# A NITROGEN REFERENCE MANUAL FOR THE SOUTHERN CROPPING REGION

**GRDC**
GRAINS RESEARCH & DEVELOPMENT CORPORATION

# Table of contents

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# FOREWORD

Nitrogen (N) is a key element of plants and how it is managed is critical for grain production and farming systems in Australia. Most of our soils are naturally low in organic matter and have a poor capacity to provide N to growing plants. Before the adoption of pasture legumes, farmers relied on mineralisation of organic matter during fallow periods to provide N to crops but this was often insufficient to meet crop demand. It was not until the development of the pasture-ley system and adoption of legumes that N supplies to the system and crop yields were boosted significantly. Over recent decades cropping rotations have intensified, pasture and livestock production have declined, and N fertiliser requirements have increased. Of concern is the fact that most cropping systems in this recent phase have been effectively mining soil organic matter and N, because the N removed in grain is not being replaced by N in fertilisers or fixed by legumes in rotation. Consequently, cereal protein levels are often low and yields are below water-limited yield potential.

Fertiliser is the single largest cost for most Australian grain growers and is dominated by N. The management of N has a major impact on grain profitability and is a key driver of crop yield and quality but can be manipulated during the growing season to manage risk. This is reflected in the GRDC Five Year Plan (2018–2023) and the following key investment targets:

**1.5** Reduce the gap between actual and potential yield through more informed and timely decision-making on: planting time, crop/variety, weed management, pest and disease control, and crop nutrition.

**2.3** Improve wheat grain protein through increased availability of N and better N-use efficiency.

**3.5** Develop technology to reduce fertiliser manufacture and/or application costs and improve fertiliser use efficiency.

**3.6** Improve N and phosphorus availability by: greater capture of value from soil biota, optimisation of nitrogen-fixing legumes in rotation, and soil amelioration to improve nutrient availability.

While our ability to measure soil N supply can be reasonably good, predictions of crop yield, N demand and therefore fertiliser N requirements are often inaccurate because these are strongly influenced by seasonal rainfall, which can vary enormously. This comprehensive manual summarises the current knowledge of all aspects of nitrogen cycling and management in farming systems in southern Australia. Grower case studies at the end of this manual provide helpful examples of different approaches to managing N by grain growers in South Australia and Victoria, many using precision agriculture techniques. This manual will be a useful reference for crop advisers and consultants, fertiliser representatives, agribusinesses and leading growers, and will help them improve fertiliser and legume N management across crop rotations, optimising profits while protecting soil fertility and the farm resource base.

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# 1  INTRODUCTION

Recent assessments have indicated that most grain cropping systems of Australia (Figure 1-1) are in negative nitrogen (N) balance (Norton and van der Mark 2016, Angus and Grace 2017); that is, more nitrogen is being exported off farm in products than is being applied as fertiliser or through biological dinitrogen ($N_2$) fixation. Therefore, soil N fertility in Australian farms is likely to be declining. While N fertiliser use in Australia has been increasing, it is unlikely to have matched the decline in area under $N_2$-fixing legume-based pastures and the associated increase in cropping in many areas. Nitrogen management is therefore coming into sharp focus.

The primary challenges are to provide sufficient N to cereal and oilseed crops such that the optimum economic yield is achieved, along with the desired grain quality (protein or oil), while maintaining soil fertility and health and not over-fertilising with N. This manual is designed to provide the background to managing these challenges in grain cropping systems of the GRDC southern region (Victoria, Tasmania and South Australia). However, it does not provide the specific prescriptive agronomic advice needed to account for individual crops, soil types, seasonal conditions and other factors.

**FIGURE 1-1  The grainbelt of Australia showing regions producing predominantly low, medium or high-protein wheats. Tasmanian grain production is <2% of the national total.**



SOURCE: ABARES 2017
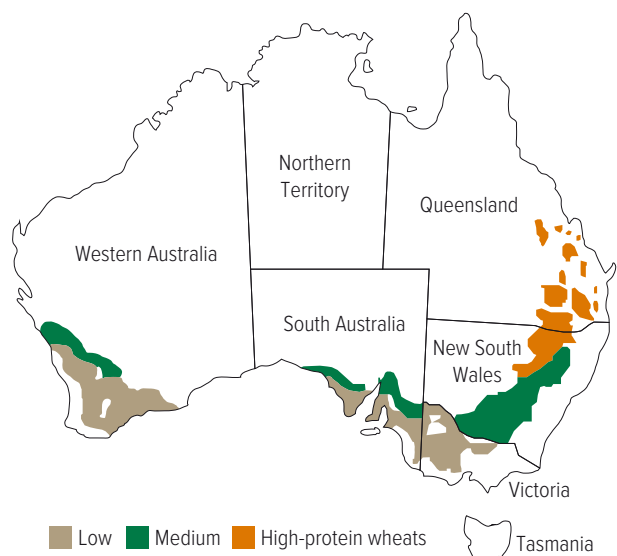
## 1.1 THE ENVIRONMENT AND FARMING SYSTEM

The southern grains region encompasses about six million hectares (ha) of cropping land across Victoria, South Australia and Tasmania (Figure 1-2), almost 30 per cent of the grain cropping area of Australia. Over most of the region the rainfall is winter dominant, with at least 65 per cent of the annual rainfall falling between April and October, although in the Victorian border region along the Murray River, in Gippsland and parts of Tasmania, the rainfall is more equi-seasonal (Figure 1-2). Annual rainfall ranges from as little as 250 millimetres (mm) along the north-western fringe of the region to as much as 700mm in the south of Victoria.

Cropping intensity varies but is about 70 per cent in the medium and low-rainfall areas, around 50 per cent in the higher rainfall zone and very low in Tasmania. For specialist grain growers, crops are overwhelmingly sown using no-till or minimum-till techniques, coupled with stubble retention. The adoption of no-till technology has been driven primarily by a desire to minimise soil erosion and structural decline, to sow crops as quickly as possible on the arrival of autumn rains, and to increase labour efficiency (Kirkegaard et al. 2011). The relatively strong winter seasonality of the rainfall means that grain cropping is very much restricted to the winter–spring period. Where irrigation is available, and in the higher rainfall parts of the southern region, some summer crops are grown for livestock feed. However, the total area of irrigated grain crops is <100,000ha. Information on management of irrigated cereals can be found in Podmore (2017).

**FIGURE 1-2** Rainfall seasonality across the crop and pasture production lands of GRDC's southern region.



Equi-seasonal

Winter dominant

SOURCE: UNKOVICH MURRAY, BALDOCK JEFF, MARVANEK STEVE (2009) *WHICH CROPS SHOULD BE INCLUDED IN A CARBON ACCOUNTING SYSTEM FOR AUSTRALIAN AGRICULTURE?* CROP AND PASTURE SCIENCE 60, 617-626.
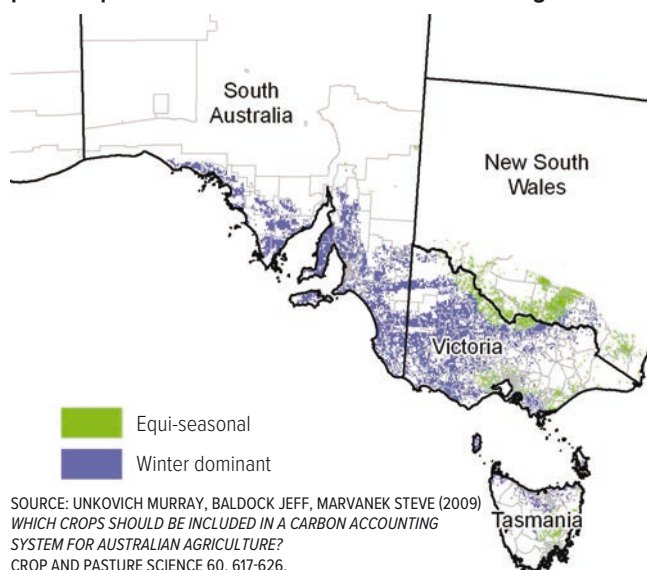
## 1.2 CROPPING SYSTEMS AND FERTILITY MANAGEMENT

Pasture and grain legumes have been important components of cereal production systems in Australia since the early 1950s, but their importance to the N requirements of cereal crops has changed over time. Before the introduction of legumes, plant-available N (nitrate and ammonium) accumulated in the soil through bare fallowing, a practice that depleted soil organic matter, damaged soil structure and led to large-scale soil erosion (Leys and McTainsh 1994, Smith and Leys 2009). Following the introduction of legume-based pastures in the 1950s, cereal yields increased substantially, due in large part to the N benefit of the $N_2$-fixing legumes.

The rotation of grazed legume pastures and cereals with applications of phosphorus (P) fertiliser developed into a characteristic mixed farming system that was generally referred to as the pasture-ley system. Net increases in soil N under the pasture ranged from 35 to 100 kilograms per hectare and reflected the productivity of the legume (Reeves 1991). This N was then used in the following years of cereal production. Soil structure also benefited from the pasture phase, resulting in enhanced water infiltration and greater plant root penetration. Although sheep hooves can cause compaction, this is very much restricted to the surface and is

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readily penetrated by standard tyned seeding implements (Bell et al. 2011). Pasture-ley system farming dominated the landscape across southern Australia for about 30 years, but its importance began to wane in the 1980s. Several factors contributed to this: a decline in the productivity of pasture legumes due to insect pests and soil acidity, increasing cereal crop diseases (particularly root and crown rots following grassy pastures), more favourable financial returns from cropping compared with livestock and the availability of several new grain legume crops.

The area of grain legumes increased dramatically between 1980 and 1987 from 0.25 million to 1.55 million hectares nationally, and by 1995 grain legume sowings had reached two million hectares. The abolition of a reserve price for wool in 1991 also forced growers to explore new cropping opportunities. The initial expansion in the early 1980s was entirely due to lupin (*Lupinus angustifolius*) in Western Australia. During the mid-1980s, both lupin and field pea (*Pisum sativum*) areas increased, and, in the late 1980s, chickpea (*Cicer arietinum*) areas expanded. In the 2000s, lentil (*Lens culinaris*) and vetch (*Vicia sativa*) sowings increased in the medium and low-rainfall areas and faba bean (*Vicia faba*) was being adopted in the high-rainfall zone.

Oilseed crops, primarily canola, became popular and by the end of the 1990s were grown on almost three million hectares nationally, coincident with the peak of grain legume sowings and before the collapse of the lupin industry in Western Australia. The relative importance of broadleaf crops has increased substantially since the 1980s in the southern region and since the late 1990s the ratio of winter cereals to broadleaf crops has remained relatively stable at about 1ha of grain legume and oilseed crops to 5ha of cereals. This increase in the frequency of broadleaf break crops, coupled with an increase in N fertiliser use and improved weed management, has led to substantial increases in cereal yields in the past two decades (Angus et al. 2001, Kirkegaard 2017). However, evidence is beginning to emerge that there has been a significant erosion in soil fertility since the decline in the use of annual pasture legume in the region (Kirkegaard et al. 2017), which will have significant implications for soil N supply and fertiliser management in the years ahead.

## 1.3 CROP NITROGEN DEMAND AND USE

Total N demand, calculated as the uptake of N from soil or fertiliser, for production of grain crops in the southern region can be estimated from crop production data (Table 1-1). While grain legumes have the ability to meet their N demands from $N_2$ fixation, they also use mineral N from the soil when it is available. Our analysis (Table 1-1) indicates that uptake of N from soils and fertiliser by broadacre crops in the southern region was at least 386 kilotonnes (kt) in 2015. At this time we do not have data on fertiliser N application to grain crops in the region, but total fertiliser usage across the three states in 2014 amounted to 516kt N (Norton 2016a): 304kt N in Victoria, 185kt N in South Australia and 27kt N in Tasmania. Although this was for all uses, most of this N would have been applied to grain crops. Regardless, in South Australia total N fertiliser use (185kt) was much less than the estimate of N from soil plus fertiliser (237kt), which implies a significant reliance on soil organic matter reserves.

## 1.4 SOILS

There is a diverse range of soil types in the southern region, with regional differences evident (Figure 1-3). Most of the Mallee area of Victoria and South Australia consists of sand hills overlying limestone deposits or heavier clays, but towards the Murray River the loam contents increase and the soils become less alkaline. Sandhill soils are prone to erosion and this risk is exacerbated if grazed. The soils are generally alkaline and very infertile and micronutrients, especially zinc, molybdenum and copper, were often required in the past. Micronutrient deficiencies have now been largely overcome and in recent times responses are much less common. The move to high analysis fertilisers has reduced incidental sulfur (S) application and this S may now need to be applied along with P and N. The decline in the use of long fallows and pasture leys since the new millennium has reduced mineral N availability in this area, as it has further south in the Wimmera. Sowings of $N_2$-fixing legumes and canola have generally been limited in the Mallee area but are increasing.

**TABLE 1-1  Area, production and approximate total crop nitrogen uptake from soil or fertiliser in South Australia, Tasmania and Victoria (2015-16).**

| Crop | Area (ha) | Grain production (t) | Crop total N (t) | Crop N from soil and fertiliser (t) |
|---|---|---|---|---|
| **SOUTH AUSTRALIA** | | | | |
| Wheat | 1,769,700 | 3,679,342 | 143,494 | 143,494 |
| Barley | 769,482 | 1,719,367 | 56,739 | 56,739 |
| Oat | 65,419 | 102,548 | 4,922 | 4,922 |
| Triticale | 17,952 | 18,487 | 887 | 887 |
| Canola | 149,169 | 218,852 | 18,165 | 18,165 |
| Lentil | 115,225 | 137,099 | 11,928 | 5,964 |
| Faba bean | 74,402 | 84,366 | 7,340 | 1,835 |
| Field pea | 114,000 | 82,100 | 7,143 | 2,857 |
| Lupin | 62,192 | 52,761 | 6,859 | 1,715 |
| Chickpea | 10,862 | 7,095 | 710 | 355 |
| **SA totals** | **3,137,541** | **6,094,922** | **258,186** | **236,933** |
| **TASMANIA** | | | | |
| Wheat | 10,545 | 53,361 | 2,081 | 2,081 |
| Barley | 5,573 | 16,453 | 543 | 543 |
| Oat | 1,875 | 4,496 | 216 | 216 |
| Canola | 983 | 1,983 | 165 | 165 |
| **Tas. totals** | **18,976** | **76,293** | **3,004** | **3,004** |
| **VICTORIA** | | | | |
| Wheat | 1,341,512 | 1,814,868 | 70,780 | 70,780 |
| Barley | 844,470 | 1,107,380 | 36,544 | 36,544 |
| Oat | 140,440 | 185,291 | 8,894 | 8,894 |
| Triticale | 14,109 | 19,076 | 916 | 916 |
| Canola | 276,634 | 287,379 | 23,852 | 23,852 |
| Other oilseeds | 2,875 | 2,431 | | |
| Lentil | 107,162 | 39,889 | 3,470 | 1,735 |
| Field pea | 54,000 | 20,600 | 1,792 | 448 |
| Faba bean | 74,454 | 57,279 | 4,983 | 1,993 |
| Lupin | 45,822 | 31,148 | 4,049 | 1,012 |
| Chickpea | 13,332 | 3,465 | 347 | 173 |
| **Vic. totals** | **2,914,810** | **3,568,806** | **155,627** | **146,348** |
| **REGION TOTALS** | **6,071,327** | **9,740,021** | **416,818** | **386,285** |

Calculated from data of Table 1-2. Total crop N = shoot N*1.4 for all crops except for chickpea where total N = shoot N*2.0.

**TABLE 1-2  Assumptions used to calculate data of Table 1-1.**

| Crop | Grain protein (%) | Grain N (kg/t) | Crop total N (kg/t grain) | N fixed (%) | Residue N (kg/t grain) |
|---|---|---|---|---|---|
| Wheat | 10.5 | 18 | 39 | 0 | 21 |
| Barley | 10 | 16 | 33 | 0 | 17 |
| Oat | 13 | 23 | 48 | 0 | 25 |
| Triticale | 13 | 23 | 48 | 0 | 25 |
| Canola | 20 | 31 | 83 | 0 | 52 |
| Lentil | 24 | 37 | 87 | 50 | 50 |
| Faba bean | 24 | 37 | 87 | 75 | 50 |
| Field pea | 23 | 37 | 87 | 60 | 50 |
| Lupin | 32 | 50 | 130 | 75 | 80 |
| Chickpea | 22 | 34 | 100 | 50 | 66 |

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**FIGURE 1-3  Soils of the southern region.**



**Australian soil classification orders**

| | | |
|---|---|---|
| Calcarosol | Kandosol | Rock |
| Chromosol | Kurosol | Rudosol |
| Dermosol | Lake | Sodosol |
| Ferrosol | Organosol | Tenosol |
| Hydrosol | Podosol | Vertosol |
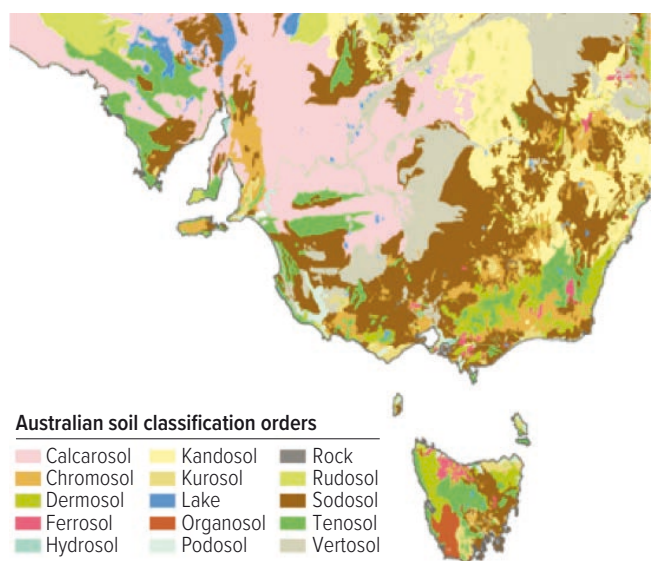
SOURCE: NORTHCOTE, K. H. WITH BECKMANN, G. G., BETTENAY, E., CHURCHWARD, H. M., VAN DIJK, D. C., DIMMOCK, G. M., HUBBLE, G. D., ISBELL, R. F., MCARTHUR, W. M., MURTHA, G. G., NICOLLS, K. D., PATON, T. R., THOMPSON, C. H., WEBB, A. A. AND WRIGHT, M. J. (1960-1968). ATLAS OF AUSTRALIAN SOILS, SHEETS 1 TO 10. WITH EXPLANATORY DATA (CSIRO AUST. AND MELBOURNE UNIVERSITY PRESS: MELBOURNE)

Soils in the Wimmera area are generally heavier (finer textured) but merge into the Mallee sands in the northern Wimmera. Heavy clay soils, including cracking clays, are common as are subsoils containing toxic concentrations of salt and/or boron; sodicity is a widespread problem in this part of the southern region. Most soils here are alkaline. Grain legumes and canola are established elements of cropping systems in the Wimmera. Subsoil constraints to root growth appear to be quite common on both coarse and fine-textured soils in the Mallee and Wimmera, substantially limiting crop water uptake and productivity (Nuttall et al. 2003, Adcock et al. 2007).

In the higher rainfall Western District, heavy grey/black soils of volcanic origin predominate. These soils are more friable than many of those in the adjacent Wimmera but crack extensively in summer. Traditionally, the region was dominated by grazing using legume-based pasture; large areas of cropping in the region is a relatively recent phenomenon. Consequently, soils still retain an N fertility legacy from the $N_2$ fixation of permanent pastures and from ley pastures that were grown in rotation with crops. Cropping intensity is lower here. Nevertheless, the high crop yields mean that considerable nutrients are being exported and there remains a challenge to meet grain crop nutrient needs in this district. During the winter the soils may be too wet for machinery to operate and this restricts opportunities for application of fertilisers during crop growth. Loss of soil nitrate through denitrification can also be a significant risk here due to prolonged waterlogging. Soil acidification can also occur due to nitrate leaching on coarse-textured soils.

Further west the soils are derived from marine deposits and become increasingly sandy. In the south-east of South Australia, water repellence is a common problem on coarse-textured soils, reducing crop establishment and nutrient availability. Some of these soils are acidic and display acid soil infertility (deficiencies of molybdenum, calcium and magnesium and toxic concentrations of manganese and aluminium). Nitrogen-fixing legumes, especially lucerne (*Medicago sativa*) and faba bean, are widely grown in this region and assist with managing N fertility.

Soil conditions improve in South Australia's Lower and Mid North, where soil texture is finer and pH more neutral, although areas of acidity occur on sandy soils across the state. Soils here are primarily loam over clay, shallow calcrete or calcareous loams with some areas of dune fields and saline land. Wind and water erosion, soil infertility, sodicity and salinity are the main soil degradation issues. Legumes and canola are frequently grown in rotation with cereals. Moving further westward and to the Eyre Peninsula, calcareous sandy soils predominate, many of which are shallow and overlay calcrete. On these calcareous soils phosphorus management (immobilisation) becomes a major focus, although the shallow rooting of crops is also a major constraint. Sandy rises are also common and, on these areas, low fertility and erosion risk are the primary management foci. In this western part of the southern region, summer rainfall is generally scant and the winter dominance of annual rainfall even more pronounced. Grain legume and canola sowings here are limited by low and unreliable rainfall and by soil constraints.

