# Nitrogen as a nutrient for wheat in southern Australia

*Introductions*

This is a guide to information that enables land managers to make better decisions about N nutrition for wheat grown in south-eastern Australia.

*Role of P in agriculture (description / contributing factors)*

The basic principles of phosphorus nutrition are :
how plants access N fertiliser and soil N
the types of N plants absorb
the role of fertiliser N as a source of N nutrition
the role of 'fixed' soil N and residual N in crop nutrition

Nitrogen is an essential nutrient required for growth, and impacts on root development which in turn effects shoot growth, access to water and other essential nutrients. In south-eastern Australia, many soils are naturally deficient in N.

*Diagnosing N deficiency (management / how to measure)*

Soil testing is the most effective means of detecting a deficiency in N before it impacts on grain yields. The soil test widely recognised for cropping systems rely on measuring nitrates via extraction. Another testing technique utilising mineral N can also be used, although more common in research settings. Good soil sampling technique is vital for ensuring accurate soil N values.

Nitrogen deficiency in a crop can be detected by watching for foliar symptoms or through tissue testing.

Historical records of N applications, soil tests, and the grain yields and conditions in prior seasons can assist to estimate a paddock's N balance and indicate if N needs to be applied to the next crop.

*Correcting N deficiency (recommendations)*

Applying the principles of good crop nutrition will ensure adequate N supply to crops. The principles are right place, right time, right type and right amount. Special consideration needs to be given to the fertiliser type used, as dosage rates are dependent upon the chemical composition of the fertiliser used. The immediate benefit of N fertiliser is limited if other nutrients are limited or if other factors constrain plant growth.  Nitrogen fertiliser remaining from previous applications has a residual effect on the next crop depending on several factors including soil type, and conditions in prior and current seasons.

# Nitrogen as a nutrient for agricultural crops in southern Australia

## Scope

This review of the literature focuses on the function, importance and use of nitrogen fertiliser (N) for wheat production in dryland cropping systems of south-eastern Australia. The review draws on a selection of cornerstone journal articles that provide foundation information about the importance of N for wheat production and the role of N in crop production. Information is sourced from the international literature and, where available, literature that provides specific regional content. The selected research and extension literature focused at the regional level is underpinned by the basic principles of N nutrition provided by cornerstone journal articles. Region-specific literature may be in the form of conference papers, fact sheets, technical reports or decision support systems (DSS).

These information sources are selected to assist advisers and growers to improve their understanding of the basis for making decisions when managing N nutrition.

## Outcome

This literature review is a guide that aims to enable advisers and growers to make better decisions about N management including whether N needs to be applied, and if so, where, when, in what form and at what rate. The review summaries the function, importance and use of N by plants in dryland cropping systems and provides a bibliography of reliable information sources. This literature review will be combined with reviews of other agronomic topics to provide growers and advisers with a carefully targeted source of information that will assist them to make more informed decisions about agronomic management.

## Function of N in broad-acre grain crops

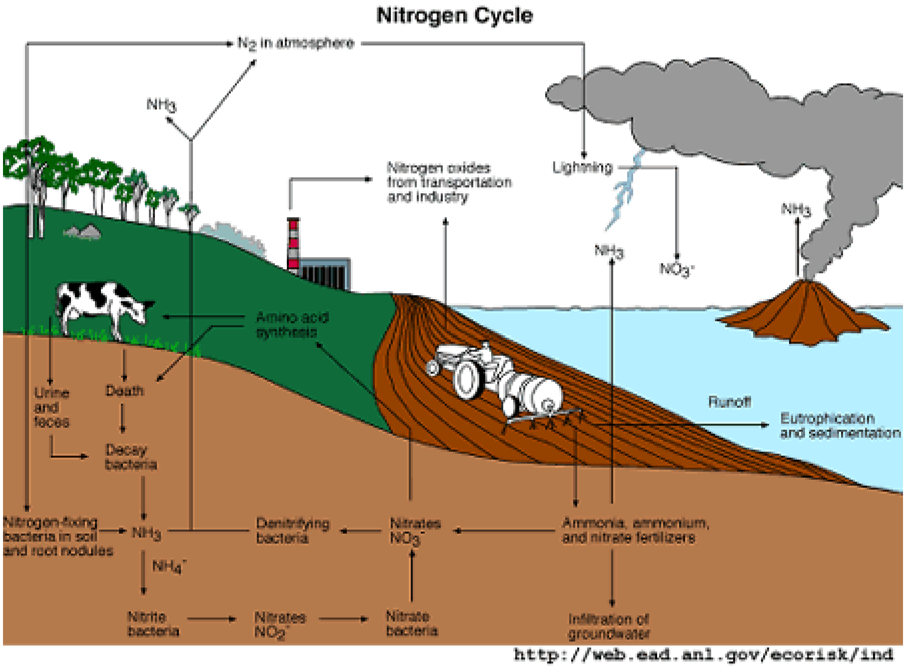
### *Nature of N in plants*

Nitrogen is an essential nutrient required for the growth of wheat (Grundon 1987) and is a key element in amino acids, proteins including grain protein, chlorophyll and root development (Olson and Kurtz 1982). Grain protein and grain yield are reduced when N supply is inadequate (Grundon 1987). Nitrogen is highly mobile in wheat hence when N is deficient, older leaves yellow as N is mobilised to younger plant parts including grain (Grundon 1987). Other symptoms of N deficiency are stunting of the plant, a reduction in the number of tillers, grain with a mottled colouring and lower grain yield (Grundon 1987, Wurst *et al.* 2010).

