (23-65%) to 56% (31-79%) and reduce loss from an average of 41% (25-50%) to 26% (13-43%) of applied N. However, yield and grain quality responses in the year of fertiliser banding were not consistently sufficient to immediately offset the increased cost of application. Further work is required to determine the longer-term crop response of this strategy. Similar to the use of EEF's, increased retention of N for future seasons or reduced rate of application may be required to justify this strategy.

While 2022 was an exceptionally wet year for most grain growing regions in south-eastern Australia, a common question arising after drier seasons relates to potential for carry-over of unused fertiliser between years. Results from the Victorian studies listed above indicate that, particularly in medium and low rainfall regions there is potential for significant amounts of unused fertiliser N to remain in the topsoil following dry seasons (26-92% of applied N). These results are typically associated with poor crop uptake in the year of application, often where N was top-dressed and limited rainfall following application meant that crop access to this N was hindered. While this N may be subject to loss mechanisms and tie-up, it nonetheless highlights the potential to gain a return on fertiliser investments in the years following application. Studies investigating N recovery over multiple years under dry seasonal conditions are currently limited, and is the subject of ongoing investigation.

Research conducted by Riverine Plains Inc from 2015 – 2017 in the *Seasonal soil moisture and nitrogen availability* project, in partnership with the North East CMA, demonstrated accumulation of N in the 30-60cm depth in 2016, which was also a very wet year (Schefe and Lowe, 2018). Segmented deep N testing can provide confidence in estimating residual mineral N after wet conditions, while understanding the depth of any N 'bulges' may inform future N fertiliser applications.

**How to monitor soil N fertility?**

Soil N fertility can be measured by analysing soil for total soil N or more commonly, soil organic carbon. Because mineral N is such a small component of total soil N and highly responsive to seasonal variation, analysis of mineral N alone (particularly in a single year) is insufficient to assess overall fertility. Because C and N are in constant ratio in soil organic matter (11.7:1.0, Kirkby et al., 2011), soil organic N can be estimated by dividing soil organic carbon values from a soil test by 11.7. Whilst these values give an indication of fertility, they are prone to sampling error and are not good at detecting small changes in values. Further to this, due to the sheer volume of C and N present in soils, building these stocks is a slow process requiring consistent, comprehensive and repeated measurements over time (>5 years) to ensure an accurate assessment of change.

Calculating a partial N balance is a simpler and cheaper way of monitoring N fertility but requires good farm records (yields, protein, fertiliser input) over many years. A spreadsheet for estimating N balances is available here;

https://www.bcg.org.au/understanding-crop-potential-and-calculating-nitrogen-to-improve-crop-biomass-workshop-recording/

This sheet uses some rules of thumb and provides a rough estimate only, but calculating N balances is an example of a situation where it is better to be approximately correct than precisely wrong! For those wanting to undertake their own calculations, percent protein divided by 5.75 and further divided by 100 provides an estimated conversion to N [e.g., ((12% / 5.75) / 100) = 0.0209 kg N]. If the grain yield in kg/ha is multiplied by 0.0209 it provides the N off-take in grain (4000 kg/ha x 0.0209 = 83.6 kg N/ha).

**It is not always N**

Whilst N is the single biggest factor contributing to the Australian wheat yield gap (Hochman and Horan, 2018), it is not the only factor (Lawes et al., 2021). If soil constraints, other nutrient deficiencies or manageable biotic stresses are present, this will reduce the plant's ability to utilise applied N. As N fertiliser is a significant input cost, it makes sense to ensure that it can be used efficiently.

The key limitations to consider in southern NSW cropping systems are:

1. Soil pH. Soil acidity is a major issue in these systems, exacerbated by several years of high productivity and export. While surface acidity has been recognised for many years, subsurface acidification has started to become more broadly detected, due to historical surface broadcasting of lime or inadequate lime application rates and or application frequency. In addition to the direct effects of acidity and high exchangeable aluminium on root growth and nutrient uptake, pH values less than $pH_{Ca}$ 4.8 also inhibit microbial function, with reduced mineralisation of N from organic matter.
2. Soil sodicity. Amelioration of surface or near-surface sodicity with gypsum can improve water infiltration, waterlogging and early plant vigour, which in turn can improve N uptake. While sodic subsoil layers are more difficult to amend, understanding their impact on root growth can inform management, with N fertiliser rates reflecting realistic expectations of productivity.
3. Soil phosphorus deficiency. Soil P levels in 0-10cm tests are being assessed against nutrient recommendations which were developed under fully cultivated systems, where it was assumed that most of the measured P was available to plants. As such, the impact of no-till systems and related stratification of P on plant-available levels may not be considered. As P is a key requirement for plant growth and organic matter cycling, maintaining adequate P fertility (as a P 'bank') is a requirement for efficient plant uptake of N.
4. Other nutrient deficiencies. Key deficiencies identified in southern NSW are sulphur (S) and potassium (K). While adequate sulphur (S) levels are needed for plant uptake of N, S levels have been depleted following several seasons of high productivity and high rainfall. Measurement of subsoil S with incremented deep soil N testing is of high value in ensuring that the applied N can be used efficiently. Soil K deficiencies are becoming more prevalent, due to ongoing high productivity and export, mostly on lighter soil types.
5. Disease and canopy management. Achieving water limited potential yield requires healthy roots and a healthy crop canopy. Growing a large canopy only to have it compromised by foliar disease or lodging severely limits the ability of a crop to capitalise on available N.

Crop yield will always be subject to co-limiting resource availability (Sadras, 2005). This means that yield will be maximised and resources used most efficiently when all resources are equally limiting. If a factor other than N is imposing a strong limitation on crop yield, the efficiency with which plants can utilise N fertiliser will be poor. While identifying and addressing other constraints or deficiencies may require some investment, it will ensure that expensive N fertiliser is used efficiently, resulting in greater yield and ROI.

**Call to action**

Think of fertiliser more as an input to maintain longer term soil fertility and fill seasonal shortfalls rather than the major source of annual N for crops. Use decision support systems such as Yield Prophet®, Yield Prophet® Lite, N Banks or variable rate application based on protein maps to maximise profit and maintain a neutral partial N balance over the long term.

Keep managing N fertiliser to try and minimise losses to the environment – make sure N fertiliser application is aligned with crop demand and likely rainfall outcomes and consider all other techniques available (e.g. mid-row banding, inhibitors, variable rate application). Burning stubble is a major loss of N and retaining crop residues helps immobilise mineral N, keeping it safe from loss and building soil organic matter, although this also requires adequate supply of other nutrients.

Don't be overly concerned about poor NUE and response to fertiliser N in year of application as the initial N recovery improves when measured over a longer time frame. Manage to minimise losses and unused N will make an important contribution to soil N fertility.

Monitor soil N fertility by either soil testing for total soil N or organic C or calculating an N balance for each paddock over your crop sequence to work out how many kg/ha of N have gone in from fertiliser, legumes and manure vs. taken out in grain, hay, burnt stubble and losses.

Make sure other factors are not limiting yield. A set of GPS-located, soil testing sites across the property with historical incremented testing to at least 60cm for major constraints (e.g. pH, Exchangable sodium percentage (ESP) etc.) and other nutrients (P, S, K etc.) provides confidence that soil constraints and deficiencies are identified and either ameliorated or managed. This means that N fertiliser applications can be used as efficiently as possible.

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