In the north-west of Tasmania, the primary cropping soils are red-brown krasnozems and rich red ferrosols of high fertility, good drainage and favourable root conditions. Trafficability when wet is often a key consideration for management of these soils, which also occur in parts of the north-east cropping area. Well-structured, self-mulching, black cracking clays are common in the Midlands and south-east but do occur throughout the cropping region. These cracking clays can form very large clods when tilled and are often also flood prone. Grey-brown 'Cressy soils' (dermosols) between Cressy and Westbury are poorly drained and make tillage a significant challenge. Texture-contrast duplex soils occur in the Midlands, south-east and Meander and Derwent valleys. Fertility can decline rapidly in these soils and waterlogging is a common problem.

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# 2 NITROGEN CYCLING IN AGRICULTURAL SYSTEMS

In land-based (terrestrial) systems, N is continually cycled between the atmosphere, where it exists in unreactive gaseous $N_2$, and the soil. In natural (non-agricultural) systems, almost all of the N moves through growing plants. In agricultural systems where fertiliser N additions increase soil N availability, some of the N is lost from the soil before the plants have had the opportunity to use it. The major loss pathways are soil erosion, denitrification (loss of nitrous oxide), ammonia volatilisation (mainly from urea) and leaching of nitrate. See section 2.4 for details of N losses. In Australian agriculture, inputs of N in fertilisers and through $N_2$ fixation are estimated to be 4.5 million tonnes annually (Angus and Grace 2017). At first glance, the N cycle (Figure 2-1) appears overly complex and unrelated to in-paddock decision-making about N. The commonly asked questions about N in farming include: How much N do legumes fix? How much N is mineralised during a fallow and in-crop? How efficiently is fertiliser N used by crops? And, how much N is lost through leaching and denitrification from soil? These may be more readily answered with a basic understanding of the N cycle, coupled with realistic local quantitative data on the rate of transformations (arrows in Figure 2-1) and sizes of pools (boxes in Figure 2-1) in the cycle.

In the following sections, the N cycle is defined in terms of the inputs, outputs and transformations important in grain cropping systems. Pasture systems with grazing animals are also important in the southern region. When animals are present, substantial amounts of plant N are recycled back into the soil in animal dung and urine.

**FIGURE 2-1  A nitrogen cycle in grains cropping, in this instance involving a legume-to-cereal sequence, showing major transformation processes, pathways and sinks.**
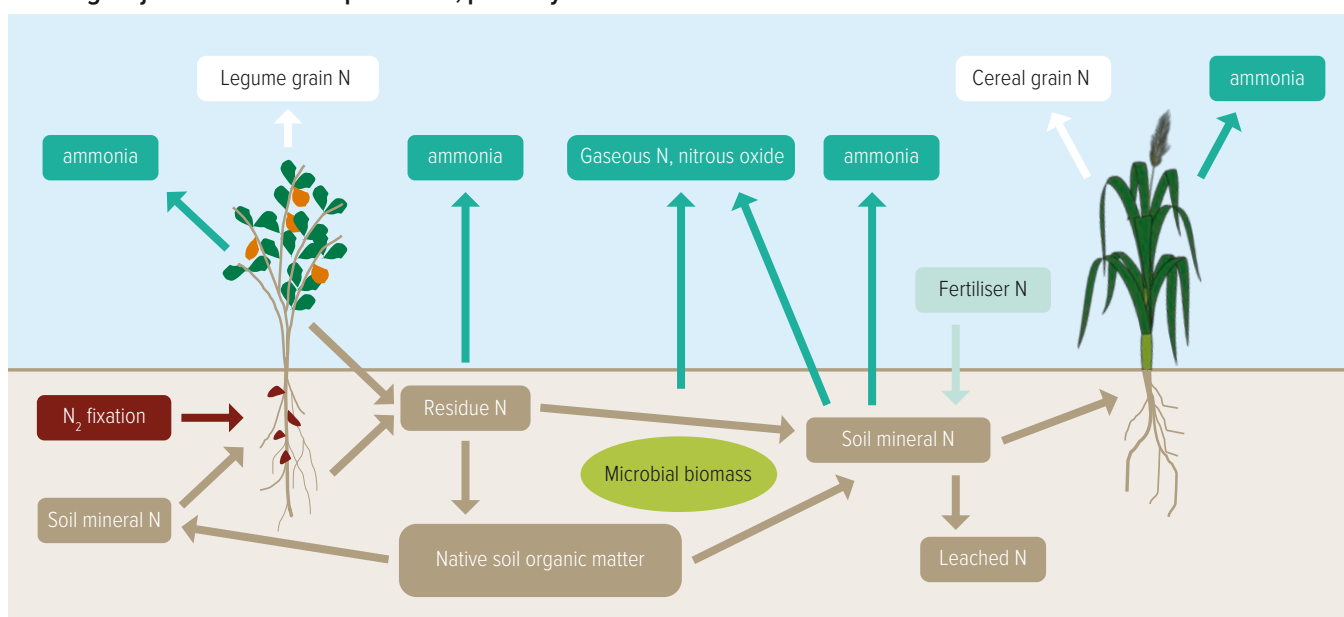
## 2.1 ADDING NITROGEN TO THE SOIL

Nitrogen can be supplied to the soil as mineral or organic fertilisers, through $N_2$ fixation by bacteria living independently in the soil (or more commonly by those associated with legumes and other plant species) and through direct deposition of N from the atmosphere. Fertiliser N and $N_2$ fixation by legumes provide the overwhelming majority of N input to agricultural soils in Australia.

### Fertilisers

In mineral fertiliser, N is present as urea ($CO(NH_2)_2$), ammonia ($NH_3$), ammonium ($NH_4^+$) or nitrate ($NO_3^-$) or a combination of these, but in all cases the same pathways of transformation, loss and plant uptake occur. Following application, nitrogen fertilisers undergo transformations that result in the N being incorporated into the soil mineral N pool ($NH_4^+$ and $NO_3^-$), incorporated into microbial biomass, taken up by plants or lost via several pathways. There are different pathways that fertiliser N may take before being absorbed by plants, therefore the efficiency of incorporation of N into soil mineral pools and then into the growing crop can vary substantially and may sometimes be quite low (see section 6).

Typically, 25 to 50 per cent of fertiliser N applied in that season is recovered in the cereal grain (Strong 1995), with 50 per cent generally regarded as efficient. The fertiliser N not only contributes to grain protein, it is also used to grow the rest of the plant, including the roots. Most estimates of fertiliser efficiency are based on short-term (for example, one season) recovery of N, but it is clear from Figure 2-1 that not all fertiliser N is taken up immediately and that N derived from fertiliser can still be taken up by plants over several pathways and years. Therefore, the concept of fertiliser efficiency can also be affected by the timeframe over which N uptake is considered. Between 50 per cent and 75 per cent of the fertiliser N applied is either lost from the system or retained in the crop residues and soil for following years.

### Biological nitrogen fixation

Biological $N_2$ fixation (termed symbiotic $N_2$ fixation) is the reduction of dinitrogen ($N_2$) from the atmosphere to form two $NH_3$ molecules and one molecule of hydrogen gas ($H_2$) as a by-product (Equation 1). The process also requires eight protons ($H^+$) and eight electrons ($e^-$). It is catalysed by the enzyme nitrogenase, which is found in specialised soil bacteria called rhizobia and occurs most intensively in the root nodules of legumes inhabited by rhizobia. The rhizobia actually fix the N, with the legume using virtually all the fixed N for plant growth. In return, the rhizobia receive both carbon (C) and N from the host plant for their growth. In $N_2$-fixing legumes, $NH_3$ is quickly converted into amino acids and other N-rich compounds in the nodules, and then transported to the shoot and utilised for plant growth.

$$N_2 + 8H^+ + 8e^- \xrightarrow{\text{nitrogenase}} 2NH_3 + H_2$$

Interestingly, this release of hydrogen gas by $N_2$-fixing legumes has been strongly implicated in some of the positive rotational effects of legumes on following crops (Dong et al. 2003, Golding and Dong 2010).

Some other types of bacteria can fix $N_2$ when living within cereals and grasses (termed endophytic $N_2$ fixation) and when closely associated with the roots of cereals and grasses (termed associative $N_2$ fixation). Some bacteria can fix N in the absence of plants (termed free-living $N_2$ fixation) (Figure 2-2).

Globally, agricultural legumes are estimated to fix 40 to 60 million tonnes of N annually (Herridge et al. 2008). The figure for Australia's legumes is close to three million tonnes, more than 90 per cent of which is fixed by pasture species (Angus and Grace 2017). On a unit area basis, the amounts fixed can be substantial, and up to 500kg N/ha/year for very high-yielding grain legume crops or legume-based pastures. More commonly, amounts are in the order of 50 to 150kg N/ha/year (see section 5).

**FIGURE 2-2  Biological $N_2$-fixing agents in agriculture.**

| Plant-associated | Free-living |
|---|---|
| • legumes–rhizobia (symbiotic) | • cyanobacteria |
| • *Azolla*–cyanobacteria (symbiotic)* | • heterotrophic bacteria |
| • grasses/cereals–bacteria (associative) | • autotrophic bacteria |
| • grasses/cereals–bacteria (endophytic) | |

\* The *Azolla*-cyanobacteria association occurs in flooded rice production systems in Asia but not in Australia.

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## Atmospheric deposition

Small amounts of atmospheric ammonia and nitrous oxide ($N_2O$) can also be assimilated directly by plant canopies. Deposition of $NO_3^-$, $NH_4^+$, nitric oxide (NO), nitrous oxide and dust on the soil in rainfall (Goulding et al. 1998, Angus 2001) also provide small but regular N inputs. In the grain cropping regions of Australia these might all add up to 5 to 10kg/ha/year.

## 2.2  NITROGEN POOLS WITHIN THE SOIL

Nitrogen can be found in different compartments (pools) in the soil, depicted by the boxes in Figure 2-1, and moves between the pools via a variety of transformation processes as described in the following sections. Detailed information about biological and chemical pools of N in soil, their measurement and interpretation for specific agricultural regions can be found on the Australian Soil Quality website (www.soilquality.org.au). The major pools of N in soil are organic matter, plant residues, dung and urine, microbial biomass and mineral nitrogen.

### 2.2.1  Soil organic matter

Soil organic matter is the organic fraction of the soil, consisting of decomposed and fresh animal and plant materials as well as the living organisms in the soil. It is, on average, 57 per cent C and about five per cent N. To convert measures of soil organic carbon (SOC) to soil organic matter (SOM), multiply the former by 1.75.

Organic matter is primarily (70 to 90 per cent) stable 'humus' material and inert charcoal, but importantly also includes 10 to 30 per cent active or 'labile' material. Humus is composed of amino acids, amino sugars and a complex of other compounds, some of which are poorly known. The labile fraction of soil organic matter is mainly in the form of decomposed plant and animal residues with 20 to 40 per cent being soil biota. Soil biota consists of fungi, bacteria, yeasts, protozoa, algae, nematodes, earthworms and a host of other soil organisms. These organisms are all part of a network in the soil, called the detritus food web. Essentially all plant residues, fertilisers, and animal dung and urine will be processed by the detritus food web.

**FIGURE 2-3**  Organic matter enhances soil structure, helps to ameliorate toxicities and facilitates efficient nutrient cycling to growing crops and pastures.
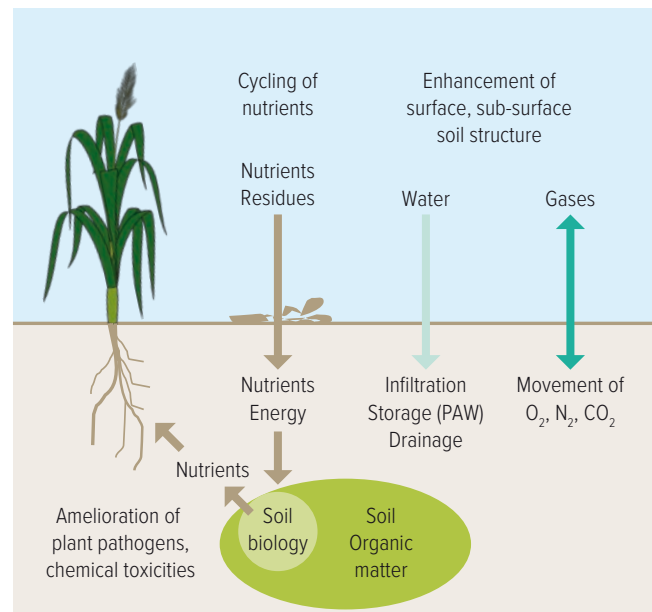


Organic matter has a critical role in soil health (Figure 2-3). It helps to ameliorate or buffer the harmful effects of plant pathogens and chemical toxicities. It enhances surface and deeper soil structure, increasing the infiltration and exchange of water and gases and soil aggregation, which also helps to reduce erosion. It marginally improves water-holding capacity of the soil and, through its high cation-exchange capacity, reduces the leaching of essential cations. Finally, and perhaps most importantly, it plays a major role in the cycling of nutrients and their delivery to crops and pastures (Skjemstad et al. 1998).

### Humification

Humification is the decomposition of plant and animal residues to relatively stable organic matter in which humic and fulvic acids dominate. The process of converting plant residues and animal manures into humus is facilitated by enzymes, either contained within the bodies of the soil organisms or released into the soil matrix. Some of the most common enzymes found in soils include cellulase (converts cellulose to glucose subunits), protease (converts protein to amino acids), urease (converts urea to ammonia and carbon dioxide) and amylase and glucosidase (convert starch to glucose) (Paul 2007).

The whole process is very dynamic – while some of the residues are being consumed and fragmented for the first time by the soil fauna, other residues have already been decomposed and ingested by soil microflora, to be in turn consumed by microfauna predators (see Figure 2-4). Eventually, the residues will have been processed to the point that they are relatively stable as humic and fulvic acids and other humic substances.

### Plant residues above and below ground

Above-ground (straw, shoots, fallen leaves) and below-ground (roots, nodules) residues remain after harvest of grain crops. Typically, the N contained in these residues range from 10 to 50kg N/ha for the above-ground and from 30 to 100kg N/ha for the below-ground material, depending on species. For many crops, including wheat, canola, field pea and faba bean, up to 30 per cent of N is below ground. In the case of chickpea and lucerne, the percentage below ground is closer to 50 per cent (for example, Unkovich et al. 2010).

**FIGURE 2-4** Decomposition of residues and manures and turnover of soil humus mediated by the soil biota in a conceptual model termed a detritus food web.



SOURCE: GUPTA AND SIVASITHAMPARAM 2003
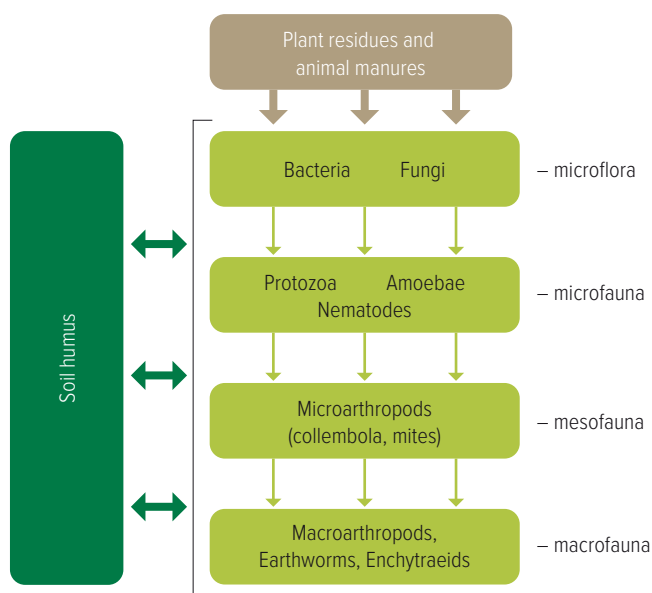
### Microbial biomass

Soil microbial biomass is the principal living part of soil organic matter (Dalal 1998), consisting of fungi (about 50 per cent of total), bacteria (30 per cent), and yeasts, protozoa, algae and nematodes (20 per cent) (Gregorich et al. 1997). Jenkinson (1977) aptly described microbial biomass as "the eye of the needle through which all nutrients pass". Essentially, all organic N that is added to soil as plant residues and animal dung, and the vast majority of inorganic (mineral) N added as fertilisers and animal urine, will pass through microbes via the detritus food web (see Figure 2-4).

The organisms may use the N for their own growth and release it to the soil environment as waste products or as they decompose after death. The bulk of microbial biomass is found in the top 30 centimetres of the soil. Typical amounts of microbial biomass N are 30 to 80kg N/ha in the top 10cm of soil, equivalent to 1 to 2t/ha biomass. More comprehensive descriptions of microbial biomass (soil biology) can be found later in section 2.3.1. Readers are referred to Dalal (1998) for a review of factors affecting the size of the microbial biomass in soils and the significance of its measurement. Useful summary information is also located on a factsheet downloadable from the soil quality website (http://soilquality.org.au/factsheets).

### Mineral nitrogen – ammonium ($NH_4^+$), nitrite ($NO_2^-$) and nitrate ($NO_3^-$)

In agricultural soils, $NO_3^-$ is the most important form of mineral N. It is usually in far higher concentrations than $NH_4^+$, particularly in the root zone, and consequently is the major form of N that plants use for growth. Typical soil tests for wheat paddocks in the southern region may show $NO_3^-$ amounts of 50 to 100kg N/ha in the top metre (m) of soil, with $NH_4^+$ less than 15kg N/ha. Greater amounts might be observed in the high-rainfall zone on soils with a long pasture legacy. Although microbial conversion of $NH_4^+$ to $NO_3^-$ proceeds quickly and efficiently in most agricultural soil, this process will be slowed in highly acid soils, resulting in more $NH_4^+$ than $NO_3^-$.

Nitrate is very soluble in water and moves principally with water movement (that is, mass flow), which makes it susceptible to losses by leaching where drainage is high. Nitrate can also

move in soil by diffusion, from an area of high concentration to an area of low concentration. In soils with a moderate to high clay content, nitrate can accumulate to as much as 200kg N/ha or more in the top one metre of soil. Nitrate can also be immobilised into soil microbial biomass or be lost from the soil through leaching, denitrification or erosion. Ammonium is less readily lost but can be immobilised by the microbial biomass.

**Dung and urine of grazing animals**

Between 5 and 25 per cent of the N of grazed pasture and fodder ends up in the body of the grazing animal, with the remaining 75 to 95 per cent expelled as dung and urine (Fillery 2001). Sheep dung contains about 1.5 per cent N and urine 5 to 6g N/L. Urine deposition results in very high N concentrations in soil under the urine patch, in the order of 150 to 300kg N/ha for sheep and 1000kg N/ha for cattle.

**Measurement of soil organic carbon and nitrogen**

Until recently, total C and N were measured in soils using the Walkley–Black (C) and Kjeldahl digestion (N) methods. Now, the preferred method for both is dry combustion analysis. Note that the Walkley-Black method (Walkley and Black 1934) only measures about 80 per cent of the C in the soil and results cannot be directly compared with those determined by dry combustion methods (Merry and Spouncer 1988, Chan et al. 2011). Where calcium carbonate ($CaCO_3$ or lime) is present in soils, it can confound soil C analysis and should be removed using sulfuric acid before measurement of the organic C pool. The weights of C and N in hypothetical soils to a depth of 10cm, with bulk densities of either 1.0 or 1.5, and organic C of one per cent and total N of 0.1 per cent, are shown in Table 2-1.

| Fraction | % | Mass (t/ha) | |
| --- | --- | --- | --- |
| | | BD = 1.0 | BD = 1.5 |
| Whole soil | 100 | 1000 | 1500 |
| Soil C | 1 | 10 | 15 |
| Soil N | 0.1 | 1 | 1.5 |

TABLE 2-1 Percentages and weights of whole soil, soil C and soil N in the top 10cm depth.

## 2.3 NITROGEN TRANSFORMATION PROCESSES

All of the soil processes associated with organic matter decomposition and N transformations are optimised in warm, moist soils (that is, 30°C and close to field capacity; Stott et al. 1986, Summerell and Burgess 1989), with good contact between the substrate (for example, crop residues) and the soil (Douglas et al. 1980). Such conditions are found in cultivated soils in which crop residues are incorporated. Rapid transformations of N are not always advantageous and the benefits of no-tillage and minimum tillage cropping are in reducing N transformations from organic matter decomposition relative to cultivation of soils (Pratley and Kirkegaard 2019).

### 2.3.1 Soil biology – making it happen

The N cycle would not function without the organisms that live in the soil, described collectively as the soil biota. This is the living part of soil organic matter. The soil organisms comprise about five per cent of soil organic matter. However, their presence and activity have a huge effect, not only on N cycling but also on the general health of the soil. The detritus food web is a network of organisms, linked to each other and to their food sources: plant residues, animal manures and soil humus (Figure 2-4; Gupta and Sivasithamparam 2007).

The smallest organisms of the food web are the microflora – the bacteria, fungi and algae. These organisms have many functions, from decomposing organic matter and releasing nutrients, principally N, P and S, to causing and suppressing plant disease. Because they are so small (0.0005 to 0.05mm), they exist in, and are protected by, very fine pores in the soil.

The microfauna (protozoa, amoebae and nematodes) decompose humus and residues and feed on bacteria and fungi. The latter function is a key step in mineralisation (release into the soil in a mineral form) of N and other elements. Their range of size is 0.005 to 0.1mm.