## *Nature of N in soil*

Nitrogen is principally in an organic form in soil and is subject to a complex cycling process that has been extensively reviewed (Jansson and Persson 1982) and represented in pictorial (Figure 1) and video formats.

Figure 1: Representation of the Nitrogen cycle.




The main components of the cycle that are important to crop production are

- Mineralisation: Mineralisation is the conversion of organic N to inorganic N ($NH_4^+$, $NH_3$) by soil organisms. This is also known as ammonification (organic N to $NH_4^+$) and is followed by nitrification ($NH_4^+$ to $NO_2^-$ to $NO_3^-$) to get N into a form that is readily accessible to plants (Jansson and Persson 1982, Jarvis *et al.* 1996).
- Immobilisation: The conversion of inorganic N to organic N in plants and soil organisms so N is no longer accessible to plants. Immobilised N is said to be 'tied-up' (Jansson and Persson 1982).
- Other components of the N cycle that have relevance in particular environments are:
    - Fixation: The conversion of atmospheric N to organic N by rhizobia bacterium that have a symbiotic relationship with legume and pasture species (e.g. field peas, faba beans, lupins, lentils, clover, *Medicago spp*.). This can be a significant source of N to plants (Herridge and Bergersen 1988). Nitrogen fixation also occurs through non-symbiotic bacteria but the amount of N made available to wheat by this method is negligible (Gibson *et al.* 1988).
    - Denitrification: The conversion of inorganic N ($NO_2^-$ and $NO_3^-$) to atmospheric N ($N_2$) or nitrous oxide ($N_2O$) by anaerobic bacteria and movement out of the soil into the atmosphere. The main factors of interest in agriculture that increase the incidence of denitrification are reduction in oxygen in the soil

due to waterlogging, and high levels of $NO_3$ and carbon in the soil (Firestone 1982).

- Volatilisation: The loss of N from the cropping system in the form of gaseous ammonium ($NH_3$). Volatilisation occurs when fertiliser-N is converted to ammonium gas through hydrolysis and is located on or very close to the soil surface such that the gas can escape from the soil. The risk of volatilisation therefore depends on soil moisture, soil disturbance, and the method used to apply the N fertiliser to the soil (Freney and Black 1988).
- Loss through movement of water: Less than 2% of soil N is typically lost through leaching and erosion and these losses can be significant in particular soils since N is a highly mobile nutrient. Leaching of N occurs in soils where water moves quickly down the soil profile and surface water movement occurs in cropped soils with poor water infiltration rates, high rainfall events or little ground cover (Rose and Dalal 1988, White 1988).

The amount of N in soil that is accessible to plants is increased through mineralisation and fixation, and decreased through immobilisation, volatilisation, leaching and surface run-off. The rate these process occur are either indirectly determined by water and temperature because the processes are facilitated by bacteria, or directly determined by water.

## Access to N by plants

Plant roots take up N from soil solution principally as nitrate ($NO_3^-$) sourced from soil or fertiliser although ammonium ($NH_4^+$) can also be actively taken up by plants (Pate and Farquar 1988). The uptake of N from the soil and into wheat depends on (Olson and Kurtz 1982):

- the chemical availability of the nutrient
- movement of the nutrient through soil to the root
- growth of roots through the soil (root interception)
- active uptake of the nutrient at the root surface itself
- translocation from the root to other parts of the plant

Nitrogen is also taken up directly through wheat leaves when applied as a solution (Altman *et al.* 1983).

## N in context of south-eastern Australia

The arable soils of southern Australia used for wheat production are inherently low in N, especially light soils (McDonald 1989). Nitrogen fixation under grain legumes adds N to the soil and the amount added varies with location, rainfall and crop type. Cropping systems devoid of legumes are likely to be responsive to N fertiliser (McDonald 1989). The amount of N added to soil through fixation by grain legumes is substantial but less than needed by wheat in wheat – field pea rotation in southern Australia except in low rainfall environments (Evans *et al.* 2001). Nitrogen fertiliser is also needed to produce wheat in crop-livestock farming systems unless about 40% of cropped land is sown to legume-based pastures that are well managed (Angus and Peoples 2012). Including pastures was the general strategy taken to address low soil

N in the 1930 – 1970s when N fixing pastures were included in cereal cropping systems (Puckridge and French 1983). During this period, grain production of wheat increased with little use of N fertiliser. However, by the late 1980s, pasture production was falling whilst the amount of N fertiliser applied to wheat was estimated to be only 2 -3 kg/ha (McDonald 1989). During this period, wheat productivity stagnated and grain protein content declined (Hamblin and Kyneur 1993). This is expected to occur in farming systems that are mainly comprised of intensive cereal production with few legumes and is particularly pronounced on soils with low organic carbon content (McDonald 1989).