Even larger organisms, the mesofauna, comprising the microarthropods (collembola and mites) feed on the microfauna, releasing additional N into the soil system. The microfauna and mesofauna also feed directly on humus and residues. Their range of size is 0.1 to 10mm.

The largest organisms in the soil food web are the macrofauna, consisting of organisms such as earthworms and centipedes. These organisms are the major biological agents of fragmentation and redistribution of residues in soil. They also predate on the smaller organisms. Their range of size is 1 to 150mm. The whole process is dynamic, meaning that decomposition of soil humus and fresh residues and manures occurs simultaneously with synthesis of new humus.

The numbers of organisms in a soil are mind-boggling, particularly in the case of the microflora (bacteria, fungi and algae, Table 2-2). The numbers of the individual groups of organisms and total biomass vary with soil type (more in clay soils than sandy soils), climate (more in warm, moist climate than hot or cold dry climates) and management (more in well-managed soils with high energy organic inputs than impoverished soils).

It has been estimated that the organisms in a typical soil might produce 50 to 60 different enzymes facilitating all manner of reactions and processes, such as breaking down cellulose, hydrolysing urea to ammonia and producing plant growth–promoting hormones (King and Pankhurst 1996). The majority of the enzymes are located within living soil organisms, but they may also be located within dead cells and cell debris. Enzymes may also leak from living and dead cells and be absorbed into clay particles and humic colloids (Nannipieri and Landi 2000). What essentially drives this vast array of life and activity is energy derived from soil organic matter.

While carbon is the major driver of biological activity in the soil, soil temperature and moisture moderate this activity. Peak activity is around 30°C, falling away to nil activity as the temperature approaches zero on one hand and 60°C on the other (Paul 2007).

Although temperatures of surface soils fluctuate substantially during the course of a day, those below the surface are far less variable. For example, diurnal fluctuations of 25°C at the surface are reduced to fluctuations of about 10°C at 10cm depth and just 2°C at 20cm depth. Temperatures at 10 to 20cm depths might be near optimum for activity of the soil biota, which may nevertheless be limited by carbon or water availability.

**TABLE 2-2  Typical numbers of the various groups of biota in soil.**

| Soil biota group | Numbers per kilogram surface soil |
|---|---|
| Bacteria | Up to 10 billion |
| Fungal hyphae | Up to 100,000 |
| Protozoa | Up to 1 million |
| Nematodes | Up to 10,000 |
| Microarthropods | Up to 5000 |
| Earthworms | Up to 10 |

SOURCE: GUPTA AND ROGET 2004

Soil moisture also has a large influence on soil biology, with activity peaking near field capacity and falling away as the soil becomes drier. Significantly, biological activity still remains at around 40 per cent of maximum at permanent wilting point, when plants have essentially stopped growing. In a clay soil, wilting point coincides with a volumetric moisture content of 20 to 25 per cent, with the water held in micropores and available for the soil organisms but not for plants. In sandy soils the wilting point is found at a much lower soil water content because the water is not held so tightly by soil pores.

Most of the biological activity (50 to 80 per cent) is in the top part of the soil profile (Murphy et al. 1998, Fierer et al. 2003). The composition of the soil biota also varies with depth, in concert with changes in environment, particularly water, temperature, soil pH and aeration, and food sources and abundance (Paul 2007). For example, mycorrhizal fungi decrease substantially below 20cm depth. Abundances of gram-negative bacteria, fungi and protozoa are highest at the soil surface, while gram-positive bacteria and actinomycetes tend to show relative increases with depth. Microbes in deeper soils are more likely to be carbon limited than are surface organisms.

**Ammonification**

Ammonification is the conversion of organic substances in the soil to ammonia ($NH_3$) and ammonium ($NH_4^+$) by energy-requiring (heterotrophic) microorganisms. The rate at which it occurs depends on soil conditions and is accelerated by conditions that are suitable for microbial activity, that is, moist soil, moderate temperature, contact between the organic matter and the soil and a low carbon-to-nitrogen (C:N) ratio of the organic matter.

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## Nitrification

Nitrification (Figure 2-5) is the conversion of $NH_3$ or $NH_4^+$ to $NO_3^-$. It is a three-step process. In the first step, the soil bacterium *Nitrosomonas* converts $NH_4^+$ to hydroxylamine ($NH_2OH$) and thence to nitrite ($NO_2^-$). A different bacterium, *Nitrobacter*, is then responsible for converting the $NO_2^-$ to $NO_3^-$.

Nitrification occurs under much the same conditions as ammonification, but the rate of nitrification decreases below pH 5 and almost ceases by pH 4.

The processes of ammonification and nitrification are together termed mineralisation. Fresh crop residues, animal manure and humus are all subject to mineralisation. Rates of mineralisation are determined by rainfall and soil moisture conditions (the higher the rainfall, generally the higher the rate), by the quality of the residues and manures (generally the higher the percentage of N the better), and N mineralisation generally increases following cultivation of soils (Powlson 1980).

**FIGURE 2-5  Nitrification process.**

| Nitrification |
|---|
| $NH_4^+ \Rightarrow NH_2OH \Rightarrow NO_2^- \Rightarrow NO_3^-$ |

$NH_4^+$ – ammonium; $NH_2OH$ – hydroxylamine; $NO_2^-$ – nitrite; $NO_3^-$ – nitrate
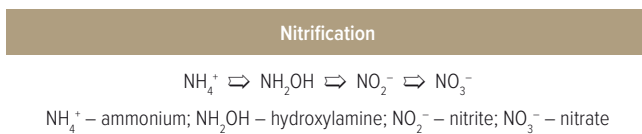
## Immobilisation

The organisms that make up the soil biota have basic requirements for C (for energy) and N (to build amino acids and proteins), and these are supplied as soil organic matter is broken down and metabolised. The incorporation of both $NO_3^-$ and $NH_4^+$ into microbial biomass is called immobilisation, and the amount of immobilised N depends on the C:N ratio of the substrate. Immobilisation of N occurs when plant residues with high C:N ratios are broken down in the soil by the soil biota (Angus 2008). Both humus and the bacteria and fungi that create humus have C:N ratios about 11:1 or less. Where the C:N ratio of residues is greater than about 20:1, there will be a requirement for mineral N by microbes to break down the residues, and hence immobilisation of mineral N if it is available in the soil. If no mineral N is available, residue decomposition will be slowed.

Net immobilisation of mineral N is normally transitory (days to weeks). Immobilisation ceases once the C:N ratio of the residues has been reduced sufficiently, and is followed by the release of mineral N to the soil. Immobilisation of fertiliser N can be longer lasting if the fertiliser is applied in close proximity to residues with high C:N ratios because the residue provides a high C source that needs a supply of N for it to be broken down and incorporated into the microbial biomass. The fertiliser N would then be a ready source of N for the microbes and for incorporation into humus.

## 2.4  LOSING NITROGEN FROM THE SOIL

Substantial amounts of N can be lost from the soil, either in gaseous form or leached as $NO_3^-$. Nitrogen can also be lost through erosion of topsoil that is rich in organic matter. Stubble management also influences losses of N from soil. For dryland cropping in the southern region the burning of stubble causes gaseous losses of approximately 4kg N/t of wheaten stubble burnt, with average losses of 15 to 26kg/ha of N in high-yielding areas (Scott et al. 2010).

### Gaseous nitrogen losses – $NH_3$, $N_2$, NO and $N_2O$

Gaseous N is present in the soil–plant–air system as ammonia ($NH_3$), dinitrogen ($N_2$), nitric oxide (NO) and nitrous oxide ($N_2O$). By far the most common form is $N_2$, which makes up about 80 per cent of the Earth's atmosphere. Each of these gaseous forms of N is associated with input ($N_2$ in biological $N_2$ fixation) and loss pathways of the terrestrial N cycle ($NH_3$ in volatilisation; NO and $N_2O$ during nitrification; $N_2$, NO and $N_2O$ in denitrification). The major issues with gaseous emissions of N via denitrification and nitrification are the cost to the grower of the loss of potentially plant-available N from the soil and the contribution of nitrous oxide to greenhouse gases (see section 6.2).

### Denitrification

Denitrification (Figure 2-6) is the reduction of $NO_3^-$ by soil microorganisms to nitric oxide, nitrous oxide and $N_2$ under low or no (anaerobic) oxygen conditions. The soil microbes use the $NO_3^-$ and nitrite ($NO_2^-$) ions in place of oxygen as terminal electron acceptors for respiration.

The process requires low oxygen conditions, a C energy source, $NO_3^-$ and moderate–high soil temperature. The low oxygen conditions usually result from waterlogging or very high soil water content. The losses are potentially greatest in flooded soils in the tropics, such as in rice paddies. In Australia, denitrification is considered to be more of a problem in subtropical and tropical agricultural regions (De Antoni Migliorati et al. 2014, Schwenke et al. 2016, Wang et al. 2011) and in irrigated farming systems (Scheer et al. 2012), than in the rainfed agriculture of the southern and western grains belts (see also section 6.2).

However, denitrification is a potential problem across all rainfall zones on vertosols (black, cracking clays) and texture-contrast or duplex (sand-over-clay) soils. This is because the low hydraulic conductivity of clay can lead to transient waterlogging and reduced oxygen in soils, conditions that are ideal for denitrification. Since denitrification is primarily a result of biological

**FIGURE 2-6  Denitrification process.**



NO$_3^-$ – nitrate; NO – nitric oxide; N$_2$O – nitrous oxide; N$_2$ – dinitrogen
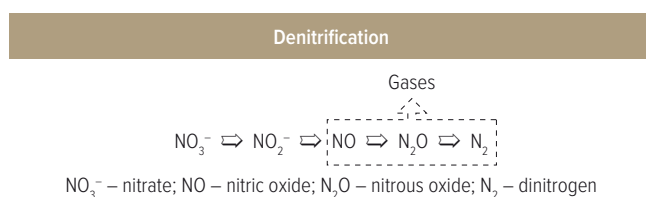
activity, microbial growth may be very limited under cold winter conditions and denitrification is thus more likely under warmer autumn and spring conditions in the southern region.

**FIGURE 2-7  Nitrification in aerobic soils.**



NH$_2$OH – hydoxylamine; NO$_2^-$ – nitrite; NO – nitric oxide; N$_2$O – nitrous oxide
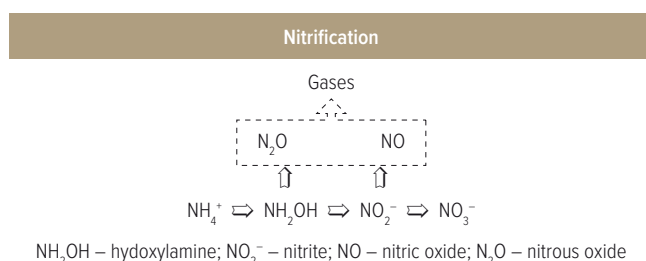
**Nitrification**

In aerobic soils, N can be emitted as NO and $N_2O$ as by-products of nitrification (Figure 2-7). The amounts of N lost through this pathway are generally very small.

**Volatilisation of ammonia from crop canopies and crop residues**

Volatilisation of ammonia ($NH_3$) from standing crops can occur throughout the life of a crop, but increases with elevated temperature, stress conditions and high tissue N content (Jenkinson 2001, Jensen and Hauggaard-Nielsen 2003). However, loss of $NH_3$ from crop canopies is usually only significant during crop maturation when leaves are senescing and N is being translocated to grain. Volatile N loss from crops can be of the order of 10 to 20 per cent of crop shoot N. This is not something that can be readily managed but might be important to consider when constructing crop N budgets.

Emissions of $NH_3$ from crop residues during decomposition are generally low but may be significant with N-rich materials under certain circumstances. If plant residues are burnt, regardless of the burn temperature, 90 per cent of plant N will be either volatilised as $NH_3$ or released as oxides of nitrogen (Scott et al. 2010). Ammonia is heavier than air and tends to have a relatively short residence time in the atmosphere (hours or days) and can be reabsorbed by soils or plants (Jenkinson 2001) at varied distances from where it was emitted, determined largely by prevailing winds.

**Leaching**

Leaching losses may be significant in coarse-textured (sandy) soils in high-rainfall areas during protracted periods of rainfall (see section 6.2) or following a single intense rainfall event on coarse-textured soils. Drainage is much less likely on soils with >25 per cent clay where the soil water storage capacity is much higher and the hydraulic conductivity lower.

## Erosion

One loss pathway that is not shown in Figure 2-1 is wind or water erosion. In certain circumstances, this can be substantial, for example, on sloped or cultivated land or by wind erosion on sandy soils. Erosion is insidious in that the process selectively removes organic matter and fine soil particles and each tonne of lost soil may contain 1kg N, mainly in the organic form. Thus, soil erosion losses of 1mm of topsoil move around of 15 tonnes soil per hectare, which equates to N loss of 15kg/ha.

Management has a large effect on erosion losses, particularly the treatment of crop stubbles in relation to soil surface cover (that is, removal versus retention, mulching or incorporation). With reduced or no-till practices across the southern region now at 80 to 90 per cent (Llewellyn et al. 2012, Pratley and Kirkegaard 2019), the annual wind erosion risk index in South Australia (McCord and Payne 2004) has been reduced over the past decade from 90 to 25 days per annum (Department for Environment and Water 2017).

**TABLE 2-3 Approximate grain protein and amount of N exported in one tonne of grain at harvested moisture content for a range of crops.**

| Crop | Grain protein % | kg N/t grain |
|------|-----------------|--------------|
| Wheat | 10.5 | 18 |
| Barley | 10 | 16 |
| Oat | 13 | 23 |
| Canola | 20 | 31 |
| Chickpea | 22 | 34 |
| Field pea | 23 | 37 |
| Faba bean | 24 | 37 |
| Lentil | 24 | 37 |
| Lupin | 32 | 50 |

## 2.5 HARVESTING NITROGEN

### Grain

Substantial amounts of N are removed from the field in grain of harvested crops. Nitrogen concentrations in grain at field moisture content vary from about 1.4 per cent (eight per cent protein) for biscuit wheats, to 2.3 to 2.6 per cent (13 to 15 per cent protein) for prime hard wheats, 3.5 per cent (22 per cent protein) for chickpea, to greater than five per cent (>30 per cent protein) for lupin. In cereals, grain protein concentrations are strongly influenced by N supply and seasonal conditions as much as by genotype. The amounts of N removed in the harvested grain may be approximated from Table 2-3 by multiplying the grain yield by the N in grain. This shows that for each tonne of yield there would be an export of 18 (barley), 20 (wheat), 42 (faba bean) or 32kg N/ha (lupin) in the grain.

The amount of N exported in grain does not represent the total N uptake of the crops as there will be considerable N remaining in crop residues, both shoots and roots (Figure 2-8). Residues from cereals contain less than 50kg N/ha for a 2t/ha wheat crop; legume crops would generally be more than double this at 2t/ha.

### Shoot biomass cut for hay, silage

Many crops and pastures are cut for hay or silage. The N or protein content of the hay will largely depend on the maturity of the crop/pasture when cut, but some example protein percentages and N yields from hay cutting are given in Table 2-4.

### Meat and wool

In rainfed grazing systems, the harvested products are primarily meat and wool and the amounts of N transferred out of the system are typically only 5 to 50kg N/ha/year (Fillery 2001, Peoples and Baldock 2001) because most of the N ingested by animals is excreted as dung and urine.

**FIGURE 2-8  Approximate amount and distribution of N at harvest for one tonne grain yield for commonly grown crops. Root N accounts for 30 to 50 per cent of crop total N depending on species.**

N at harvest for 1t grain yield (kg N/ha)



■ Root N  ■ Shoot residue N  ■ N in 1t grain
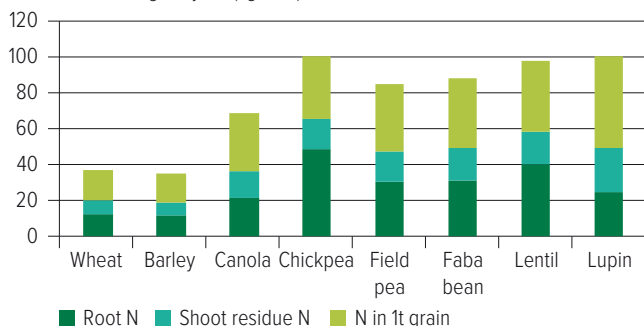
**TABLE 2-4  Approximate N harvested (kg/t at field moisture) from cutting crops or pastures for hay at around mid-flowering unless otherwise indicated. Values for hay would be higher for earlier harvested material and lower for later harvested material.**

| Crop | Protein % dry matter (DM) | N yield kg/t |
|---|---|---|
| Lucerne hay | 15 | 24 |
| Vetch hay | 15 | 24 |
| Field pea hay | 15 | 24 |
| Field pea straw | 5 | 8 |
| Canola hay | 18 | 29 |
| Oat hay | 5 | 8 |
| Barley hay | 10 | 16 |
| Wheat hay | 10 | 16 |
| Wheat straw | 1 | 2 |

# 3 NITROGEN AND PLANT GROWTH

The N concentration of plant tissues varies from one to five per cent. Protein, which contains 16 to 18 per cent N, constitutes 80 to 85 per cent of the N in plants. Proteins are the building blocks of plant growth. They serve a range of functions including storage, such as the storage proteins found in seeds, enzymes involved in plant metabolism, transport proteins that move ions and molecules across cell membranes, and photosynthesis. Without an adequate supply of N, plant growth is severely impaired.

The N requirement for early seedling growth comes from the N stored in the seed. During germination protein is broken down into amino acids, which are used to support the growth of the plant until the seedling roots become functional and are able to take up sufficient N from the soil to meet the seedling N requirements.

Nitrogen promotes vegetative growth and common responses to increasing supplies of N include increase in tillering and branching, increase in leaf size and crop leaf area and delay in leaf senescence. Leaf chlorophyll content is also sensitive to the N concentration of leaves and high N increases leaf chlorophyll and greenness. The net result of adding N is a larger and greener leaf canopy, a longer leaf area duration and higher crop growth rates. This will improve yield as long as there is sufficient moisture to sustain the higher crop growth without causing moisture stress during key periods of development.

Plants take up N mainly as an inorganic ion (nitrate or ammonium) by the roots but, to use the N for growth, the mineral N needs to be converted into a range of organic molecules such as amino acids and proteins. The starting point of these metabolic reactions is ammonium. The uptake and assimilation of N requires considerable expenditure of energy and the provision of C skeletons for the synthesis of these organic molecules. Consequently, the rate of assimilation of N is closely linked to the rate of photosynthesis. Assimilation of mineral N into amino acids can occur in the roots and the leaves; where this occurs can vary among plant species and depends on the supply of N. The largest proportion of protein in plants is rubisco, the protein responsible for photosynthesis in the green tissues of the plant. Approximately 40 per cent of the protein in green tissue is rubisco.

Nitrogen is mobile within plants and it moves between different plant parts in response to changes in N supply and demand. The movement of N from leaves is largely a result of the degradation of rubisco and mobilisation of N from the leaves causes an inevitable loss of photosynthetic capacity. During a plant's life cycle, mobilisation of N occurs continually as a response to changes in the patterns of growth and the availability of soil N. When N is mobilised it generally moves from mature plant tissues to the actively growing parts of the plant.

In annual plants, the end of the life cycle is characterised by senescence of the leaves and stems when most of the N in the vegetative tissue is remobilised to the grain. Here it is stored as protein and used to support the growth of the germinating seed and early development of the seedling in the following season.

## 3.1 NITROGEN UPTAKE

Nitrogen can be taken up by plant roots and through the foliage, although root uptake is the primary pathway. Plants can take up different forms of N, including nitrate, ammonium, urea, amino acids, amines and amides. The relative importance of the different forms of N varies with plant species and the environmental factors that influence the chemistry of N in soil.

### Uptake from soil

Crop plants take up N from the soil solution mainly as nitrate and ammonium, although they are also able to take up simple organic forms of N. In most soils, the concentration of nitrate is about 10 times higher than that of ammonium and so nitrate uptake dominates discussion of N uptake by plants. In highly acidic soils (pH<5), however, $NH_4^+$ concentration can exceed that of $NO_3^-$. Soil moisture content is an important factor in the availability of N to plants, because of its influence on the rate of mineralisation of organic N, the movement of N through the soil to the root surface, and root growth.

The concentration of mineral N in soil may vary over a 100-fold range. Plants have evolved several mechanisms to cope with this heterogeneity: they have a high degree of plasticity in root growth and they possess uptake systems for nitrate and ammonium that have different affinities for mineral N, allowing N to be taken up over a wide range of concentrations. The relative importance of these two adaptive features may change with the availability of N. When N is abundant, the size and distribution of the root system may be less important in exploiting soil N than the physiological properties of roots that control uptake and assimilation of N. This is because nitrate-N is mobile in the soil and so it can move to the root surface in solution as water is taken up by plants, and because N can move rapidly within the plant once it is taken up. When the supply of N is low or if root growth is restricted by some other soil property, root characteristics may become more important.

The amount of soil N affects root morphology. When N is abundant, the ratio of root growth to shoot growth (the root:shoot ratio) is lower than when the N supply is low. Root growth will also respond to the spatial variation on soil N and roots will proliferate in patches of soil with high N.

The predominant form of N taken up by plants can influence the chemical characteristics of the rhizosphere – the small column of soil that surrounds the root axes where the root can affect the soil environment. When plants are only supplied with ammonium N the rhizosphere will acidify; when fed with nitrate the rhizosphere will become more alkaline; and when fed a mix of both ammonium and nitrate the pH change will reflect the relative uptake of the two forms of N. These changes in pH in the soil immediately next to the roots have the potential to change the availability of other nutrients in the rhizosphere. However, the changes are likely to be localised to the immediate vicinity of the root surface and the magnitude of the change will very much depend on the pH buffering of the soil.

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## Foliar uptake of nitrogen

Nitrogen can enter the plant through the green leaves and stems. Foliar application has the advantage of bypassing the root uptake pathway, which may lead to a more rapid response to N. The leaves have a waxy outer covering – the cuticle – that helps them to retain moisture and remain cool. It also acts as a barrier to the entry of foliar sprays. Nevertheless, the main pathway of entry of foliar N is through pores in the cuticle that allow the N solution to move through the cuticle into the leaf. Many of these pores are near the stomata; the density of pores may be related to stomatal density on the leaf surface. Uptake is often greater on the underside of the leaf where there are more stomata. Uptake can be rapid and is affected by factors such as the size of the leaf canopy, thickness of the cuticle and the use of adjuvants.

The method of application, such as droplet size and water rate, can also influence uptake. Cuticle thickness is greater when leaves are older and if they have been exposed to stress, such as heat and water stress, uptake will be slower. Conversely, uptake by young green leaves can be high because of the thin cuticle; toxicity symptoms first appear on the youngest leaves. The effect of some adjuvants on uptake is shown in Table 3-1. Nitrogen that is not intercepted by the leaf canopy and reaches the soil can enter the plants through root uptake and, in small canopies or where there is a considerable amount of runoff from the leaves, this may be more important than direct uptake by the leaves.

## Nitrogen losses from plants

Movement of N occurs both into and out of plants. Efflux (release) of nitrate and ammonium occurs from the roots during growth. Nitrogen can also be lost from the leaves of plants as volatilisation of ammonia and amines. Ammonium in leaves is a natural by-product of photorespiration and the magnitude of the losses depends on the balance between N accumulation and N assimilation. Volatilisation losses peak during the grain-filling period and coincide with the degradation of leaf protein during senescence. Losses may also be greater under high N rates. Estimates of N losses from plants are variable but are generally small, with post-anthesis losses from <1kg N/ha up to 15kg N/ha being measured in wheat and barley.

## 3.2 NITROGEN ASSIMILATION

Once nitrate and ammonium are taken up by plants they can be reduced to amino acids, stored or transported to other parts of the plant. Plants have a limited capacity to store and transport ammonium because it is toxic at high concentrations and it needs to be converted quickly to amino acids after uptake, which occurs mainly in the roots. On the other hand, considerable amounts of nitrate can be stored in plant tissues and freely transported to other parts of the plant.

| TABLE 3-1 The effect of adjuvant type applied as 0.1% solution with foliar-applied urea solution (15kg N/ha) on the disappearance of N from the surface of cereal leaves. The loss of urea is assumed to be due to absorption of urea. | | |
|---|---|---|
| Adjuvant type | | Time for 50% of urea to disappear from surface of leaf (hours) |
| None | | 48.6 |
| Spreader | Organosilicone surfactant | 1.4 |
| Penetrant | Soya lecithin based | 1.5 |
| Sticker | Latex based | 44.4 |

To synthesise amino acids, nitrate first needs to be converted to ammonium in a series of reactions. Nitrate is reduced initially to nitrite by the enzyme nitrate reductase, which requires cobalt (Co) and molybdenum (Mo) to function. Therefore, an effect of Mo deficiency is that nitrate reduction can be slowed and nitrate may accumulate in plant tissues. The enzyme nitrite reductase then reduces nitrite to ammonium, which is used to produce amino acids through a complex biochemical pathway. Irrespective of the source of N (mineral N or $N_2$ fixation) the pathway of protein synthesis from ammonium is the same.

The production of amino acids from simple mineral forms of N requires considerable amounts of energy and supply of C skeletons to form the backbone of the amino acids; therefore, high rates of photosynthesis drive the assimilation of nitrate and ammonium. The nitrate concentrations in the plant reflect the balance between the supply of N from the soil and the ability of the plant to assimilate the N. For example, as the supply of soil mineral N increases, the capacity to assimilate becomes more limiting and nitrate concentrations may increase in plant tissues. Similarly, when rates of photosynthesis are low, the plant's ability to assimilate the mineral N is also reduced and nitrate concentrations may increase in plant tissues. Consequently, nitrate concentrations in plant tissues can show significant changes over the course of a day and variation from day to day.

## Nitrogen and plant composition

Increasing the N supply to plants, and its uptake, will increase the protein concentration of plant tissue and may alter the carbohydrate composition of the leaves and stems. The strong interrelationship between N assimilation and photosynthesis means that the N nutrition of a plant can influence the relative amounts of structural and non-structural carbohydrates. The sugars that are produced from photosynthesis are used to synthesise structural compounds, metabolic compounds and storage carbohydrates (starch, water-soluble carbohydrates) as well as contributing to N assimilation. The changes in composition associated with changes in supply of N reflect the competition for photosynthate among these different metabolic pathways. Adding N fertiliser can lead to a reduction in the concentration and amount of water-soluble carbohydrates and an increase in structural compounds such as cellulose and lignin (Figure 3-1).

**FIGURE 3-1** The relationship between (a) the concentration of protein and fructans in three winter cereals and (b) the concentration of protein and the amount of water-soluble carbohydrates (WSC) or structural biomass in wheat caused by different N fertiliser rates.

a)

Tissue fructan (%)

SOURCE: BATTEN ET AL. 1997

b)

Structure and WSC (g/m²)

SOURCE: VAN HERWAARDEN ET AL. 1998B

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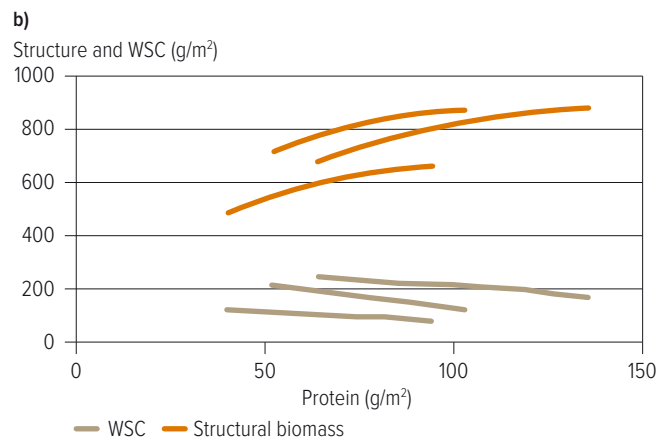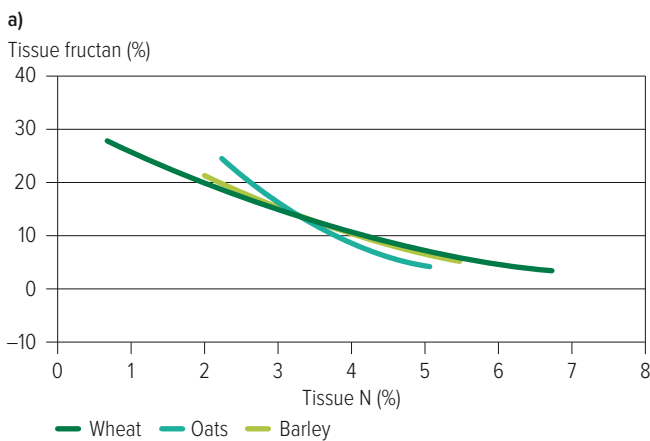
Storage carbohydrates act as C reserves that help plants maintain growth and fill grain under stress. When net photosynthetic production is high, storage carbohydrates can accumulate in leaves and stems, and when net photosynthetic production is low, these reserves can be used to sustain growth. In cereals, storage carbohydrates accumulate before flowering and during early grain fill and are remobilised and used during grain fill. Tolerance to heat and water stress have been linked to the ability of plants to accumulate and use stored reserves of carbohydrates. High rates of N may reduce the amount of these carbohydrate reserves in the stems and so reduce the ability of the crop to cope with stress during flowering and grain fill.

## 3.3 PATTERNS OF NITROGEN UPTAKE IN CROPS

Uptake of N depends on the growth rate of the crop and shows a characteristic sigmoidal pattern of accumulation over the growing season (Figure 3-2). In the case of wheat, N uptake relative to dry matter accumulation tends to be greater early, but nevertheless the maximum daily uptake of N corresponds to the period of maximum growth rate during stem elongation. By the start of stem elongation, the crop may have accumulated about 50 per cent of its total N and by flowering about 90 per cent of the N may have been accumulated (Figure 3-2). In southern Australia, the slowing in N uptake after anthesis is often due to the drying of the soil, which reduces mineralisation of organic matter and movement of

N in soil, a reduction in root growth and a decline in crop demand. Losses of N after flowering have been measured and this is generally attributed to the loss of leaves as they senesce. The pattern of N uptake may vary with seasonal conditions; for example, in a dry spring that curtails growth, a higher proportion of the total crop N may have accumulated by stem elongation and anthesis, while mild growing conditions after anthesis may allow N uptake to continue for longer.

This pattern of accumulation means that about 50 per cent of the total crop N is taken up by the start of stem elongation, with most of the remaining N accumulated during stem elongation, before flowering (Figure 3-3).

### Nitrogen remobilisation

Nitrogen is a mobile element and it can be moved from one part of the plant to another in response to changes in N supply and demand. The N is derived from the breakdown of protein in plant tissues. The general pattern is for N to move from older, mature tissue to young, rapidly growing tissue or from weaker tillers and branches to the dominant stems in the plant. This recycling of N helps to maintain growth of the plant when the supply of N is low. The other time when N is recycled in this manner is after canopy closure, when the lower leaves and young tillers in the canopy are shaded and senesce. When under stress the youngest and least developed parts of the plant will die and much of the N from these tissues will be mobilised to the more dominant plant parts.

**FIGURE 3-2** The general pattern of dry matter accumulation and N uptake by a wheat crop during a growing season. The time of flowering (F) is indicated.

Proportion of final biomass or uptake (%)



SOURCE: M UNKOVICH UNPUBLISHED
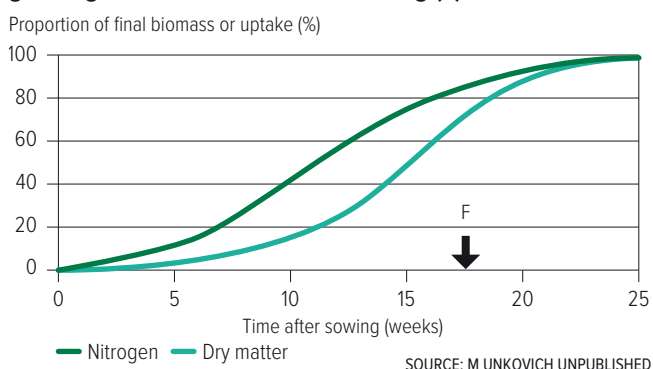
**FIGURE 3-3** The proportion of final crop N accumulated at tillering (growth stage (GS) 22; n=3), stem elongation (GS30; n=11) and flowering (GS65; n=22). Error bars are the standard deviations. The values are based on N uptake in N rate published experiments from NSW and SA and n=the number of studies from which the data were obtained.

Nitrogen uptake (% total uptake)



SOURCE: M UNKOVICH UNPUBLISHED
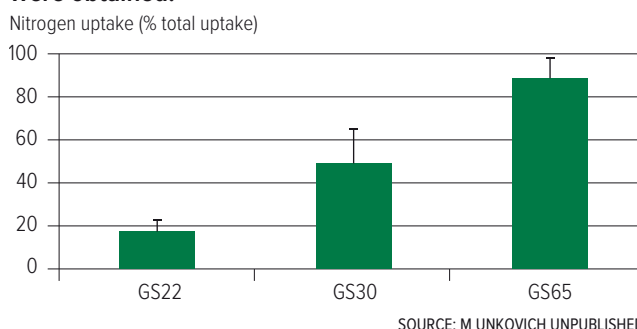
**FIGURE 3-4  The distribution of dry matter and nitrogen among different plant parts of irrigated wheat at (a) flowering and (b) maturity.**



a) Flowering

Root ■ Stem ■ Live leaves ■ Dead leaves ■ Head

b) Maturity

Root ■ Stem ■ Dead leaves ■ Chaff ■ Grain

SOURCE: HOCKING 1994
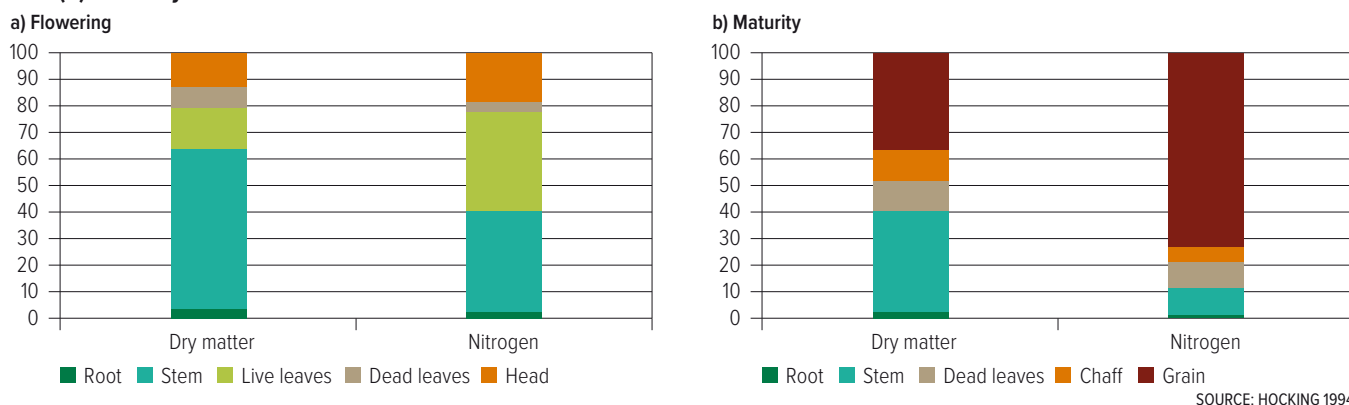
Using wheat as an example, the distribution of dry matter and N at flowering illustrates the importance of the green leaves to the total N of the crop (Figure 3-4a). Together, the green leaves and stems make up about 80 per cent of the dry matter and the N content of the crop, but the leaves only make up about 15 per cent of the dry matter compared with about 40 per cent of the crop N content. The roots are often shown to account for <30 per cent of the total crop N but this may be an underestimate as it is very difficult to recover all of the root-derived N when soil sampling.

### 3.3.1  Canola and other crops

Crops such as canola tend to have a high early requirement for N. For the grain legumes, the patterns of N and dry matter accumulation are reasonably similar and crop N will be derived from $N_2$ fixation and the soil almost to maturity. For canola, the period of N uptake is greatest between the rosette stage and the start of flowering when the accumulation of N is much greater than that of

dry matter (Figure 3-5). At the rosette stage more than 40 per cent of the total N may have been taken up in contrast to just 25 per cent of the crop biomass (Figure 3-5). By the start of flowering, when the crop has produced approximately 50 per cent of the final dry matter, 60 to 90 per cent of its N has been accumulated and by podding 80 to 90 per cent of final N may have been taken up (Figure 3-6). This pattern of N uptake highlights the importance of the early supply of N to the crop to support growth during the critical stem elongation phase.

The different patterns of dry matter and N accumulation mean that growth during the period of flowering, pod set and seed growth relies largely on the mobilisation of N taken up before the start of flowering. In canola and pulse crops the pod walls play important roles in recycling of C and N to the developing seed. Canola can also lose substantial amounts of N from leaf drop during pod development and in many cases there may be a reduction in total shoot N during this period (Figure 3-5).

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**FIGURE 3-5  The relative accumulation of dry matter and N in canola at two sowing times and supplied with 75kg N/ha. The growth stages are stem elongation (SE), start of flowering (SF) and end of flowering (EF).**
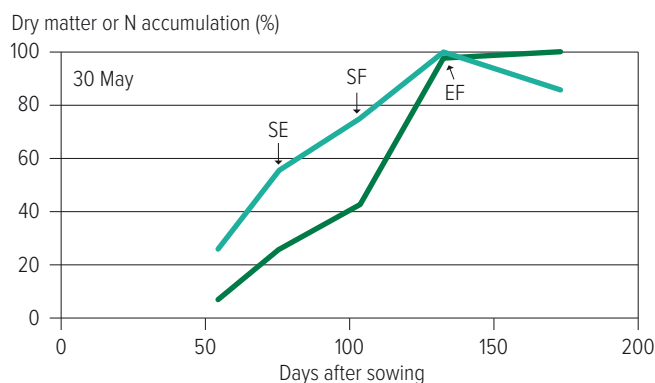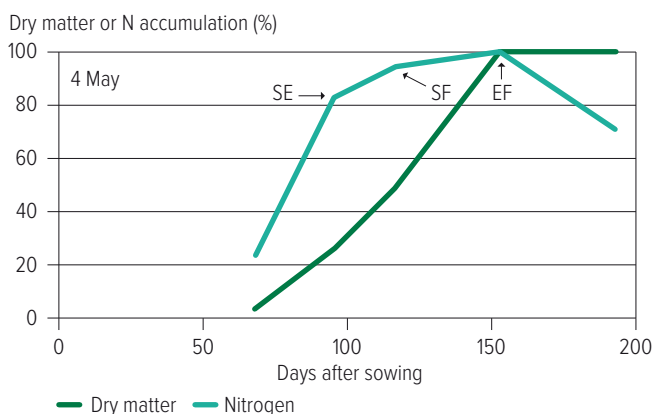


SOURCE: BASED ON HOCKING AND STAPPER 2001

## 3.3.2  Sources of nitrogen for grain fill

For cereals, the N required for grain development and protein accumulation comes mainly from the mobilisation of N from the stems and the leaves, especially the upper leaves of the plant (Figure 3-4b). Between 70 and 80 per cent of N in the leaves and stems may be mobilised between flowering and maturity, compared with 20 to 30 per cent of the dry matter (Table 3-2). The leaves may contribute 30 to 40 per cent, the stems 20 to 30 per cent, the glumes about 20 per cent and the roots about 10 to 15 per cent of the N translocated to the grain.

Only the upper few leaves may still be green by the start of grain fill and so the N content of these leaves greatly affects the protein of the grain. Boosting leaf N content by higher rates of N or delayed applications of N will contribute to higher grain protein.

**FIGURE 3-6  The proportion of final crop N accumulated at the rosette stage (GS30; n=2), the early 50% flowering (GS60–65; n=4) and end of flowering-maximum podding (GS67–75; n=4). Error bars are the standard deviations. The values are based on N uptake in N rate published experiments and n=the number of studies from which the data were obtained.**
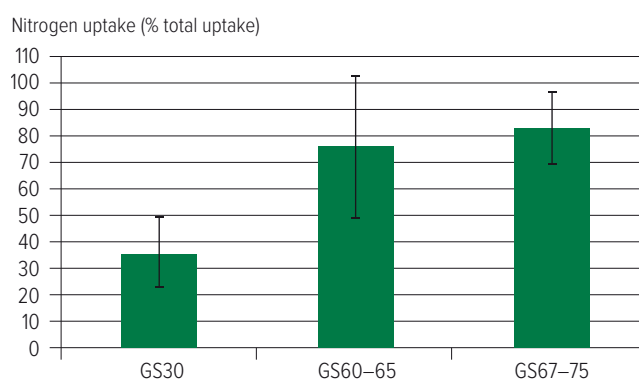


**TABLE 3-2  The percentage of dry matter and N from the leaves and stems after anthesis mobilised to developing grain in irrigated wheat.**

|  | Stem | Total leaves | Flag leaf |
|---|---|---|---|
| Dry matter | 24 | 25 | 26 |
| Nitrogen | 72 | 76 | 75 |

SOURCE: HOCKING 1994

An inevitable consequence of remobilisation of N from the leaves is a decline in photosynthesis because the photosynthetic proteins in the leaves are the main stores of N. Conversely, maintaining green leaves for longer during grain fill may enhance grain growth and may result in large grain with low protein concentration.

The partitioning of N in the mature crop is measured by the N harvest index (NHI):

$$NHI\ (\%) = \frac{N\ content\ of\ grain}{Total\ shoot\ N} \times 100$$

The NHI can vary considerably and is closely linked to the partitioning of dry matter within the crop (Figure 3-7). For wheat, a NHI of about 70 per cent is typical; the very low HI and NHI in Figure 3-6 were from crops that were severely stressed from drought, which reduced grain set and grain growth. Adding large rates of fertiliser N also can reduce the NHI.