Relatively recently, the decline in pasture production in Australia has continued and average N fertiliser use has increased; estimated at 43 kg/ha in 2000 (Angus and Peoples 2012, Chen *et al.* 2008). Nitrogen fertiliser application rates vary between regions with rates in the 1990s below 10 kg N/ha applied to most of the Wimmera, Mallee, southern Victoria and Eyre Peninsula, 10 -20 kg N/ha for most other regions of Victoria and South Australia, and higher rates ranging from 40 – 200 kg N/ha in most of southern New South Wales (Australian Natural Resources Atlas 2001).

The impact of these differences in N application rates are evident in the N balance for cropping in each State (Australian Natural Resources Atlas 2001) where N balance is fertiliser N imports less N exported in commodities :

- Negative N balance for crops in Victoria
- Negative to neutral N balance for crops in South Australia
- Neutral to positive N balance for crops in New South Wales.

A similar audit in 2009/2010 shows that the trend of a negative N balance is widespread occurring throughout the cropping districts of Victoria, South Australia and southern New South Wales.

# Local tools help N fertiliser decision making

Decision support for N management is based on the concept of having a target or expected grain yield and working out how much N the crop needs to achieve that yield. The source of N is an important part of the decision-making process as N is sourced from the soil at sowing (i.e. initial N), N estimated to become available through net mineralisation during the growing season and fertiliser N. This approach to N management is the basis used to calculate how much N fertiliser to apply to a whole wheat crop (McDonald 1989, DPI 2005).

There is a plethora of information targeted at agronomists and growers to improve the management of N nutrition for wheat production. Historically, management of N is decided prior to sowing, In this situation, information is focused on managing N nutrition at a paddock scale and for the whole season with little regard for temporal

or spatial differences in a crop's demand for N. Information relevant to this approach is found in:

- rules of thumb used to estimate the total amount of N removed by a wheat crop (GRDC 2010, GRDC 2011a)
- decision-support tools operating at a district scale that estimate the grain yield response to nominated N rates with unspecified timing such as
    - the Nitrogen Calculator (Payne and Ladd 1993) and
    - the Whopper Cropper

More recently information to farmers about N management has incorporated recognition that wheat has a varying demand for N throughout the season and N supply needs to match this demand (DPI 2006). This has resulted in field equipment such as crop sensors being developed that are capable of monitoring plant N in real time (GRDC 2012a). Local decision-support tools that focus on the temporal variation in N supply and N demand by wheat are:

- the principles and advantages of matching N fertiliser application with crop demand for N as the season progresses (GRDC 2009a)
- decision-support tools operating at a district scale that estimate the grain yield response to nominated N rates with specified timing of N applications and for specific soils (Riffkin *et al.* 2009)
- decision-support tools operating at a paddock scale that estimate the crop demand for N at specific times during a specific season to achieve target yields and for specific soils (e.g. MaNage Wheat (CSIRO 2004) and Yield Prophet.
- *The Break* and *The Fast Break* digital newsletters for climate forecasting

Soil properties effect the response of wheat to N however consideration of spatial differences in crop demand for N is in its infancy in terms of how this knowledge is applied at the paddock scale. Currently, N management to accommodate spatial differences is largely confined to dividing paddocks into two or three large areas based on soil type or soil properties such as pH and electrical conductivity (GRDC 2012a and 2012b), MSF N tool.

Many of the computerised decision support tools or information from simulated crop growth are based one computer model; APSIM-Wheat (Keating *et al.* 2003). Alternative wheat models such as CERES-Wheat-N are available but are designed for research purposes rather than crop management (McDonald 1989).

## Principles of better crop nutrition

Fertilisers need to be considered when N through other sources including leguminous pastures and grain crops is insufficient for the next wheat crop. Effective use of fertiliser is achieved by selecting the right source of nutrients, and applying them at right rate, in the right place and at the right time. These principles of

effective fertiliser management are interconnected and if one is altered, the whole approach should be reconsidered (Bruulsema *et al.* 2012, Norton and Roberts 2012).

## Right place

Wheat's requirement for N throughout the growing season dictates that N fertiliser must be placed where it can be readily accessed by the plant at all stages of plant growth if soil N is insufficient for the crop to meet targeted grain yields. However, the mobility of N in lighter soil or under heavy rainfall events gives scope for N to be applied on or near the soil surface yet still be available to deep roots later in the season (Doyle and Holford 1993). Nitrogen placement in soil is therefore shallow when plants are young and fertiliser-N is required immediately. When soil-N is inadequate later in the season, N placed at depth during sowing is accessed by roots deeper in the soil.

*'Safe' placement with seed*

The amount of N required by wheat can be higher than is 'safe' to place with the seed at sowing,. The 'safe' amount of N that can be placed with the seed is limited to about 25 kg N/ha in moist light-textured soil with a narrow row spacing. Under these conditions, higher fertiliser-N rates reduces crop emergence and plant density (Carter 1967). This 'safe' rate is higher on heavy soil types, with high soil water content, narrow row spacing and wide seed distribution in each drill row (GRDC 2011b). Further information for heavier soil and a range of sowing implements is available. When higher rates of N are required at sowing, fertiliser must be place either directly below the seed (i.e. centre banding) or below the seed and off-set (*i.e.* side-banding or ribbon sowing).

*In-season placement*

An alternative to deep N placement at sowing is to apply N directly to the soil surface. Recovery of N applied directly to the soil at flowering is up to 70% in soil at field capacity and leads to increased grain protein in wheat given sufficient N to reach maximum potential grain yield (Alkier *et al.* 1972, Rawluk *et al.* 2000).

There is also scope to place N directly on plants by foliar application. Foliar application places N on leaves and on the soil surface depending on canopy density and movement of N with rain water (Smith *et al.* 1991). Either placement leads to N uptake by the plant, but N recovery is lower when applied to leaves (< 27%) instead of soil (32 – 70%) (Rawluk *et al.* 2000, Strong *et al.* 1982).

## Right time

Nitrogen is highly mobile through soil and can be accessed by wheat through roots and leaves. Therefore, N can physically be applied to the crop anytime during the season and be accessed by plants. This flexibility is critical for wheat production since N is demanded by wheat in all growth stages (Olson and Kurtz 1982). However, this flexibility does not mean that N *should* be applied at anytime.

*Supply and demand*

Efficient use of N by wheat depends on matching fertiliser-N supply with fertiliser-N demand (Shanahan *et al.* 2008) with recovery of added N ranging from 38% to 88% depending on timing and rate of application (Angus and Fischer 1991, Chen *et al.* 2008, Fischer 1993, Ladd and Amato 1986). Crop demand for N is particularly high at growth stage (GS) 31 (Zadok *et al.* 1974); the date of which varies with cultivar due to time of sowing, maturity type and yield potential (Fischer *et al.* 1993, Riffkin *et al.* 2009,). The importance of particular growth stages for crop nutrition is recognised by farmers throughout Victoria with a change from applying all N at or before sowing to splitting N application between sowing and GS30-31 with an additional application at flag leaf (GS47) is seasons with above average rainfall (Fitzgerald *et al.* 2010, Riffkin *et al.* 2009).

Some of this need for N can be met by the N made available in soil through mineralisation (Angus 2001). The rate of N mineralisation depends on soil water, temperature and the type and quality of soil organic matter. Variation in these factors throughout the year cause N mineralisation rates to be temporally and spatially variable, difficult to predict or extrapolate between locations and not always matched to crop demand (Angus 2001, Angus *et al.* 2006).

Insufficient supply of N from mineralisation is estimated by visual assessment of leaf colour or tiller count. Earlier indications of a need for additional N is achieved using remote-sensing of N in the crop by satellite, aerial photography or ground-based sensors. Assessment of remote-sensing in Victorian wheat crops shows that aerial techniques accounts for up to 41% of the variability in N status and ground-based techniques account for up to 76% of the variability in N status (Tilling *et al.* 2007). Thus these techniques have practical application to broad acre agriculture but are still challenged by practical issue such as accounting for incomplete canopy closure (Fitzgerald *et al.* 2010, Shanahan *et al.* 2008).

*Early application*

Applying all N at or before sowing is a strategy used when there is a risk that heavy rain will cause waterlogging (i.e. saturation) and the sown paddock will not be able to be trafficked for in-season fertiliser applications. The risk of a paddock being too wet to traffic is largely alleviated through installation of raised beds in higher rainfall environments (Peries *et al.* 2001).

*In-season application*

The alternative practice of applying minimal N at or prior to sowing is supported by field research in New South Wales showing grain yields are not reduced by delaying N application until stem elongation (GS31) (Fischer 1993). This finding supports the option of applying N after sowing based on crop demand and a flexible target yield as determined by crop growth with actual rainfall.

Whilst remote-sensing tools for crop assessment are further developed, the advantages of different timings of N fertiliser application are determined using crop

modelling grounded in field experience (Riffkin *et al.* 2009). In the higher rainfall zones, of Victoria, NSW and South Australia N fertiliser is commonly applied at two (sowing and GS31) or three (sowing, GS31 and G39-S47) times during the season. Crop modelling shows that at most locations the response of wheat to N fertiliser is higher when N is applied at least twice in the season rather than once (Riffkin *et al.* 2009). Applying N at or after stem elongation (GS30-GS39) generally increases grain protein content rather than wheat grain yield in crops that have sufficient N to attain their maximum potential grain yield (Alkier *et al.* 1972, Fischer *et al.* 1993).

*Minimising N loss*

Nitrogen applied in-season to the soil surface is at risk of loss through volatilisation depending, in part, on how application is timed with rainfall, soil moisture and water holding capacity. Volatilisation is minimised when urea-N is applied to the soil surface and has sufficient rain or irrigation to hydrolyse the N and move it into the soil profile. Rainfall or irrigation events sufficient only for hydrolysis causes solid N fertiliser to be lost from the cropping system through volatilization Turner *et al.* (2012). In the dry sands of the Victorian Mallee, 4mm rainfall is sufficient to move urea-N into the profile and keep losses of N through volatilisation to less than 6%. However, 23% of urea-N volatilises when fertiliser is applied to moist soil in the Wimmera with only 1-3mm rainfall events in the 2 weeks after application. These local results concur with the general principles given by Freney and Black (1988).