**FIGURE 3-7**  The relationship between the harvest index and nitrogen harvest index in bread and durum wheat. The data were obtained from dryland and irrigated field trials in which grain yields ranged from <1t/ha to 6.8t/ha and grain protein concentrations from 9% to 14.5%.
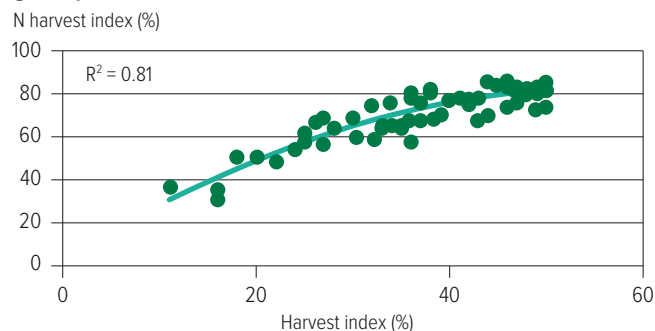


The literature contains a range of values for NHI of canola, other oilseeds and the grain legumes (Table 3-3) and may reflect adverse growth conditions such as heat and drought stress during flowering and pod filling. Another factor in the reported variation is the way in which NHI is calculated. Unlike the cereals, a number of these oilseed and legume crops lose significant amounts of leaves during grain fill (Figure 3-4). This loss of N can increase the estimates of crop HI and NHI (Table 3-4).

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**TABLE 3-3** Examples of nitrogen harvest index (NHI, %) for some oilseed and grain legume crops. Many of these studies may not have included fallen leaves and so may overestimate NHI.

| Crop | NHI | Location | Source |
|------|-----|----------|--------|
| Canola | 71–81 | S NSW; rainfed | Smith et al. 1988 |
| | 69–81 | S NSW; irrigated | Smith et al. 1988 |
| | 72–79 | S NSW | Hocking et al. 1997 |
| | 69–85 | S NSW; rainfed | Hocking and Stapper 2001 |
| | 72–81 | S NSW; rainfed | Hocking et al. 2002 |
| | 50–91 | WA; rainfed | Mason and Brennan 1998 |
| | 32–66 | Greece; rainfed | Papantoniou et al. 2013 |
| | 60–66 | Canada; rainfed | Ma and Zheng 2016 |
| | 53–72 | NW US | Maaz et al. 2016 |
| Mustard | 82–90 | S NSW; rainfed | Hocking and Stapper 2001 |
| | 61–79 | S NSW; rainfed | Hocking et al. 2002 |
| Linseed | 19–79 | S NSW; rainfed | Hocking et al. 2002 |
| Lentil | 24–86 | Canada; rainfed | Malhi et al. 2007 |
| | 75–85 | US; rainfed | Whitehead et al. 2000 |
| | 78 | New Zealand; rainfed | Ayaz et al. 2004 |
| Chickpea | 66–90 | Greece; rainfed | Koutroubas et al. 2009 |
| | 63 | Pakistan; rainfed | Kurdali 1996 |
| | 75 | New Zealand; rainfed | Ayaz et al. 2004 |
| Field pea | 48–79 | Canada; rainfed | Malhi et al. 2007 |
| | 64–69 | New Zealand; rainfed | Ayaz et al. 2004 |
| Lupin | 77–78 | Pot trial | Hocking and Pate 1978[A] |
| | 26–60 | WA; rainfed | Unkovich et al. 1994 |
| | 84 | New Zealand; rainfed | Ayaz et al. 2004 |

[A] Based on N in fruit (seeds+pod) at maturity.

**TABLE 3-4** Estimates of harvest index (HI) and N harvest index (NHI) in canola based on shoot biomass excluding dropped leaves and shoot biomass including dropped leaves.

| | Low N | | High N | |
|------|-------|-----|--------|-----|
| | HI | NHI | HI | NHI |
| Excluding dropped leaves | 21 | 73 | 22 | 74 |
| Including dropped leaves | 14 | 56 | 15 | 56 |

Values are %.  SOURCE: BASED ON DATA FROM SVEČNJAK AND RENGEL 2006

## 3.4 GRAIN PROTEIN CONCENTRATION IN CEREALS

Grain protein concentration is a ratio of the mass of protein to the total mass of the grain. Grain mass is mainly determined by the amount of starch that is deposited in the grain. The patterns of starch accumulation and N accumulation in the grain generally show a similar sigmoidal pattern of growth in which there are three distinct phases: an initial slow phase, a linear phase in which the majority of the N and grain mass accumulates, and a final phase of little to no growth as the grain reaches physiological maturity and the grain moisture content declines. Although they show similar patterns of increase during grain fill, accumulation of starch and N in the grain are independent processes. The grain protein of cereals is estimated as:

Protein concentration (%) = N concentration (%) x 5.7

For the cereals, N accumulation in grain is largely source limited, which means that it is sensitive to the amount of N in the tissues supplying the N to the grain (mainly the upper leaves). In contrast, starch accumulation in grain is largely sink limited; it is insensitive to the supply of sugars to the grain with grain growth rate determined by the ability of the grain to convert the sugars to starch. As the grain protein concentration is a ratio, it will increase if the supply of N to the grain is high and/or the accumulation of starch is curtailed (for example, from heat stress).

Like growing leaves, grain starts to accumulate N before the main period of growth and the duration of N accumulation is similar to or slightly longer than the duration of dry matter accumulation. The grain protein concentration changes as the relative amounts of N and starch change during grain growth. Initially grain protein concentration is high; it then falls to a relatively constant value at about the time the grain enters its linear phase of growth and grain growth rate is at its maximum (Figure 3-8).

Figure 3-8 shows that there may be relatively small differences in the amount of N accumulated in grain under different conditions when supplied with the same amount of N, and changes in grain protein concentration will reflect differences in the duration of grain growth and final grain weight.

**FIGURE 3-8  Changes in grain dry weight, N content and grain protein concentration during grain fill for (a) irrigated and (b) rainfed crops.**



**a) Irrigated crops**

Grain weight (mg) and grain N (mg x $10^2$)  Grain protein conc. (%)

Days after anthesis

● Dry weight  ● N content  ● Grain protein concentration



**b) Rainfed crops**

Grain weight (mg) and grain N (mg x $10^2$)  Grain protein conc. (%)

Days after anthesis

● Dry weight  ● N content  ● Grain protein concentration

SOURCE: ADAPTED FROM PANOZZO AND EAGLES 1999

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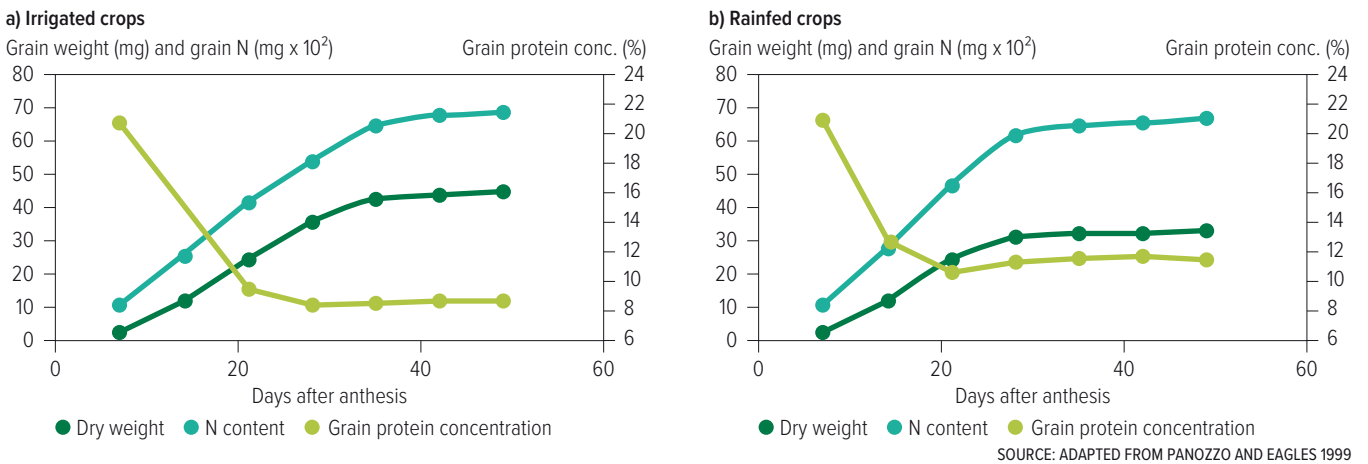
# 4 NITROGEN IN CROP ROTATIONS

Usually when we talk about crop rotations in the southern region it is in the context of either wheat or barley production, which dominate most grain farms. A cereal monoculture is continuous wheat or barley. A rotation involves other crops grown in sequence with the wheat or barley. Rotation crops usually mean canola and/or one or more of the grain legumes. Crop rotation has a positive effect on crop yield if it leads to improved availability of soil N or soil water, or where pests, diseases and/or weeds are reduced. Choice of rotational crop must consider the pest, disease and weed load of the paddock and the pest and disease susceptibility of the crop to be grown and subsequent crop/s to be grown, along with the potential $N_2$-fixing capacity in the case of legumes.

A net positive N benefit from a rotation can occur when:

* $N_2$-fixing legumes increase total soil N stocks;
* crop residues break down and release additional mineral N; or
* mineral N is 'carried over' from a previous crop due to residual fertiliser N or unused soil mineral N.

However, a crop rotation can have a negative effect on crop N nutrition when, for example, soil mineral N supply is reduced following decomposition of high C:N ratio crop residues. Soil N stocks are also reduced when removal of N in products and losses exceeds the N input as fertiliser or $N_2$ fixation and 'mining' of soil N stock occurs. As mentioned in the introduction, this appears to be occurring in many crop-intensive systems in Australia where soil organic matter levels are declining.

Several recent studies have shown that the N benefits of legumes to following cereals in south-eastern Australia usually last at least two years (Peoples et al. 2009, McBeath et al. 2015) and four or more in some cases (Kirkegaard and Ryan 2014). On average, the beneficial effects of broadleaf break crops last two or three years in the southern region (Kirkegaard and Ryan 2014). Nitrogen benefits from canola breaks tend to be more short-lived than benefits from $N_2$-fixing legumes.

**TABLE 4-1  Available N (kg/ha) to 0.5m depth in the autumn following a range of previous crops sampled on the Yorke Peninsula and Upper North of South Australia (2002–14).**

| Previous crop | No. fields sampled | Range | Average |
|---|---|---|---|
| Wheat | 847 | 8–200 | 67 |
| Barley | 267 | 9–203 | 56 |
| Faba bean | 99 | 26–187 | 97 |
| Field pea | 110 | 43–158 | 90 |
| Lentil | 248 | 26–245 | 87 |

SOURCE: PEOPLES ET AL. 2015

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**FIGURE 4-1  Soil mineral N at sowing (kg N/ha, 0–60cm) in 2012 following a range of different crops or fallow in 2011 at Appila, South Australia.**

Mineral N at sowing (kg/ha)



Previous crop
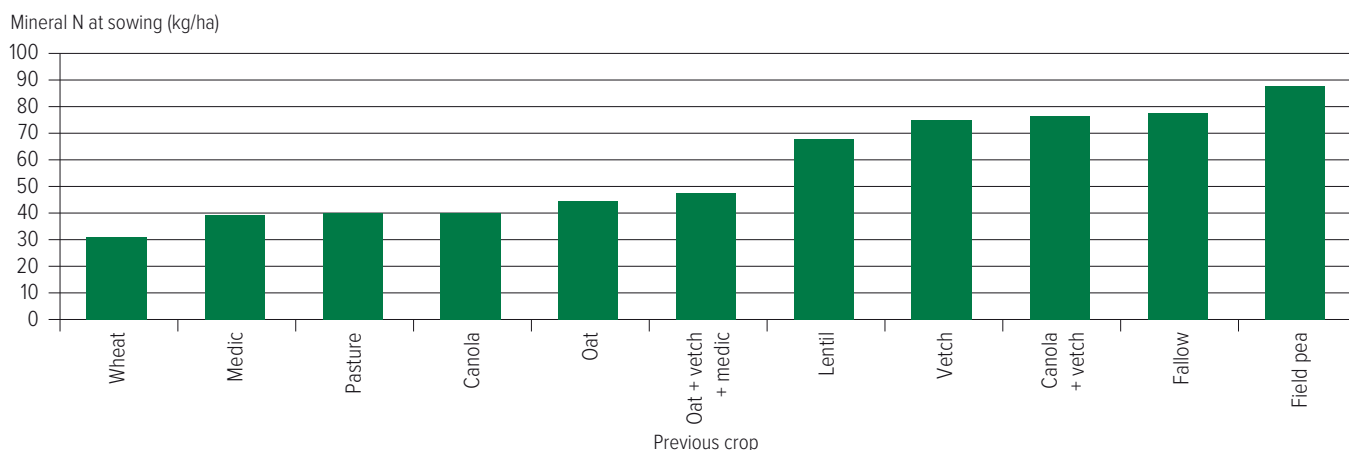
SOURCE: DATA COURTESY M. MOODIE

It has been clearly demonstrated over decades that mineral N following annual crop or pasture legumes is usually greater than that following cereals, and usually greater than that after oilseeds. A summary of soil samples taken from cropping systems in South Australia (Table 4-1) shows that, on average, soil mineral N in the autumn following grain legume crops is about 20 to 40kg/ha higher than it is following wheat or barley. A rotation trial at Appila, also in the Mid North of South Australia (Figure 4-1), highlights the build-up of mineral N following legume and canola crops compared with wheat.

An analysis of a larger dataset (Peoples et al. 2017) has shown that, on average, mineral N at sowing following grain legume crops is 98kg/ha, about 35kg/ha higher than following non-legume crops. Typically soil mineral N in the autumn after canola is higher than after cereals and, at times, higher than some legumes. Interactions between residue quantity, quality and soil organic matter are implicated. Another reason may be that canola crops receive about double the N fertiliser of cereal crops, yet the efficiency of uptake is about the same, so there should be greater residual N after canola than cereal crops.

The higher soil mineral N  could also relate to the amount of root residue N in canola compared with other crops, to increased microbial activity following canola compared with other crops (McNeill et al. 2000) or to reduced nitrification and increased immobilisation under canola (O'Sullivan et al. 2016). Canola produces a high-protein grain, typically 20 to 23 per cent, and it is likely that the residues remaining in the soil post-harvest are also high in N and therefore prone to rapid mineralisation.

Interestingly, an analysis of the effects of crop rotations indicated that the effects of oat and canola on following wheat yields tended to be around 0.4t/ha following oat and 0.8t/ha following canola, whereas the yield increase following legumes was not a fixed amount but tended to increase with the yield of the wheat (Angus et al. 2015).

Although long fallows can result in the accumulation of substantial amounts of mineral N, in the absence of annual organic matter inputs frequent fallowing will result in the rundown of soil total N and an ultimate decline in mineral N supply in cropping systems. This decline in N fertility would likely be more rapid in coarse than fine-textured soils (McBeath et al. 2015).

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**FIGURE 4-2  Relationships between the N in crop shoot residues and the soil mineral N at sowing of a following wheat crop and the uptake of N by the following wheat, Wagga Wagga, NSW.**

Mineral N at sowing or wheat shoot N (kg/ha)



Narrow leaf lupin

Field pea

Albus lupin

Barley  Chickpea

N in crop shoot residues (kg N/ha)

— Wheat shoot N uptake  — Mineral N at sowing

SOURCE: ARMSTRONG ET AL. 1997
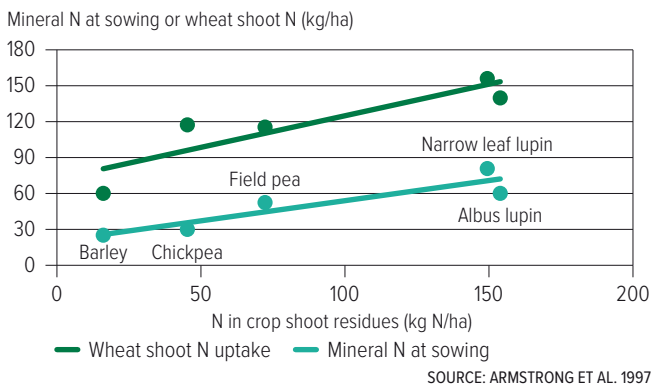
**FIGURE 4-3  Correlation between N in crop shoot and root residues and mineral N at sowing of a following wheat crop at Junee, NSW, following different rotational crops.**

Mineral N at subsequent sowing (kg N/ha)



Lupin (brown manured)

Lupin (grain)

Wheat  Canola

N in crop residues (kg N/ha)

SOURCE: GOWARD ET AL. 2016
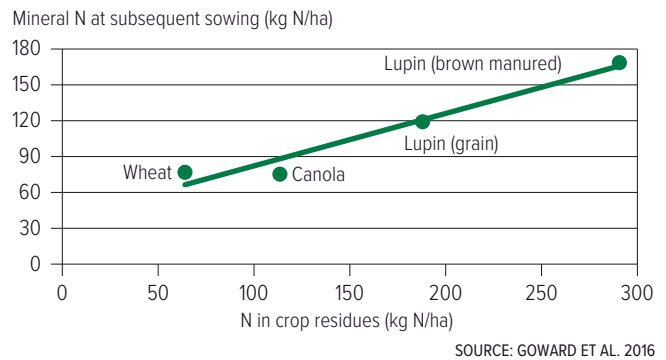
The amount of N mineralised from crop residues and the quantity of N taken up by a following wheat crop (Figure 4-2) are strongly related to the amount of N in crop residues. Another example, from the recent GRDC crop sequence initiative trial at Junee, NSW (Figure 4-3), shows soil mineral N at sowing of wheat was highest following brown manuring (for example, herbicide desiccation of the crop at flowering) of lupin, then grain harvested lupin, canola and lowest after wheat. These amounts of soil mineral N corresponded directly to the amount of N in residues. There are several datasets of this nature that show good correlations between crop residue N and either mineral N at sowing of a following crop or the N uptake by a following wheat crop not receiving fertiliser N.

Relationships such as those of Figure 4-2 and Figure 4-3 are attractive in their simplicity because they can be derived from simple measurements; however, they reflect the soil fertility, temperature, water availability, residue quality and management for that particular situation and they may not apply to other fields or times. These empirical relationships are thus different to dynamic simulation models that may be able to respond to local environmental and management influences.

**TABLE 4-2** Soil-available N (kg/ha 0 to 120cm) following termination (green manuring) of a vetch crop at different times after sowing (March 2012) or at harvesting for grain, and for the following wheat crop sowing and harvest at Birchip, Victoria. Statistically significant differences within a column are indicated.

| Vetch termination date in 2012 | Time of sampling | | |
|---|---|---|---|
| | Nov 2012 | 2013 Pre-sowing | 2013 Harvest |
| 6 June | 158a | 150a | 22 |
| 18 July | 122ab | 132b | 22 |
| 19 August | 108b | 127b | 21 |
| 17 September | 113b | 132b | 23 |
| 13 November (grain harvest) | 89b | 108c | 23 |

SOURCE: GOWARD ET AL. 2016

Nevertheless, the key principle illustrated by these results is that management practices that increase the total amount of residue N in the legume phase are likely to increase soil mineral N. For example, at Junee in NSW (Figure 4-3) and Birchip in Victoria, soil mineral N following brown or green manuring of a grain legume was greater than that after the crop was harvested for grain (Table 4-2).

One way of increasing the amount of N in crop residues is to increase the biomass of the legume crop. This reflects, in part, the symbiotic relationship between the growth of the legume and the activity of the rhizobia, where the amount of $N_2$ fixed by the legume depends on the supply of energy (as sugars) to the nodules. Working across NSW, Victoria and South Australia, Peoples et al. (2017) explored relationships between legume grain yield, legume residue N and the mineral N benefit to a following crop. The following rules of thumb emerged.

Mineral N benefit (kg/ha) = kg legume residue N x 0.28

Where the 'mineral N benefit' is the additional N available after a legume crop compared with that following a non-legume crop, and legume residue N includes N in roots as well as shoot residues. This equation can also be used for brown manure legume crops.

If one does not have a direct measure of the legume residue N for a grain crop, then the following approximation can also be used, although this is much less reliable, explaining only 27 per cent of the variance in mineral N benefit compared with 57 per cent for the above.

Mineral N benefit (kg/ha) = legume grain yield (t/ha) x 18

In some instances researchers have also related the mineral N availability or uptake in a following crop to the N balance of legumes (for example, Evans et al. 1989) as expressed by the amount of N fixed minus the amount exported in grain (for example, Armstrong et al. 1997). However, while the N balance is important from a system and longer term fertility perspective, it is the total amount of N in the residues that is most important in terms of mineralisation before and during the next crop, not whether the legume residue N was from $N_2$ fixation or soil derived.

In addition to elevated soil mineral N at the time of sowing a cereal or canola crop following legumes, higher levels of soil mineral N at grain harvest of the legumes are also observed, and are often referred to as "spared N" (see for example, Herridge et al. 1995). Higher levels at harvest reflect mineral N not used by the crop. The origin of this N is not entirely clear and effects of crop species and associated rhizosphere organisms on in-season N mineralisation are quite likely to be implicated, as well as perhaps a weaker appetite for mineral N by legumes.

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The increased N uptake by cereals following legume crops is not due entirely to increased soil N availability since, even where additional N is applied to continuous cereals, they do not always match the total N uptake of a legume–cereal or even canola–cereal rotation. This is because the rotational benefits are due to more than just N.

**Tillage, stubble and mineral nitrogen**

The amount of mineral N in a given soil is very dynamic in time and is responsive to management operations in both the short and long term. Effects of minimum tillage and stubble-retention systems on N mineralisation in the southern region are unclear. Tillage effects on N mineralisation have not been consistent (Heenan and Chan 1992, O'Leary and Connor 1997). Stubble retention in wheat had no effect on N mineralisation compared with stubble removal (Stein et al. 1987), although this may have been because the wheat sequence followed a long-term pasture and there was abundant labile N still available from soil organic matter.

In a long-term trial at Wagga there was a tendency for stubble-retained treatments to accumulate more total N than treatments where the stubble was removed; this translated into more mineral N in some years (Heenan et al. 1998). Years without significantly more mineral N from stubble retention were thought to reflect climate interactions with summer weed growth and leaching of nitrate below 20cm. A field study in NSW examining short-term soil responses to stubble retention and tillage (Gupta et al. 1994) found that microbial biomass N was higher when stubbles were incorporated into the soil, but this did not appear to translate into greater total net seasonal N mineralisation. In a recent rotation experiment at Wagga, NSW (Li et al. 2016), tillage did not increase soil N mineralisation above that observed in no-till plots.

**Grazing and mineral nitrogen**

Grazing of crop residues can also affect the mineral N available for crops, both directly through the recycling of N in manure and urine returns, and indirectly through rotational effects. The C:N ratio of urine is about 0.5, making the N in urine highly available compared with that in crop residues. Data from experiments in Western Australia (Unkovich et al. 1998) and NSW (Heenan et al. 1998) have both demonstrated the positive effects of grazing pastures on mineral N availability to following crops.

**Mineral nitrogen in fallow/crop sequences**

Leaving the soil uncropped (fallow) was once a common practice used to increase soil mineral N stocks and soil water (Ridge 1986). Fallows were either long (18 months), if a crop was bare fallowed for a whole cropping season, or short (nine months) when annual pastures were sprayed out in early spring. More recently, the use of fallows in the southern region has substantially declined because it has been found that the opportunity cost of fallowing is much higher than the benefits received by only growing one crop every two years (Whitbread et al. 2015). In the absence of a fallow, strict weed control over the summer period can help retain some soil water for the next crop (Hunt and Kirkegaard 2011), although the significance of this declines as soil clay content decreases and in the western parts of the southern region where rainfall becomes more strongly winter dominant.

## 4.1  IN-CROP MINERALISATION

The mineral N present in the soil when a crop is sown is supplemented by further soil N mineralisation during the life of the crop. This in-crop mineralisation will be governed by the same factors responsible for the accumulation of mineral N during the fallow before sowing, with the growing crop sometimes influencing mineralisation through root exudates and mineral N extraction. Nitrogen fertilisers applied by growers may also influence mineralisation. Hence the rate of mineralisation of N during crop growth may well be different to that occurring before sowing.

Smith et al. (2000) conducted a detailed study of N mineralisation and crop N uptake for fertilised and unfertilised wheat at Wagga Wagga in NSW.

**TABLE 4-3  In-crop mineralisation (kg N/ha to 1.2m) in the wheat phase at two experimental sites in Victoria in 2012.**

| Location | Rotation | Mineralisation (kg N/ha) |
|---|---|---|
| Longerenong (SCRIME) | Continuous wheat | 41 |
| | Canola/wheat/pulse | 40 |
| | 3yr lucerne/fallow/canola/wheat/pulse | 113 |
| | Fallow/wheat/pulse | 48 |
| Walpeup (MC14) | Direct drill wheat/pasture/fallow | 32 |
| | Direct drill wheat/fallow | 35 |
| | Cultivated wheat/pasture/fallow | 24 |
| | Cultivated wheat/fallow | 35 |

SOURCE: DUNSFORD ET AL. 2015

Net mineralisation occurred throughout the life of the crop but was higher in the spring when temperatures increased. In another study that examined N mineralisation in four successive wheat crops after four years of pasture in NSW (Stein et al. 1987), net mineralisation was 62kg N/ha, with maximal daily rates of 1kg N/ha recorded in September and minimum rates of about 0.2kg N/ha/day in August. At Walpeup in Victoria in 2012, in-crop N mineralisation ranged from 24 to 35kg N/ha for wheat crops established under cultivated or direct drilled conditions and following fallows (Table 4-3). In the SCRIME trial at Longerenong in Victoria, in-crop mineralisation under wheat ranged from 40kg N/ha following one year of annual pasture and canola to 113kg N/ha following three years of lucerne and one year of canola (Table 4-3).

In studies at Goomalling in Western Australia (McNeill et al. 2000), net N mineralisation under wheat following faba bean (47kg N/ha) was much greater than that following wheat (26kg N/ha). Clearly there are legacies of previous crops on the rate of mineralisation during the crop growth period and simple models that fail to consider the contributions from previous crop residues might not be very useful. Such effects may be more important in soils of low fertility where low residue N or labile C inputs are a more significant resource for microbial growth. In soils with high background fertility, such as those with N mineralisation supported by previous pastures (for example, three-year lucerne in Table 4-3), the effect of recent crop residue inputs may be less noticeable.

In studies on wheat in NSW, about 50 per cent of the N mineralised during crop growth appears to be taken up by the cereal crop (Stein et al. 1987; Angus et al. 1998; Smith et al. 2000). Clearly, there is much more N mineralised in soil during the life of a wheat crop than taken up by the crop. It is thought that the efficiency of uptake of soil mineralised N is similar to that for well-managed fertiliser N.

Tools for estimating in-crop mineralisation from soil properties or paddock history are considered in section 7.

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# 5 LEGUMES AND N$_2$ FIXATION

Growers plant legumes for multiple reasons. As rotation crops they help spread risk and manage disease, weeds and pests in the production system. In addition, several grain legumes are valuable crops in their own right, attracting high prices for good-quality grain and producing profitable gross margins with moderate yields. However, the enduring attractive feature of legumes is arguably their ability to form a mutually beneficial (symbiotic) association with rhizobia – soil bacteria that fix atmospheric N$_2$.

Rhizobia infect the roots of the legume to eventually be enveloped in modified appendages of the roots called nodules. In the nodules, the rhizobia convert nitrogen gas (N$_2$) into ammonia (NH$_3$), which is then largely used by the legume for growth. In return, the legume provides rhizobia with nutrients, a large amount of energy and a secure habitat. With fully functioning nodules, legumes can grow in soils that are deficient in available N. However, these 'N factories' are subject to variation in establishment and performance. To maximise N$_2$ fixation, a supportive environment must be provided. Rhizobia must be inside legume nodules to fix N$_2$, as they do not fix N$_2$ when they are living free in the soil.

Although rhizobia tend to be widespread in soils, they are not all equally effective. While most are able to become established inside legume nodules, not all are able to fix N$_2$ efficiently. For this reason, to ensure large numbers of efficient rhizobia are present in the legume nodules, it is wise to inoculate legume seed at sowing with the recommended strain of rhizobia if the paddock has not been inoculated with that rhizobia, or has not grown a crop of a suitable host legume for that rhizobia in the past four years (see section 5.3). Nodulation is sensitive to adverse soil conditions, especially soil pH. Survival of rhizobia and legume nodulation will be reduced in acid soil (pH <5), except for narrow-leaf lupin. To maximise N$_2$ fixation in low pH soils, more regular inoculation and/or liming is required. Detailed advice on legume inoculation and N$_2$ fixation can be found in section 5.3 and in Drew et al. (2013).

Legumes produce N-rich residues that remain in and on the soil after the crop is harvested. The mineral N released from these residues as they decompose is taken up by the following crop or crops. Legumes, therefore, have a role in supplying N to the cropping system following their harvest and their value to agricultural systems is strongly influenced by how well they grow and fix N$_2$. High grain and biomass yield generally mean high economic returns to the grower and more N added to the system via the N-rich residues. Legumes should be grown in soils that are low in plant-available mineral N, otherwise nodulation and N$_2$ fixation will be suppressed.

Legumes typically have a greater dependence on soil mineral N early in their life, especially for the first few weeks before the nodules are established. During this time soil N supply can often meet much of the crop N requirement (Figure 5-1) but as legumes increase their growth rate in the spring, the N$_2$ fixation rate increases and meets most of the crop N demand.

In the case of the field pea crop of Figure 5-1, the percentage of plant nitrogen derived from the atmosphere (%Ndfa) was 18 per cent 40 days after sowing and 75 per cent at peak crop biomass 120 days after sowing, by which time it had fixed 90kg N/ha in shoot biomass and taken up 30kg N/ha from the soil. At the start of flowering for the average crop legume, rates of N$_2$ fixation are still increasing and only about 25 per cent of the total crop N will have been assimilated. Maximum rates of N$_2$ fixation are most likely to occur during the most rapid period of crop growth, usually during podding, and may reach 4 to 5kg N/ha/day for very productive legume crops.

**FIGURE 5-1  N$_2$ fixation and soil mineral N uptake by a field pea crop at Goomalling in Western Australia.**



SOURCE: M. UNKOVICH AND A. McNEILL (UNPUBLISHED)
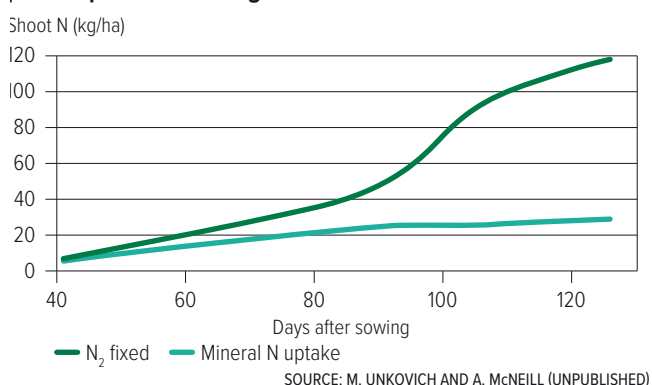
## 5.1  DO ALL LEGUMES FIX THE SAME AMOUNT OF NITROGEN?

The amounts of N$_2$ fixed by legumes will vary with site and season and are a function of crop growth, crop type, and the available soil N. Where available soil N is low, the amount of N$_2$ fixed is directly proportional to legume dry matter production (Figure 5-3). In any one location, legume crops and pastures having about the same total dry matter would be expected to fix about the same amount of N (see Table 5-1). Moderate available soil N (>35kg/ha) will reduce crop legume N$_2$ fixation by a similar amount. Approximate amounts of shoot N fixed by crops and pastures can be gauged from Figure 5-3, but remember this does not include fixed N in the roots that might contribute another 30 to 50 per cent.

On average crop legumes fix about 70 per cent of their N, with lupin and faba bean fixing the most (Figure 5-2). Up to 400kg N fixed has been recorded for lupin at Wagga Wagga, NSW (Evans et al. 1987). Chickpea seems to fix less N than other crop legumes. Probably the best way to estimate how much N might have been fixed by a legume crop is to use Table 5-1, which gives an amount of N$_2$ fixed per tonne of total shoot dry matter for legume crops and pastures. Table 5-1 highlights subtle differences between legumes in the amounts of N$_2$ fixed per tonne of shoot dry matter, with field pea and faba bean appearing to be the more efficient N$_2$ fixers. The total amounts of N$_2$ fixed can easily exceed 200kg N/ha for productive legume crops on low fertility soils. Summarising data from 33 legume crops across NSW, Victoria and SA from 1989 to 2015, Peoples et al. (2017) reported an average N$_2$ fixation (shoots + roots) of 126kg N/ha, ranging from 6 to 338kg N/ha.

**FIGURE 5-2** Average (and range) of total N₂ fixed (including an estimate of the amount in legume roots) for a range of legume crops across Victoria, NSW and SA.



Nitrogen fixed (kg N/ha)

Note: Numbers in brackets are the number of observations.

SOURCE: PEOPLES ET AL. 2017
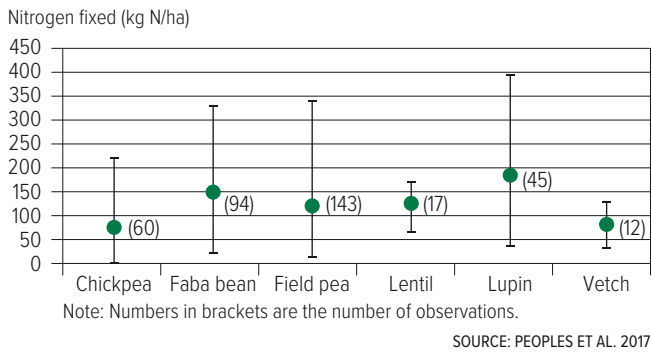
**FIGURE 5-3** Relationship between legume peak shoot dry matter and shoot N fixed for crops and pastures in Australia. Note that the N₂ fixation values do not include the N fixed in roots and nodules.



Shoot N fixed (kg/ha)

Legume shoot dry matter (t/ha)

● Pasture legumes   ● Crop legumes

SOURCE: UNKOVICH ET AL. 2010
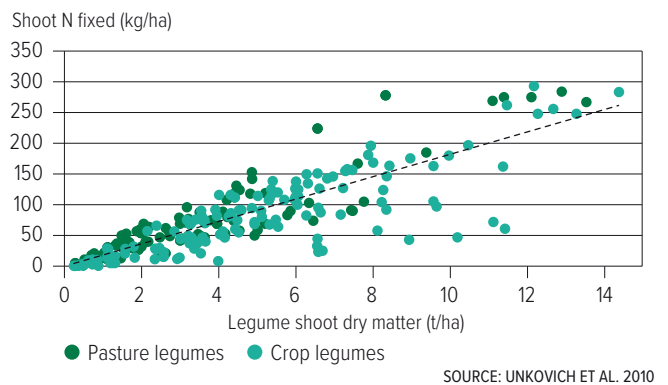
**TABLE 5-1** Average amount of fixed N (kg N/ha) in shoots plus roots of legumes per tonne of peak seasonal shoot dry matter.

| Legume shoot dry matter (t/ha) | Chickpea | Field pea and faba bean | Lupin | Annual clovers | Lucerne |
|---|---|---|---|---|---|
| 1 | 18 | 30 | 23 | 36 | 38 |
| 4 | 76 | 124 | 77 | 140 | 150 |
| 8 | 153 | 249 | 149 | 279 | 300 |
| 12 | 229 | 375 | 220 | 419 | 450 |

SOURCE: ADAPTED FROM UNKOVICH ET AL. 2010

### 5.1.1 Legume nitrogen in rotations

The value of legume N in rotations is twofold. First, the N-rich residues can release a considerable amount of mineral N for a following crop, reducing the N fertiliser requirement. Second, legumes can actually build soil organic matter and N stocks if the amount of N added through $N_2$ fixation exceeds that removed in legume grain or, in the case of pasture legumes, in animal product. This is a key benefit of legumes and was largely the basis for the introduction of pasture and crop legumes to farming systems in Australia. However, the low intensity of legumes grown in rotation with cereals and canola is often insufficient to have a positive effect on soil N across the rotation. Not all legume crops effect a net input of N into the cropping system, which is dependent on the balance between N removed as grain and $N_2$ fixed. Figure 5-4 summarises N balance data for 243 legume crops across NSW, Victoria and SA. The data are calculated as the total amount of $N_2$ fixed, including an estimation of the N contained in legume roots, minus the amount of N harvested as grain. The calculations indicate that, on average, legume crops generally effect net inputs of N after grain harvest. However, negative balances do occur for all crop species (except for the very few observations made on vetch). In some cases, the net input of N following a legume crop can exceed 100 or even 200kg N/ha, especially for productive faba bean and lupin.

From these data one would conclude that build-up of soil fertility is more likely when lupin and faba bean crops are regularly included in rotations than field pea or chickpea. Greater benefits are likely to accrue through healthy legume-based pastures than for crop legumes because a much smaller fraction of the legume total N is harvested and because much of the N is rapidly cycled to mineral N via the grazing animal.

**FIGURE 5-4** Average (and range) of net nitrogen balance (total $N_2$ fixed – grain N harvested) for a range of legume crops across Victoria, NSW and SA. The data include an estimate of the contributions of legume root N.



Note: Numbers in brackets are the number of observations.
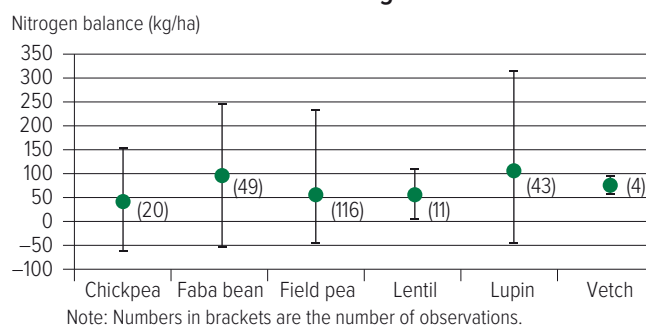
SOURCE: PEOPLES ET AL. 2017

## 5.2 $N_2$ FIXATION AND SOIL ACIDITY

Nitrogen fixation is known to result in the production of some acidity, however the amount of acid produced by $N_2$-fixing legumes is actually very small. The fixation of 100kg N/ha would carry with it the production of 7100 mol of $H^+$, requiring only 3.5kg lime/ha to neutralise it. Nitrate leaching is likely to be much more significant in urine patches under grazing and this can be a substantial contributor to soil acidification if it is not carefully managed.

## 5.3 RHIZOBIA AND LEGUME INOCULATION

Legumes must be nodulated by effective, compatible rhizobia to fix $N_2$. In agriculture, highly effective rhizobia are introduced into legume-growing soils via inoculation with commercially available cultured bacteria. A practical guide to the inoculation of legume crops and pastures in Australia is available (Drew et al. 2013).

### 5.3.1 Rhizobia

Rhizobia are medium-sized, rod-shaped bacteria. They are called microorganisms because of their very small size – a chain of 500 rhizobial cells placed end to end is about 1mm long. Although usually found in soil, rhizobia are characterised by their ability to nodulate a legume (see nodules on roots of faba bean in Figure 5-5A).

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Rhizobia in the soil and attached to legume roots can be observed using a microscope. Rhizobia can grow in a wide range of temperatures. They can be frozen and will survive temperatures of 35°C, although they prefer temperatures of 25°C to 30°C. They require oxygen to survive and multiply.

Rhizobia are part of the soil biota, but outside their legume hosts they do not fix N$_2$ and have to compete for nutrients with the rest of the soil microorganisms and contend with predators, toxicities and stresses. The populations of rhizobia in soils vary enormously, primarily influenced by the presence of the host legume and factors such as soil pH, soil texture (clay content), temperature, moisture and salinity (Howieson and Ballard 2004).

Slattery et al. (2004) reported dramatic effects of soil pH on the number of rhizobia that nodulate vetch, lentil, pea, faba bean, chickpea and lupin at a range of sites in northern Victoria. The number of rhizobia, except for the lupin rhizobia, increased with increasing soil pH. Clover rhizobia are far more tolerant of acid soils than are medic rhizobia, which is consistent with the acid tolerance of clover (and acid intolerance of lucerne).

## 5.3.2 Legume nodulation

When rhizobia in the soil make contact with the roots of a host legume, a complex set of reactions occur between the plant and the rhizobia. Rhizobial numbers increase in the vicinity of the legume roots (rhizosphere), then rhizobia attach to the root hairs (Figure 5-6). Population densities of rhizobia are much greater in the legume rhizospheres than in the bulk soil or in soils with no host legume, often by a factor of 1000.

Following attachment of the rhizobia, the root hairs respond by curling and branching. Rhizobia are trapped in the folds of the deformed root hairs. Once in the folds, they penetrate the cell walls of the root hairs (infection) to form infection threads. Rhizobia are enclosed in the infection threads, which grow towards differentiating plant root (cortical) cells. The rhizobial cells are eventually released from the infection threads into the cortical cells of the root, where they multiply and develop into the modified bacteroid form. Other structures develop that allow the exchange of water and nutrients between the nodule and plant. Finally, the nodule enlarges to the point that it becomes visible and starts to function as an N$_2$-fixing factory.

**FIGURE 5-5  (b) Root nodules on faba bean. The rhizobia live within the nodules in which they fix atmospheric N$_2$. (a) Rhizobia grown on nutrient-rich agar media in a Petri plate.**

PHOTOS: (A) M. UNKOVICH AND (B) D. HERRIDGE

**FIGURE 5-6  Schematic representation of the process of nodulation.**



1. Rhizobia come into contact with the rhizosphere of the plant root

2. Rhizobial numbers increase in the vicinity of the root hairs, and the rhizobia attach

3. Root-hair curling occurs, then invasion of the root hair and multiplication of rhizobia within the infection thread in the hair

4. Finally, nodules are formed in root cells and begin to fix nitrogen, i.e. convert atmospheric N$_2$ to ammonia

Nodules are sheltered habitats for the rhizobia. The plant regulates nutrient and water supply and oxygen tension. In return, the rhizobia convert atmospheric N$_2$ to ammonia, which is expelled to be immediately converted into amino compounds by plant enzymes in the nodule. Young, active nodules may contain >500 million bacteroids, each of which is contributing to the N nutrition of the plant (Bergersen 1982).

The process of nodulation and establishment of N$_2$ fixation as illustrated in Figure 5-6 takes about 5 to 10 days under laboratory conditions. In the field, nodules usually start to function within three to four weeks of seed germination, but nodule function can be delayed by unfavourable conditions and by elevated soil NO$_3$-. Although the N$_2$ fixation process requires oxygen, the nitrogenase enzyme is deactivated by oxygen. For this reason, the nodules contain a type of haemoglobin to control the oxygen concentration. Healthy N$_2$-fixing nodules are usually red or pink. White nodules suggest that N$_2$ fixation has not been established and black or green nodules indicate that the nodules are breaking down. At the end of the life of the nodule, the rhizobia are released back into the soil.