Similarly, timing of N fertilisation is important to minimise loss of N through denitrification in higher rainfall environments. Nitrogen losses in the form of nitrous oxide ($N_2O$) are dramatically higher in waterlogged soil than in moist soil at 40% water filled pore spaces (Ciarlo *et al.* 2007). This general principle is exemplified in southern Victoria on clay soil where waterlogging and loss of $N_2O$-N occurs under crop both on flat land and under raised beds (Harris *et al.* 2013). Under conditions of high rainfall (> 600mm/annum), these soil types also lose N through leaching, subsurface flow and to a small extent, surface run-off (Ridley *et al.* 2001). Leaching of N in turn cause acidification of soil in these types of high rainfall environment (Ridley *et al.* 2001).

## Right source

Nitrogen in urea, ammonium sulphate and potassium nitrate are equally accessible to wheat crops and equally mobile in soil (Ladd and Amato 1986). Differences between N fertiliser types are of interest when determining the 'safe' rate for placement of N fertiliser, and when aiming to minimise loss of N through volatilisation, denitrification or leaching.

*Difference between sources for safe rates*

The 'safe' rate for placement of N fertiliser with seed differs between some fertiliser types and is based on the chemical constitution of the fertiliser. Urea fertiliser reduces plant density at a lower N rate (25 kg N/ha) than ammonium nitrate (77 kg N/ha) in sandy soil on a narrow row spacing (Mason 1971) and the reduction is more severe with urea than calcium ammonium nitrate or ammonium sulphate in loamy

soil (Carter 1967). Urea, mono-ammonium phosphate and di-ammonium phosphate have the same 'safe' rates GRDC (2011).

*Minimising N loss*

Loss of fertiliser-N from cropping systems is partially determined by soil type and some fertiliser types are more prone to loss in particular conditions than others. The risk of loss of N by volatilisation when fertiliser is spread a dry soil surface is effected by fertiliser type with more urea-N volatilised in sandy Mallee soil than liquid urea ammonium nitrate-N (Turner *et al.* 2012). However, there is no difference in N loss by volatilisation for the two fertiliser types liquid urea ammonium nitrate and ammonium sulphate when applied to moist alkaline clay in the Wimmera.

Volatilisation of urea-N is reduced in alkaline soil from the Wimmera with a low organic carbon content (< 1.5%) by applying a urease inhibitor. A urease inhibitor is particularly effective at temperatures below 15°C (Turner *et al.* 2012). These local results when using urease inhibitors in the field concur with controlled studies that recovery of urea-N is increased from 32-37% to 50-57% through application of a urease inhibitor.

Nitrification inhibitors applied to wet or waterlogged soils also reduce loss of N. Nitrogen loss as $N_2O$-N from urea is reduced in wet acid-clay soil by up to 84% when a nitrification inhibitor after surface application of urea (Harris *et al.* 2013). Conversely a urease inhibitor has little effect on the rate of urea hydrolysis when applied to acid soil with high (11%) organic carbon content as occurs in dairy pastures in Victoria (Suter *et al.* 2011).

- Experimental comparisons of N fertiliser types – inc coated and liquid especially for NSW - under various soil conditions preferably in southern Australia but drawing universal information from other sources as needed.

## Right amount

Calculating the right amount of N requires all inorganic sources of N to be estimated and the crop requirements of N to be known (McDonald 1989). This is complicated in environments with variable rainfall that dramatically alters target grain yields as the season progresses and varies N mineralisation rates (Strong and Mason 1999). The right amount of N is highly variable between soils and seasons with economic assessment showing that N fertiliser is largely unprofitable in rotations that include pasture. The change to more intensive cropping systems with less legume pastures increases the need for N to be used for profitable crop production (Angus and Fischer 1991).

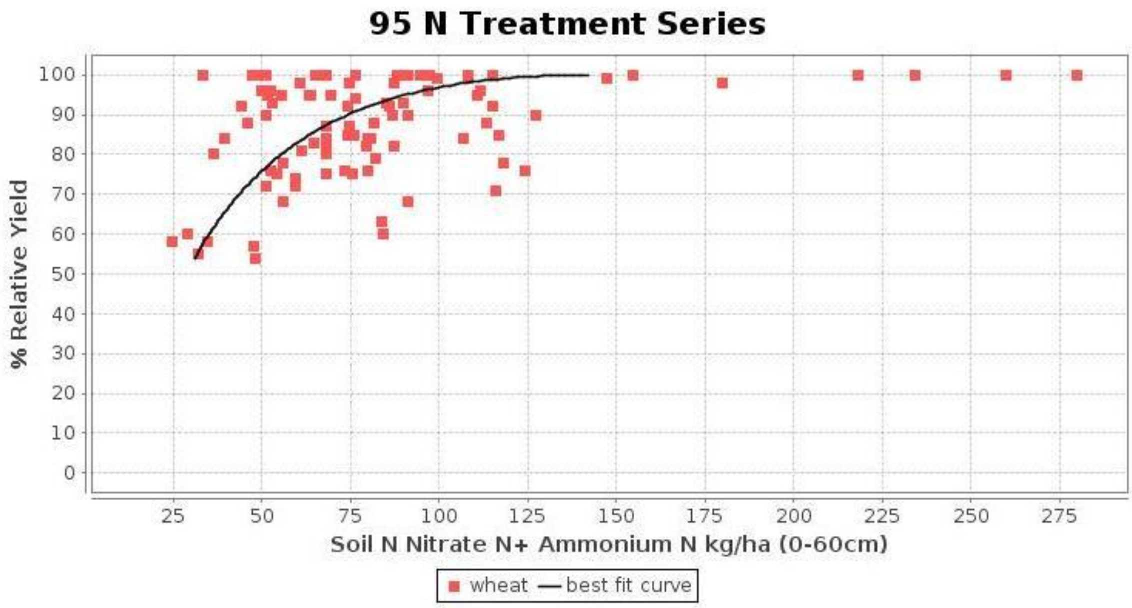
There are three general approaches to determining whether a nutrient needs to be applied and how much needs to be applied: soil testing, historical records plant testing. All three of these approaches need to be used together to estimate N requirements for a wheat crop (Strong and Mason 1999).

*Soil testing*

Soil testing for mineral N is promoted as a means of accurately estimating a crop's N requirements even when grower's are under financial pressure (GRDC 2008). Soil testing enables initial N supply to be measured and N supply throughout the season due to mineralisation to be estimated. The combination of total N, mineral N, potentially mineralisable N accounts for up to 94% of grain yield when considered with growing season rainfall in the low rainfall environment of New South Wales (Xu and Elliott 1993).

Initial N supply is measured almost exclusively by testing soil for nitrate-N and ammonium-N by extraction in 2M KCl followed by colourimetric assessment (Rayment and Higginson 1992). In south-eastern Australia, inorganic-N by itself is only well correlated to wheat responsiveness to N in South Australia (Strong and Mason 1999). Soil assays for potentially mineralisable N tends to only be conducted for research purposes and mineralisable N is more commonly estimated from bulk density, organic C and total N than measured directly (Payne and Ladd 1993, Xu and Elliot 1993).

Figure 2: Calibration curve of responsiveness of wheat to N relative to soil mineral N. Data sourced from the Better Fertiliser Decisions website.




Critical levels for mineral N are have been developed for a limited number of environments in Australia and are used widely as an indicator of N fertiliser requirements (Holford and Doyle 1992). The critical levels of mineral N required to meet the demands of wheat varies with seasonal rainfall (Holford and Doyle 1992). In seasons with average rainfall, the critical value for nitrate-N at 0-15 cm depth in northern New South Wales is 24 mg N/kg and falls to 6-7 mg N/kg in years with low rainfall or high rainfall that causes leaching (Holford and Doyle 1992). An analysis of the 92 N experiments in the Better Fertiliser Decisions database shows that 90%

maximum grain yield is achieved in south-eastern Australia when soil mineral N is 69-83 kg/ha (Figure 2). This critical range is only a guide with the same data set showing a lower range of critical values for lower rainfall environments (62 – 75 kg N/ha at < 450 mm growing season rainfall (GSR)) and a higher and broader range for higher rainfall environments (77-120 kg N/ha for > 450 mm GSR).

*Soil sampling techniques*

The spatial arrangement of samples and how they are handled between sampling and analysis are critical when measuring inorganic-N as N is spatially variable over very short distances and varies with soil water content and temperature. Sampling procedures that acknowledge the dynamics of N are provided by Brown (1999).

The timing of soil testing for nitrate-N and ammonium-N is important given the amounts of inorganic N in soil fluctuate throughout the year (Angus 2001). An analysis of 53 nitrogen fertiliser experiments with wheat in New South Wales concludes that sampling soil 6 weeks prior to sowing provides a good indication of amount of N that will be taken up by the coming crop (Doyle and Holford 1993).

The required depth of soil sampling is 0-10cm for estimating or measuring N mineralisation since this is where most microbial activity occurs. Deeper sampling is required to test for initial nitrate-N and ammonium-N since wheat accesses inorganic N throughout the season. Ideally, soil is sampled to rooting depth which can be over 120cm in both sandy and clay soils in southern Australia when there are no subsoil constraints (GRDC 2009b). However, soil only needs to be sampled to 30cm in southern New South Wales and 60cm in a wide range of crops in South Australia to predicting N fertiliser requirements (Taylor *et al.* 1988, Xu and Elliot 1993a).

*Historical records*

Historical records assist in estimating the amount of N fertiliser needed for a wheat crop to meet a target grain yield. The historical records of use are those that indicate a gain or loss of N from the targeted paddock. Relevant records for most cropping systems are rotations, prior crop types and grain yields, stubble management practices and historic fertiliser applications. The relevance of leaching, denitrification and volatilisation to a particular wheat crop depends on soil type, rainfall patterns and timing of prior N fertiliser applications.

Gains or stability of soil N are indicated by a history of extensive legume-based pastures, inclusion of grain legumes in the rotation or prior use of N fertiliser (Angus and Peoples 2012, Nuttall *et al.* 2010). Wheat grown after a drought-effected crop are considered have access to residual N fertiliser and inorganic N that has not yet been mineralised due to the dry soil conditions (GRDC 2008).