### 5.3.3  Inoculating legumes with rhizobia

Inoculation of legumes with rhizobia is one of the success stories of world agriculture. Guthrie (1896) stated "… it will prove to be one of the most valuable contributions ever made by science to practical agriculture …". He showed remarkable foresight because now, more than 100 years later, legumes growing on 25 million hectares of land in Australia fix about $3 billion worth of N annually. Essentially all of that N can be attributed to current and past inoculation (Brockwell 2004).

**FIGURE 5-7  (a) Inoculated lupin crop and (b) uninoculated lupin crop growing in different parts of the grains belt during 2003.**



PHOTOS: D. HERRIDGE

**FIGURE 5-8** Effects of inoculation on nodulation and yield of faba bean in low and high-rhizobia soils. Data are aggregated from 18 experiments conducted from 1997 to 2003 in WA, Victoria and NSW.

Nodules per plant

Grain yield (t/ha)

SOURCE: D. HERRIDGE
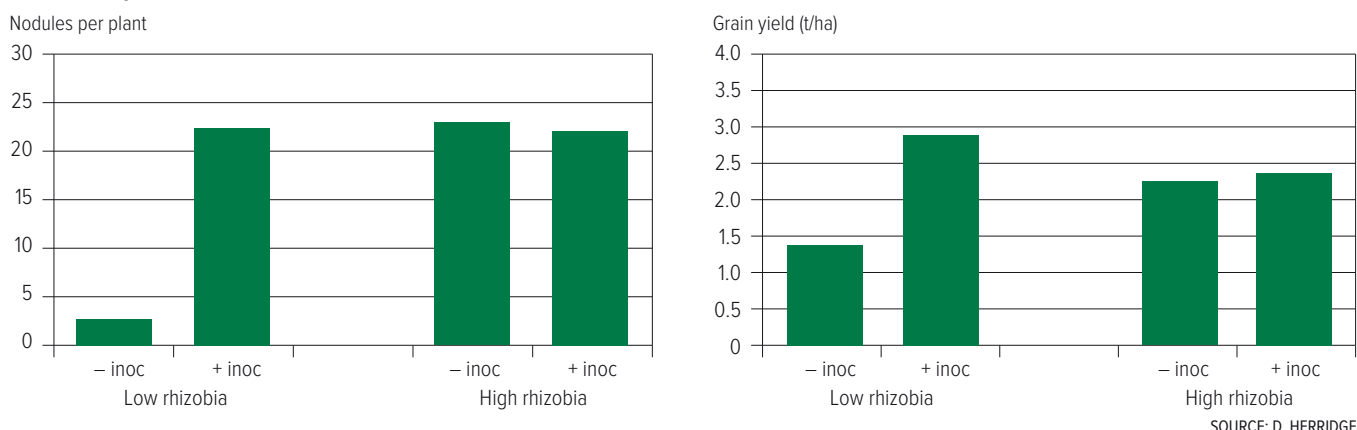
Benefits of inoculation can be dramatic. With reasonable seasonal conditions, inoculated legumes are well grown and green, signifying functioning N$_2$-fixing nodules (Figure 5-7A). In contrast, a crop of the same species (in this case the narrow-leafed lupin) that had not been inoculated was poorly grown and yellow because of N deficiency (Figure 5-7B).

In soils that have low numbers of rhizobia or do not contain any rhizobia at all, the benefits of inoculation are dramatic (Figure 5-8). Typical grain yield increases are 50 to 150 per cent, equivalent to 0.7 to 2t/ha. In soils that already have high populations of rhizobia or high available soil N, there may be little or no effect of inoculation on legume nodulation and yield.

Nodulation failures in crops or pastures that have been inoculated can sometimes occur. In some cases, the failure is because of poor-quality inoculant (Steinborn and Roughley 1974, Denton et al. 2009) or the purchase of pre-inoculated seed

(Gemell et al. 2005). More likely, the problem is associated with the storage or application of the inoculant, rather than inoculant quality itself. The most likely problems include:

- poor storage of the inoculant before application;

- toxic chemicals such as fungicidal seed dressings on the seed causing death of the rhizobia;

- mixing inoculants with other products at planting, including organic and mineral fertilisers;

- delay in sowing after inoculation of seed, resulting in the death of the rhizobia;

- low volumes of water (<50L/ha) used to apply liquid inoculants 'in furrow';

- the wrong inoculant used for a particular legume; and

- very hot, dry conditions (air and soil) when sowing causing death of the rhizobia.

Growers should always follow the label instructions. Ideally, seed should be sown within four to six hours of inoculation. If sowing is delayed for more than a day, the grower should certainly consider re-inoculating the seed. The inoculant should never be mixed with chemicals toxic to the rhizobia. If in doubt about the chemical, contact the inoculant manufacturer. If possible, inoculated legumes should be sown into cool to warm, moist soil, rather than hot, dry soil.

### 5.3.4 Inoculants – rhizobial strains

Good-quality inoculants contain strain(s) of highly effective rhizobia in a formulation that protects the rhizobia in storage and during the process of inoculation. Strain improvement is conducted at several laboratories in Australia, primarily at Murdoch University, Perth, and the South Australian Research and Development Institute (SARDI), Adelaide. Although each centre has its own particular set of protocols, there is a common approach as described by Howieson et al. (2000). It involves a stepwise program that starts with many hundreds of strains evaluated on the particular legume(s) grown in pots in a glasshouse

and ends with multi-locational field trials of elite material across the country.

In 1953, just 17 strains were used for 25 different legume species (Bullard et al. 2005), but by 2008, in response to the greatly expanded range of legumes, Australian growers had access to 41 different inoculant types, each with its own particular strain of rhizobia. Many of the strains used in inoculants originated from outside the country and some strains, for example, TA1 for white and red clover and WU425 for lupin, have been used for many years (Table 5-2).

### 5.3.5 Inoculant brands and formulations

A diverse range of inoculant products with different modes of application are available from several manufacturers (Table 5-3). Note that each of the manufacturers produces a set range of inoculant groups. For example, inoculants for lupin, faba bean, field pea and chickpea are produced by all of the manufacturers in a variety of formulations. On the other hand, inoculants for the less popular legumes, such as sainfoin and sulla, are only produced by one or two manufacturers and usually as peat inoculants.

| TABLE 5-2  Rhizobial strains used in the major inoculants in Australia. | | | | |
|---|---|---|---|---|
| Inoculant group | Strains since 1953 | Current strain | Introduced | Origin |
| Lucerne | 10 | RRI128 | 2000 | Australia (Vic.) |
| Annual medic | 10 | WSM1115 | 2002 | Greece |
| White clover | 9 | TA1 | 1956 | Australia (Tas.) |
| Sub clover | 7 | WSM1325 | 2000 | Greece |
| Faba bean | 3 | WSM1455 | 2002 | Greece |
| Lupin | 4 | WU425 | 1970 | Australia (WA) |
| Chickpea | 2 | CC1192 | 1977 | Israel |
| Soybean | 5 | CB1809 | 1966 | US |

SOURCE: BULLARD ET AL. 2005

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Irrespective of manufacturer or brand, for each of the legume groups all inoculants contain the same strain of rhizobia (for example, strain CC1192 is used by all manufacturers for chickpea). Current inoculant strains were selected on the basis of exhaustive laboratory, glasshouse and field research conducted over many years. Fresh cultures of the strains are supplied annually to the manufacturers by the NSW Department of Primary Industry's (DPI's) Australian Inoculants Research Group (AIRG; www.dpi.nsw.gov.au/agriculture/soils/australian-inoculants-research-group). In the future, it is possible that the manufacturers will use different strains from each other and some of the strains may originate from their overseas operations.

**Peat inoculants**

Peat inoculant, applied to the legume seed as a slurry, remains the most widely used of the formulation–application combinations and the benchmark for efficacy. Results of two nationwide surveys in 2013 and 2017 involving a total of 560 growers indicated that 83 per cent used peat inoculants compared with 19 per cent using granular inoculants, 16 per cent using freeze-dried inoculants and just four per cent using liquid inoculant (soybean only) (Maarten Ryder, University of Adelaide, and colleagues, unpublished data). Commonly, peat-based inoculant is applied directly onto the seed as it is augured into the seed bin on the sowing rig.

**TABLE 5-3** Rhizobial inoculants available for use in Australia. Inoculants are applied to seed in a slurry, in furrow as a liquid or as a dry product in furrow.

| Manufacturer | Brand | Formulation | Application |
|---|---|---|---|
| BASF | Nodulaid® | Peat | Seed or furrow |
| | Nodulaid® N/T | Peat (rhizobia) plus sachet (*Bacillus subtilis*) | Seed or furrow |
| | Nodulaid® N/T | Liquid (rhizobia) plus bottle (*Bacillus subtilis*) | Seed or furrow |
| | Nodulator® | Clay granule | Dry in furrow |
| NewEdge Microbials | EasyRhiz™ | Freeze-dried | Seed or furrow |
| | Nodule N™ | Peat | Seed or furrow |
| Novozymes Biologicals Australia | N-Prove® | Peat | Seed or furrow |
| | N-Prove® | Peat granule | Dry in furrow |
| | TagTeam® | Peat granule (rhizobia plus *Penicillium bilaii*) | Dry in furrow |
| ALOSCA Technologies | ALOSCA® | Clay granule | Dry in furrow |

Arguably, the major issues with this method of inoculation are unacceptably high rates of death of the rhizobia resulting from toxicity of seed dressings and delayed sowing. The rhizobia are rather fragile and many will die on the seed as the inoculant slurry dries. Under normal circumstances, sufficient numbers survive to facilitate effective levels of nodulation. However, if the seed dressings are particularly toxic or sowings are delayed by a few or more days, numbers of live rhizobia on the seed can fall below that required for optimum nodulation.

Peat inoculants can also be suspended in water and applied directly to the soil 'in furrow' at rates of 50 to 100L/ha (also termed liquid inoculation, spray inoculation and liquid injected inoculation; Gault 1981, Gault et al. 1982, Brockwell et al. 1988).

### Granular inoculants

Granular inoculants, also called soil or solid inoculants, were developed about 50 years ago and have been widely used in the US for at least 30 years (Brockwell et al. 1980). Essentially, the granules are a peat prill or a solid, inert core, such as clay, coated or impregnated with rhizobia. Rates of application are generally 3 to 10kg/ha, with the inoculant delivered into the seed row from a box on the sowing rig. Major advantages of granular inoculants are ease of storage, handling and application. Soil inoculation using granules separates the rhizobia from toxic, seed-applied chemicals and seed-coat compounds. Disadvantages are the need for an additional box on seeding equipment, the bulk of the granules with the high rates of application (3 to 10kg/ha versus 0.25kg/ha for peat inoculants), the increased transport costs and problems if the granules are not free-flowing.

Although not a new technology, granular inoculants have only become available to Australian growers during the past 15 years (Denton et al. 2009). In 2002–04, ALOSCA Technologies developed and released a bentonite clay granular inoculant for the WA grainbelt with small amounts sold in the southern and northern grains regions. Subsequently, BASF (was Becker Underwood) and Novozymes sold granular products, based on attapulgite clay and peat/attapulgite, respectively.

### Freeze-dried inoculants

The major advantage of freeze-dried inoculants is the ease of use – just add the contents of the small vial containing the freeze-dried rhizobia to the contents of a larger vial (protective polymer) and to water and either apply directly to the seed or spray into the seeding furrow when sowing. This formulation has proved to be highly efficacious in trials, particularly when sprayed in furrow (Denton et al. 2013). However, it does not appear to handle hot, dry conditions as well as the other formulations.

### Liquid inoculants

Liquid inoculants (not to be confused with liquid injected or spray inoculation) are only used for soybean in Australia. Normal application rates are 2 to 4mL/kg seed, with the inoculant applied to the seed as a batch or continuously via an applicator as the seed is augured into the seed box. Less commonly, liquid inoculants are diluted with water and applied directly into the seeding row.

### Pre-inoculated seed

The majority of pasture legume seeds now sold in Australia are pre-inoculated with rhizobia. Pre-inoculation is usually part of a seed-pelleting process that may also involve the coating of growth factors. Claimed shelf lives of pre-inoculated seed vary from two to three months to 12 months, according to species and manufacturer recommendations. As part of the quality program, AIRG also tests pre-inoculated seed, mainly lucerne and subterranean clover, sourced from retailers across the country. Results from surveys conducted during 1999–2003 highlighted large differences between pasture legume species, with 73 per cent of lucerne seed samples exceeding the standard of 1000 rhizobia/seed, compared with only a 32 per cent pass rate for subterranean clover and just three to four per cent for white and red clover (standard for white clover 500 rhizobia/seed) (Gemell et al. 2005). The surveys are continuing as is research to increase the numbers of rhizobia on pre-inoculated seed.

### 5.3.6 Inoculant delivery methods

Brill and Price (2011) concluded from three years of field testing of chickpea inoculants and application methods in NSW that the standard slurry-on-seed method (either peat or freeze-dried formulations) gave consistently good results. In some cases, nodulation was less than with the 'water inject' method (in furrow application), but this needs to be balanced against the cost of setting up a machine to handle the large volumes of water. Results of 37 field trials in the southern region demonstrated that peat slurry inoculants have also shown consistently good nodulation on pulses; granules were more site-specific and, of those, peat-based granules provided better results (Denton et al. 2009). Peat performed better than liquid injected inoculant or peat granules for faba bean and lupin (Denton et al. 2017). Growers should make decisions about which inoculant to use and the method of application based on their own experience, product availability and perceived advantages or disadvantages.

### 5.3.7 Inoculant quality – the role of the Australian Inoculants Research Group

The AIRG based at NSW DPI conducts independent quality testing of inoculants at both the point of manufacture and the point of sale as well as supplying fresh rhizobial cultures to the inoculant manufacturers on an annual basis. The quality testing is in addition to the internal quality control conducted by the companies themselves. The principal quality trait assessed is the number of live rhizobia in the inoculant. For example, in 2007 AIRG tested 96 batches of inoculants at manufacture and 95 per cent passed the test. Failed batches were withdrawn from sale. AIRG also tested 280 inoculants at the point of sale, finding a 95 per cent pass rate. Another four per cent just failed the standard (Herridge 2009).

## 5.4 MANAGING LEGUME N$_2$ FIXATION

Legume growth is the major driver of legume N$_2$ fixation. In the Australian environment, growth is mostly determined by the amount of water that the crop or pasture can access. Growers cannot control the weather but they can optimise their management to sow at the best time to use seasonally available moisture, to capture and store more water in the soil, to keep soil mineral N as low as possible and to provide the legume with ideal, stress-free growing conditions. Efforts to increase N$_2$ fixation by reducing the mineral N available to legume crops through incorporation of cereal straw have generally not been effective (Evans et al. 1987, Evans et al. 1997). The best management option is to reduce the amount of soil N by crop rotation. Ensuring that legumes have a good population of efficient N$_2$-fixing rhizobia associated with their roots is critical (see section 5.3) and a separate manual on this aspect of legumes is available (Drew et al. 2013).

**Optimising agronomy**

Since biomass production is the main driver of N$_2$ fixation, optimising crop agronomy is critical for high legume productivity and N$_2$ fixation. This means maintaining a good cover of stubble on the soil surface in the pre-crop fallow, sowing on time and establishing the appropriate plant density. It also means optimising nutrient inputs such as P, molybdenum (Mo) and zinc (Zn), reducing soil acidity with lime and managing weeds, diseases and insects.

Rhizobia also have a requirement for cobalt and where this is deficient rhizobial growth and nodulation will be compromised. Sowing at the appropriate time to take full advantage of growing season rainfall and temperatures, and to minimise deleterious effects of pest and disease cycles, provides opportunity to enhance N$_2$ fixation. With field pea in the southern NSW grainbelt, N$_2$ fixation was increased from 64kg N/ha to 180kg N/ha by planting in April instead of June (O'Connor et al. 1993).

Soil acidity and P deficiency are common constraints to legume N$_2$ fixation. In a three-year study in south-eastern Australia, N yields and N$_2$ fixation of subterranean clover pastures were increased by 65 to 70 per cent with P fertiliser and by 120 to 130 per cent with a combination of lime and P. Lime increased pH and reduced extractable aluminium and manganese, both of which were found in the soil in concentrations toxic to legumes and rhizobia (Peoples et al. 1995).

Other soil constraints include salinity and sodicity. Such constraints need to be avoided or addressed if potential legume biomass production is to be realised. Research has established that N$_2$-fixing legumes may have additional nutritional requirements compared with plants that do not fix N. Examples are the higher requirements for calcium, boron and molybdenum (O'Hara et al. 1988). Specific agronomic advice for the production of legume crops in the southern region can be found in the GRDC 2018 GrowNotes™ series (see section 10, Resources).

# 6 FERTILISER NITROGEN

Nitrogen is the element generally required by plants from the soil in greatest quantity and is the most widely used fertiliser in agriculture. Globally, in excess of 110 million tonnes of mineral N fertiliser are used each year to produce crops and other agricultural products. The process for the industrial production of N fertilisers, developed by the German chemists Fritz Haber and Carl Bosch, was one of the most significant inventions of the 20th century. Half of the world's population is alive today as a result of N fertiliser produced by the conversion of atmospheric $N_2$ to ammonia in a reaction with hydrogen ($H_2$) using metal catalysts under high temperature and pressure (Erisman et al. 2008). The $H_2$ source is typically natural gas (methane ($CH_4$)). As carbon dioxide ($CO_2$) is a major by-product of the Haber–Bosch process, this can be conveniently used onsite to produce urea ($CO(NH_2)_2$) fertiliser, made from the $CO_2$ and $NH_3$.

**FIGURE 6-1  Production of ammonia for fertiliser synthesis using the Haber–Bosch process.**
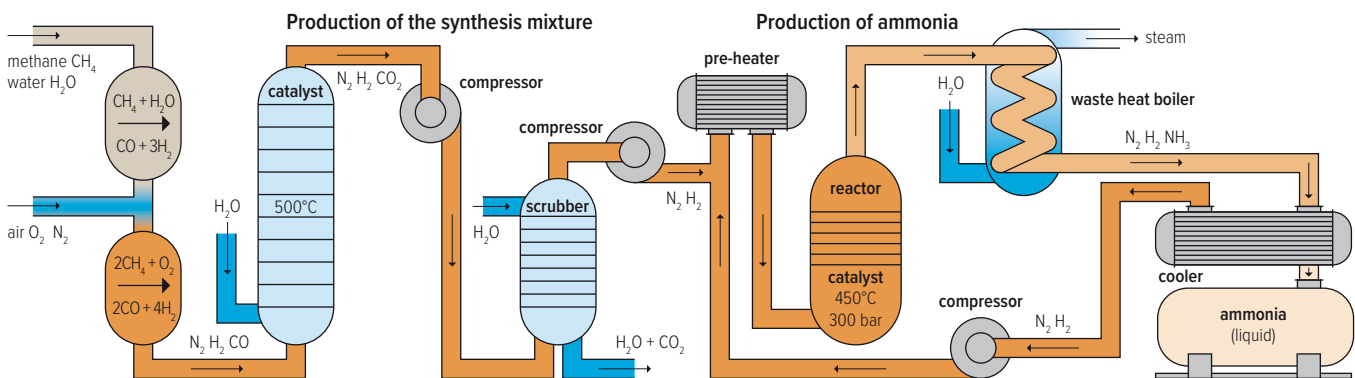


SOURCE: HTTPS://COMMONS.WIKIMEDIA.ORG/WIKI/FILE:HABER-BOSCH-EN.SVG

**FIGURE 6-2** Nitrogen fertiliser use in Australia 2002–17.

Million tonnes of N



SOURCE: : FERTILIZER AUSTRALIA (NICK DREW; PERS. COMM.)
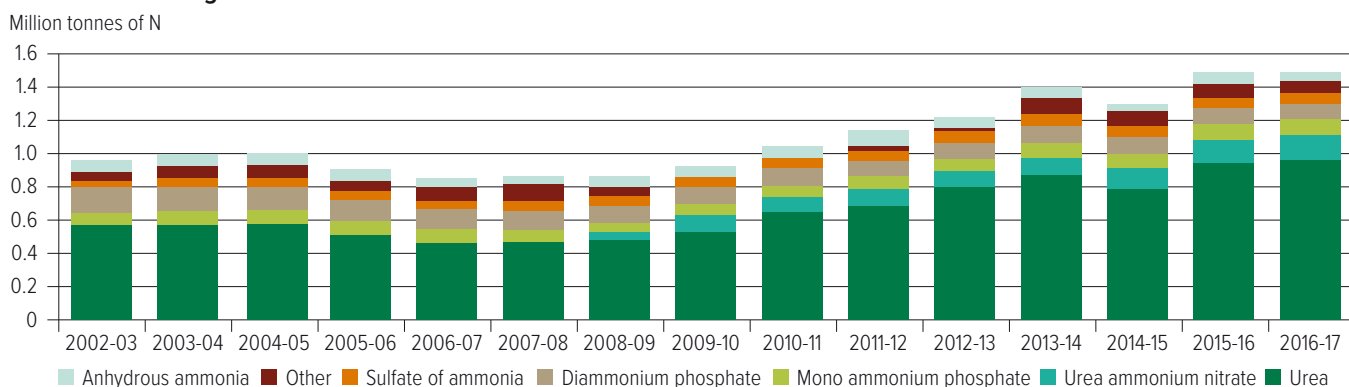
### Nitrogen fertiliser use in Australia

Although urea and a range of other N fertilisers are manufactured in Australia, more than 80 per cent of the N fertiliser used in Australia is imported. Fertiliser N can be in the basic ammonia form (anhydrous ammonia) or further processed into a variety of liquid and solid formulations – urea, ammonium sulfate, ammonium nitrate and ammonium phosphates. Nitrogen is also applied to soils in the form of organic fertilisers, typically waste products from animal production, composts and human activities. The amount of mineral N fertiliser sold in Australia is about 1.5 million tonnes, about two-thirds of which is urea (Figure 6-2). The use of urea ammonium nitrate (UAN) solutions is increasing, mainly in WA, due to recent interest in fluid applications of N fertiliser.