Losses of soil N are expected in continuous cereal cropping systems or when there is a long-term decline in grain yields or protein content. These circumstances indicate

the next crop will be deficient in N without N fertiliser (Angus and Peoples 2012, Holford *et al.* 1992).

Stubble management in a rotation without a legume has little effect on N supply to the following wheat crop from soil and plant residue (Nuttall *et al.* 2010) with N immobilised in retain stubble and lost in burnt stubble (GRDC 2011). However, stubble management effects the nitrogen use efficiency of urea-N applied to the following wheat crop as shown in north-eastern Victoria (Newton 2001). In that high rainfall environment, stubble retention by incorporation resulted in only 16% of urea-N being accounted for in the grain compared to 24% where stubble was incorporated and 35% of urea-N where stubble was burnt.

A seemingly obvious indicator that crops require N fertiliser is N deficiency in prior crops. However, due to the strong influence of in-season rainfall and temperature on N mineralisation and crop growth, there is no certainty that N deficiency symptoms in the prior crop means N is deficient in the next crop (Angus and Fischer 1991).

*Crop testing*

Nitrogen deficiency in wheat can be corrected during the season thus monitoring crops for N deficiency is a worthwhile exercise. Electronic equipment that assesses leaf colour and sap nitrate-N testing is used to detect N deficiency before visual symptoms occur. These tests assess the crop at a particular point in time and indicate the crop's current N status. They are not predictive of future N deficiency as the season progresses and roots grown into deeper sources of N.

Tissue sampling and testing is also a valid option for diagnosing and correcting N deficiencies as wheat grows. A comprehensive description for sampling and preparing plants for tissue analysis are provided by Reuter *et al.* (1997b). Nitrogen content below the range 3.4% – 3.5% in the youngest emerged blade (YEB) at GS23-30 indicates the plant is N deficient at the time of sampling. The critical N content that demonstrates deficiency in N decreases in whole wheat plants as the plant matures (Reuter *et al.* 1997a).

# Other factors affecting availability of N to crops

## *Residual value*

Organic N in legumes, wheat and fertiliser-N is a source of inorganic N for several years in the agricultural soils of south-eastern Australia (Amato *et al.* 1987, Ladd and Amato 1986).

Field studies with a medic in South Australia shows that about 40% of legume-N is mineralised within 12 months of incorporation and 31-38% remains in the organic form after 8 years (Ladd *et al.* 1985, Ladd and Amato 1986). Mineralisation of wheat is slower that legumes at 33% mineralised over 2 years (Amato *et al.* 1987).

The rate of mineralisation is affected to a small extent by soil type with rates being slower in the soils with a higher clay content and more organic matter, and faster under higher rainfall conditions (Amato *et al.* 1987). Similar field work with urea, $(NH_4)_2SO_4$ and $KNO_3$ show that N is sourced by wheat from fertiliser-N applied in prior seasons (Angus and Fischer 1991, Ladd and Amato 1986). There is also evidence that some leaching of legume-N and fertiliser-N occurs in clay and sandy soils down to at least 90 cm. Nitrogen losses of up to 25% are attributed to leaching below 90 cm and volatilisation (Ladd *et al.* 1985, Ladd and Amato 1986).

The presence and availability of residual N in Australia supports the recommendation for growers to include some of the prior fertiliser N in their nutrient budgets when considering wheat after a season of low rainfall and poor crop growth (CSIRO 2007, GRDC 2008).

## *Soil water and temperature*

The processes in N cycling in soil are heavily influenced by temperature and water due to the role of microbes and other soil biota in mineralisation, immobilisation and denitrification (Ladd and Foster 1988, Paul *et al.* 2003). Temperatures of 25°C - 37°C are optimal for microbial activity (Jarvis *et al.* 1996) and soil temperature account for 35% of the variation in net N mineralisation rates in an environment with average annual rainfall over 1000 mm (Gill *et al.* 1995). Soil water also has an optimal range for maximising net N mineralisation that is measured in the proportion of pore spaces in soil that are filled by water (WFPS). The optimal range for WFPS is 80 – 90% (Jarvis *et al.* 1996). Where WFPS is higher than 90% and soils are water logged wheat is deficient in N. This type of situation occurs in the higher rainfall environments of southern Victoria (McDonald and Gardner 1987).

In addition to these factors that are particular to N cycling, plants in dry soil or waterlogged soil have less root growth and less ability to grow into sections of the soil profile that contain inorganic N (McDonald and Gardner 1987, GRDC 2009b). This can impede plant access to N where N is located deeper down the soil profile due to leaching (Ladd and Amato 1986).

This suggests that soil water content in between dry and waterlogged enables adequate N uptake. However, under conditions that are favourable to wheat growth such as a decile 9 year in the Wimmera (330 mm) wheat still experiences N deficiency later in the season due to the high rate of plant growth causing higher demands for N (Tilling *et al.* 2007). Combating this effect by increasing N supply early in the season leads high rates of plant growth early in the season and a depletion in soil water such that water availability is inadequate late in the season for grain fill (Tilling *et al.* 2007, van Heraarden *et al.* 1998). Thus N supply and soil water need to be balanced throughout the season for wheat to achieve maximum potential grain yield and a high harvest index.

## *Soil Physicochemical constraints*

Physical and chemical constraints restrict root growth and limit the volume of soil that roots access. This reduces the plant's access to water and nutrients, including nitrogen at depth, and leads to reduced crop growth and grain yield (GRDC 2009b). The types of physical and chemical constraints that effect wheat varies with soil type.

The chemical constraints identified in neutral and alkaline soils of south-eastern Australia are summarised by as boron toxicity, carbonate, aluminate, salinity, sodicity and alkalinity (Adcock *et al.* 2007). Alkalinity, boron toxicity, sodicity and salinity restrict root growth particularly at depths greater than 50 cm in calcarosols in the Mallee and Wimmera, and sodosols in Wimmera and central Victoria (Nuttall *et al.* 2003, GRDC 2009b). Similar constraints are present in the Calcarosols and Sodosols in South Australia with toxic levels commencing at shallower depths (GRDC 2009b). Chemical constraints identified for the higher rainfall environments of south-eastern Australia are sodicity and acidity (MacEwan *et al.* 2010). Conversely, chemical constraints are rarely found in Vertosols of the Wimmera (Dunbabin *et al.* 2009) with sodicity being of note at depths below 1 metre (GRDC 2009b).

Physical soil properties such as high bulk density, high clay content, calcrete layers or hard-setting properties also limit root growth and consequently access to water and nutrients like nitrogen. High bulk density (mean 1.6 kg/m3) and high clay content in the subsoil (mean 90%) physically restrict root growth in the higher rainfall environments of south-eastern Australia including south-east South Australia, southern and central Victoria, and the southern Highlands and Slopes of New South Wales (MacEwan *et al.* 2010). In South Australia, root growth is restricted in the Mid-North, south-east and on the Eyre Peninsula due to high clay content in the sub-soil or soil being hard-setting. Furthermore, root growth in restricted across large tracts of calcarosols in South Australia due to the presence of calcrete layers and calcium carbonate rocks in the subsoil (GRDC 2009b).

## *Effect of other nutrients on response to N*

Nitrogen, phosphorus and sulphur have a synergistic relationship with all nutrients interacting to affect the uptake and use efficiency of each nutrient in wheat (Archer 1974). Some of these interaction are caused by the lack of one nutrient restricting the growth of roots such that roots cannot physically access other nutrients (Grant *et al.* 2001). This occurs in vertosols in the Wimmera for N applied very early in the season (GS13) with root growth only proliferating when an N application is accompanied by P fertiliser (Officer *et al.* 2009).

Inadequate supply of sulphur (S) also restricts the uptake of N fertiliser when N is applied at high rates and inadequate N nutrition limits the effectiveness of higher rates of S fertiliser (Salvagiotti *et al.* 2009). Hence N use efficiency is lower when S supply in low and maximum grain yields are obtained when both N and S are applied

to wheat that is responsive to both nutrients (Muldoon 1986). The same interactions occur for N and S concentrations in wheat grain (Randall *et al.* 1981).

### *Genetics for N efficiency*

The efficiency with which wheat takes up and uses N is assessed with a range of measurements that are often modified and are ill-defined (Dawson *et al.* 2008, Rathke *et al.* 2006). Common types N efficiency used in the research and extension literature for grain production are:

- Nitrogen use efficiency (NUE) – kg grain / kg available soil N and fertiliser N (Moll *et al.* 1982).
- Nitrogen uptake efficiency ($NU_pE$)- the total amount of N in the plant / total amount of available soil N and fertiliser N (Youngquist *et al.* 1992).
- Nitrogen utilisation efficiency ($NU_tE$) – kg dry matter produced or kg grain produced / kg N taken up into the plant (Maranville *et al.* 1980).

These efficiencies of N in wheat production are genetically variable even though the exact mechanisms are not well defined (Dawson *et al.* 2008, Olson and Kurtz 1982). Conventional breeding programs have increased the NUE and $NU_tE$ of wheat throughout the world by actions such as breeding dwarf cultivars which have higher $NU_tE$ than tall cultivars (Grant *et al.* 2001, Singh and Arora 2001, Stapper and Fischer 1990).

Genetic variation in N efficiency is demonstrate in Australia through comparisons between wheat cultivars. A comparison of 33 Australian cultivars in Western Australia shows variation between cultivars for $NU_tE$ and a variant of NUE (Anderson and Hoyle 1999). Cultivars such as Tincurrin, Kulin and Amery are efficient at converting applied N to grain (mean $NU_tE$ = 39 kg/kg, mean NUE variant = 22 kg/kg) whilst Janz, Machete and Cadoux are inefficient (mean $NU_tE$ = 31 N kg/kg, mean NUE variant = 14 kg/kg). Similar $NU_tE$ is achieved with irrigated wheat in southern New South Wales (Stapper and Fischer 1990).

Interestingly, differences in N efficiency for the 33 cultivars is not related to their quality grade but is related to their efficiency at converting applied N to grain protein (Anderson and Hoyle 1999). The reasoning behind these differences are not fully understood and could be related to root growth and distribution in the soil profile.

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