### Applying N fertiliser – the four Rs

When planning to apply N fertiliser, four questions need to be asked: What should I apply? How much should I apply? Where should I put it? And, when should I apply it? These four questions form the basis of the four Rs: the right product (source), at the right rate, at the right time and in the right place. They underpin best management practice and the nutrient stewardship promoted by the International Plant Nutrition Institute (Norton 2013a). They make good sense and provide a rational framework for making the best use of the N fertiliser resources available.

## 6.1  SELECTING THE RIGHT NITROGEN SOURCE

There is a range of different forms of N fertiliser available on the market today, each with a different concentration of N and other nutrients (Table 6-1). Generally speaking, one form of N is as good as another in terms of its crop nutritional value. Trials in Australia have shown no consistent difference in the response to N between different types of fertilisers. The selection of the most appropriate fertiliser will be affected more by factors such as price, transport, handling and storage logistics, and potential loss mechanisms when applied to soils or to crop canopies, rather than any intrinsic differences in N responsiveness. Urea is overwhelmingly the dominant N fertiliser used in broadacre cropping and any advantages of other N fertiliser types are restricted to very few specific circumstances. There is a small number of other N fertilisers available in Australia (for example, calcium ammonium nitrate (CAN)), but they are not important at present in the grains industry in the southern region.

The fertilisers listed in Table 6-1 are marketed under a range of proprietary names and may be modified in some way to be slow release or to have a range of other specified properties. Nitrogen fertilisers may also be blended with other fertilisers to produce convenient combination products and nutrients. Slow-release

| TABLE 6-1 The nitrogen, phosphorus and sulfur concentration of principal N fertilisers. | | | |
|---|---|---|---|
| Fertiliser | N (%) | P (%) | S (%) |
| Urea | 46 | 0 | 0 |
| Urea ammonium nitrate (UAN) | 32 | 0 | 0 |
| Sulfate of ammonia | 21 | 0 | 24 |
| Anhydrous ammonia | 82 | 0 | 0 |
| Mono ammonium phosphate (MAP) | 10 | 22 | 0 |
| Diammonium phosphate (DAP) | 18 | 20 | 0 |

N formulations are for the most part standard N fertilisers coated with a product to render them less soluble, the idea being to slow the rate of dissolution of the fertiliser from the granule into the soil. Examples of slow-release formulations are wax-coated urea, polymer-coated urea and plastic-coated urea.

**Urea**

Urea is the main N fertiliser used in crop production in the southern region due to its lower cost compared with other N fertiliser sources and its high N content (46 per cent), making it cheaper to transport per unit of N than other granular fertilisers. Although plants can take up some urea directly from the soil (Witte 2011), the N in urea is primarily taken up by plants after urea has been hydrolysed in the soil.
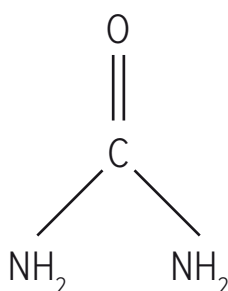
Hydrolysation (Figure 6-3) is an important transformation and involves the conversion of urea ($CO(NH_2)_2$) to ammonia ($NH_3$), catalysed by the enzyme urease, with ammonium carbonate (($NH_4)_2CO_3$) as an intermediary. The urease enzyme is present in the soil biota and in plant tissues. It is also released by bacteria into the soil and can persist there in a stable form. Urease activity is sensitive to soil pH, moisture, and the concentration of ammonium ($NH_4^+$) in soil solution, which can be altered by addition of plant residues or $NH_4^+$-based fertilisers.

Although urea fertiliser can be subject to high losses through $NH_3$ volatilisation under certain conditions (see section 6.2), if carefully managed typical losses are still less than the price differential of other more expensive fertiliser formulations less subject to $NH_3$ volatilisation.

**FIGURE 6-3 Urea hydrolysis.**



Urea hydrolysis

$(NH_2)_2CO + H_2O \Rightarrow NH_3 + H_2NCOOH \Rightarrow 2NH_3 + CO_2$ (Gases)

$(NH_2)_2CO$ – urea; $H_2O$ – water; $NH_3$ – ammonia;
$H_2NCOOH$ – ammonia carbonate; $CO_2$ – carbon dioxide
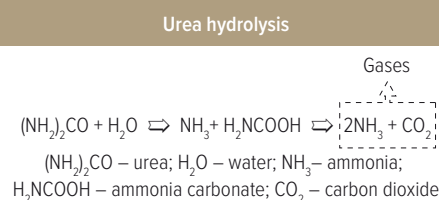
## Urea ammonium nitrate

Urea ammonium nitrate (UAN) is a fluid fertiliser containing 42 per cent N (weight by volume) in a 50:50 mix of urea and ammonium nitrate ($NH_4NO_3$). While UAN can be applied to the crop foliage and there is some direct leaf uptake, the primary mode of uptake is likely to be through the soil, after the product has been washed off the leaves by rain. The main attractions of UAN are that it can be readily stored for long periods in suitable tanks and it can be applied at the same time as other crop-protection chemicals and using the same equipment, thereby saving application costs. Compared with topdressing urea or ammonium sulfate, it is easy to apply UAN evenly and rapidly and it can be handled in wet conditions. Putting the logistical benefits aside, there is little evidence to suggest that liquid N fertilisers are any more effective than granular fertilisers. It is possible that in late-season dry soil conditions, uptake of N from the soil will be limited, while foliar uptake might be possible. There are some examples of later foliar application of UAN increasing grain protein of wheat in Australia's northern grains region (Zhu et al. 2008) and in WA (Pol and Loss 2004).

Rates of foliar N application should be less than 20L/ha unless 'dribble bars' or similar equipment are used. Higher rates of up to 70L/ha can be used up until mid-tillering (cereals and canola), but only under good moisture conditions where much of the fertiliser will be washed off the canopy and onto the soil. In this way it becomes more of a fluid than foliar fertiliser. UAN can be mixed with other fertilisers containing macro and microelements, or with growth regulators, nitrification inhibitors or pesticides and therefore can be applied in a single pass with these other agents. Consult your supplier for full details for use in conjunction with other products, as leaf burn or scorch may occur. Leaf damage is typically temporary and of little impact on yield, especially before the flag leaf stage in cereals. Liquid N sources containing urea, such as UAN, are volatile in the same way as urea. Since 50 per cent of the N in UAN is as urea and 25 per cent as ammonium ($NH_4^+$), the rest being nitrate, then three-quarters of the N will have the same risk of loss as urea and should therefore be considered in a similar manner to urea in terms of potential N losses.

## Mono and diammonium phosphate

These fertilisers contain 20 per cent diammonium phosphate (DAP) or 22 per cent mono ammonium phospate (MAP) P and 18 per cent (DAP) or 10 per cent (MAP) N and are manufactured from $NH_3$ and phosphoric acid. Mono and diammonium phosphate fertilisers are primarily used as a P source and applied at sowing with the seed. The quantities of N applied at typical P rates are less than the N fertiliser requirement for a crop; so these fertilisers are not used as a primary N source for grain crops. Nevertheless, the amounts of N added need to be taken into account in N fertiliser budgets and decision-making.

## Sulfate of ammonia

Ammonium sulfate (21 per cent N) can also be of use, particularly where sulfur (S) deficiency is suspected and on alkaline soils. Containing $NH_4^+$, it has a slightly higher capacity to acidify soil than some other N fertilisers, which may be a consideration on neutral to acid soils. Research on vertosols in NSW (Schwenke et al. 2014) found that when ammonium sulfate was applied to soils containing more than 20 per cent free lime, 20 to 30 per cent of the N in it was lost to the atmosphere as $NH_3$, so care needs to be taken with this fertiliser on soils with a high lime content.

## Anhydrous ammonia

Anhydrous ammonia is the most concentrated of the nitrogenous fertilisers at 82 per cent N. It is applied as a pressurised liquid in some high-input cropping systems (for example, irrigated grains, cotton). Since it is stored and transported as a liquid at high pressures, it requires specialised equipment for transport, storage and application. As it is a gas at normal temperatures and pressure, some ammonia can be lost from the soil during and after application. It requires free soil movement around the application tyne so is not very suitable for no-till cropping systems. It is most effective in soils with a high clay content where the $NH_4^+$ can be absorbed onto the clay particles present, thereby minimising losses. At present, the infrastructure to distribute anhydrous ammonia is not present in South Australia, Victoria or Tasmania.

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FERTILISER NITROGEN

## Nitrate fertilisers

Fertiliser $NO_3^-$ does not suffer from $NH_3$ volatilisation and is readily taken up by plants. It is, however, subject to denitrification where soils are very wet, as well as to leaching when there are high rates of drainage. Ammonium nitrate ($NH_4NO_3$) has been used as a fertiliser in Australia, although its primarily use has been as an ingredient in explosives in the mining industry. Unfortunately, the explosive potential of $NH_4NO_3$, when mixed with other chemicals, has been exploited in major acts of international and domestic terrorism. Therefore, fertilisers containing $NH_4NO_3$ are under strict government control in Australia, and those containing more than 45 per cent $NH_4NO_3$ are classified as 'security sensitive ammonium nitrate'. As a consequence, $NH_4NO_3$-based fertilisers have very restricted availability. As UAN contains only 12 per cent $NH_4NO_3$ it does not come under these restrictions. Similarly, calcium ammonium nitrate (about 25 per cent N), a mixture of lime (calcium carbonate) and $NH_4NO_3$, has been developed as an alternative to straight $NH_4NO_3$ fertiliser and is available in some regions.

## Organic fertilisers

Organic fertilisers are those originating from biological (plant and/or animal) material and are typically sourced from waste animal products (for example, chicken manure, pig bedding litter, human wastes) or plant products (for example, compost, mulch). These materials can supply nutrients and organic matter and improve soil biological activity and soil structure (aggregate stability, porosity, bulk density, water-holding capacity, erodibility) if applied over a long period of time or at a high rate. In recent years and with greater community emphasis on recycling and environmental management, the availability of organic fertilisers (Table 6-2) has increased along with more intensive animal industries.

Table 6-3 provides approximate concentrations of major elements in some organic fertilisers. The major plant nutrients in the organic fertiliser – N, P and potassium (K) – can be valued using the cost of those elements in mineral fertilisers. Costs of using organic fertilisers vary from site to site and include the costs associated with transport, handling, storage and spreading.

| TABLE 6-2 Some organic fertilisers used in Australia. | |
|---|---|
| Organic fertiliser source | Annual tonnages (million tonnes) |
| Biosolids | 1.60 |
| Feedlot manures | 1.30 |
| Poultry litter | 1.10 |
| Cotton gin trash | 0.12 |
| Total | 5.21 |

SOURCE: RECYCLED ORGANIC FERTILISER (2010) GRDC FACT SHEET

| TABLE 6-3 Properties of different organic fertilisers. | | | | | |
|---|---|---|---|---|---|
| Fertiliser | Water (%) | C (%) | N (%) | P (%) | K (%) |
| Fresh poultry litter | 21–36 | 28–36 | 2.6–5.0 | 1.2–2.6 | 1.0–2.8 |
| Feedlot manure | 20–54 | 11–44 | 2.2 | 0.8 | 2.3 |

SOURCE: RECYCLED ORGANIC FERTILISER (2010) GRDC FACT SHEET

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**A NITROGEN REFERENCE MANUAL FOR THE SOUTHERN CROPPING REGION** 55

| TABLE 6-4  Effects of initial N concentration (%) of organic fertiliser on N availability. | | | |
|---|---|---|---|
| % N of organic fertiliser | % N released in Year 1 | % N released in Year 2 | Tonnes to deliver 100kg $NO_3$-N in Year 1 |
| 1.0 | 22 | 13 | 45 |
| 1.5 | 31 | 13 | 22 |
| 2.0 | 41 | 12 | 12 |
| 2.5 | 50 | 12 | 8 |
| 3.0 | 60 | 12 | 6 |
| 3.5 | 70 | 11 | 4 |
| 4.0 | 80 | 11 | 3 |
| 4.5 | 89 | 10 | 2 |

SOURCE: MATHERS AND GOSS 1979

The availability of nutrients in organic fertilisers, particularly N, needs to be considered by the user. Because the nutrients are part of the organic matter of the fertiliser, they must be processed by the soil biota into plant-available forms and may not be immediately available to crops and pastures. Data from Mathers and Goss (1979) provides a guide to the release of N from organic fertilisers. The key factor for the proportion of the organic fertiliser N that became available was the initial N concentration (Table 6-4). However, the age of the organic fertiliser also affects its N concentration and N availability, with losses of N over time as gaseous $NH_3$ or through $NO_3^-$ leaching reducing the N concentration. There is an Australian Standard outlining the desirable properties of organic amendments in agriculture (Committee CS-037 2012).

The study concluded that to deliver 100kg of plant-available mineral N/ha would require about 14 tonnes/ha feedlot manure, 4t/ha dewatered biosolids and 2 to 10t/ha fresh poultry litter. These manures would at the same time deliver 90kg available P/ha (feedlot manure), 120kg P/ha (dewatered biosolids) and 35 to 80kg P/ha (chicken manure).

Although phosphorus availability may be more immediate because much of it is in the plant-available phosphate form already, it is subject to the same immobilisation reactions as phosphate fertiliser in soils. Fertilising to N needs using manures and other organic nutrient sources can result in over-fertilising with P, with the potential for significant off-site effects. Care needs to be taken with balancing the nutrients applied in organic materials.

Other recommendations (P. Wylie, personal communication) are that manures and composts are:

- incorporated into top 10cm of soil to enhance mineralisation, reduce ammonia volatilisation and position immobile nutrients such as P where they will be used;

- applied several months before sowing;

- aged and screened for uniformity; and

- used at rates of 10t/ha every four to five years.

With long-term use, ongoing soil testing should be done to monitor any build-up of nutrients or contaminants.

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Organic N sources, such as piggery bedding litter, can supply N to crops, although the low nutrient density (usually less than one per cent fresh weight) restricts their usefulness to areas close to the sources of these materials due to high transport costs relative to concentrated inorganic fertilisers. These materials are best incorporated, as a significant proportion of surface-applied organic manure N could be lost as $NH_3$.

There is increasing interest in the deep placement (>30cm) of chicken manure, pig bedding litter and other organic materials to improve soil fertility (physical, biological and chemical) and provide ongoing crop nutrition, especially for sodic subsoils. Such practices are in their infancy although striking productivity improvements have been demonstrated (Gill et al. 2008), in many cases due to substantially improved rooting depth, soil water extraction and N nutrition (Armstrong et al. 2015, Celestina et al. 2019).

## 6.2 REDUCING FERTILISER NITROGEN LOSSES

Fertiliser or soil N can be lost to the atmosphere through $NH_3$ volatilisation or as nitrogen gas ($N_2$) or nitrous oxides ($N_2O$) through denitrification of nitrate. Nitrate can also sink beyond the rooting depth of crops if it moves down with soil water (leaching). Fertilisers containing ammonia ($NH_3$), ammonium ($NH_4^+$) or urea are all potentially subject to $NH_3$ volatilisation losses, especially on alkaline soils.

**Ammonia ($NH_3$) volatilisation**

The key determinants of urea N loss as $NH_3$ are the $NH_3$ concentration and pH of the soil. During urea hydrolysis, the pH of the area around the urea increases, greatly enhancing $NH_3$ volatilisation. The ability of a soil to buffer against the alkalinity produced during urea hydrolysis influences the rate of $NH_3$ volatilisation; therefore, finer textured soils may have lower rates of $NH_3$ volatilisation than coarse-textured soils (Fillery and Khimashia 2016b). Ammonia losses from urea nevertheless occur on both acid and alkaline soils and can be high unless rainfall occurs soon after topdressing. Similar but smaller losses can also occur from UAN because the $NH_4^+$ in the ammonium fraction of N in the $NH_4NO_3$ is also converted to $NH_3$ as a result of the release of alkali from the urea hydrolysis.

Ammonia losses from urea and UAN spread on the soil surface are greatest under dry conditions because the $NH_3$ remains concentrated around the urea. However, if it rains the $NH_3$ is diluted and moves down into the soil where it is transformed into the $NH_4^+$ ion and losses are then very much less likely. Typical $NH_3$ losses from urea are 10 to 20 per cent (Turner et al. 2012), but under extreme conditions of warm temperatures and no following rain, $NH_3$ losses from surface applied urea of up to 40 per cent have been measured (Fillery and McInnes 1992). Ammonia losses from urea can be minimised by burying urea deeper than about 2cm (Figure 6-4). Urea N losses may also be exacerbated where the fertiliser is intercepted by crop residues because these have high concentrations of the urease enzyme and the crop residues do not have the pH buffering capacity of the soil.

Another option for improving the efficiency of urea or UAN is to band the fertiliser in high concentrations away from the seed or plants. High concentrations of fertiliser can deactivate soil microorganisms and slow the conversion of $NH_4^+$ to $NO_3^-$, reducing the likelihood of $NO_3^-$ leaching or denitrification for a short period of time. Recent research (Sandral et al. 2017a) indicates that mid-row banding of urea increases the uptake efficiency of the N applied when compared with spread or spread + incorporated urea, and that grain yields were higher following mid-row banding than following spread and incorporated urea.

There are some urea fertilisers available that contain 'urease' inhibitors (for example, NBPT). This is an enhancement added to urea that reduces the rate at which $NH_3$ is released for some time after application. While such enhancements should reduce the rate of $NH_3$ volatilisation (Chen et al. 2008, Suter et al. 2011c), the place and economic value of these in the grains industry is yet to be clearly demonstrated (Li et al. 2018). Fertiliser formulations containing urease inhibitors, which slow the conversion of urea to $NH_3$, could be useful where urea fertilisers are applied to foliage or heavy trash loads and cannot be incorporated into the soil.

**FIGURE 6-4** An example use of the Fillery and Khimashia (2016a) urea loss calculator, contrasting the difference between incorporated and broadcast application of 130kg of urea in stubble-retained or stubble-removed systems. All of the inputs can be changed except for the fertiliser product.

| Inputs | SCENARIO 1 | SCENARIO 2 |
|---|---|---|
| Soil pH (water) | 8 | 8 |
| Soil clay content (%) | 20 | 20 |
| Fertiliser product | Urea | Urea |
| Fertiliser N rate in (kg/ha) | 60 | 60 |
| Soil texture/rainfall | Loam – 10 to 16mm | Loam – 10 to 16mm |
| Days after application | 1 | 1 |
| Crop stage | Bare soil | Bare soil |
| Fertiliser placement | Broadcast | Inc to 3cm |
| % hung up in stubble | 10 | 0 |
| N cost ($/kg N) | 1 | 1 |
| | | |
| **Calculated emission factor** | 17% | 1% |
| **Estimated N loss (kg/ha)** | 10 | 1 |
| **Estimated value of loss ($/ha)** | $10 | $1 |

SOURCE: FILLERY AND KHIMASHIA (2016)

Fillery and Khimashia (2016b) provide a basis for estimating losses of $NH_3$ following urea application depending on soil type, application rate, placement, weather and crop or stubble cover. This has been incorporated into a readily accessible web-based tool (Figure 6-4) that can be found in Fillery and Khimashia (2016a).

### Denitrification losses

During denitrification, N is emitted as gaseous $N_2$, $N_2O$ or NO. Nitrous oxide ($N_2O$) is of particular significance as it has a greenhouse warming potential about 300 times greater than that of $CO_2$ (Dalal et al. 2003). Denitrification results from the combination of low $O_2$, high soil $NO_3^-$ and soluble organic carbon, and warm temperatures. It is important to note that measurement of $N_2O$ loss underestimates the total gaseous N loss through denitrification because gaseous $N_2$ is also produced. Since $N_2$ is not a contributor to global warming and it is very difficult to measure unless isotopically labelled N is used, denitrification losses as $N_2$ are usually not reported.

Nitrous oxide emissions measured in semi-arid rainfed grain cropping in south-eastern and south-western Australia have generally been extremely low, ranging from 0.1 to 2.0kg N/ha/year (Barker-Reid et al. 2005, Barton et al. 2008, Barton et al. 2010, Barton et al. 2013, Li et al. 2016) and contrast with higher emissions in the north-eastern grains region (Schwenke et al. 2015, Li et al. 2016).

However, under high-rainfall conditions at Hamilton in Victoria up to 35kg N/ha has been lost from cereal crops as $N_2O$. Management can influence the potential magnitude of $N_2O$ emissions. Emissions tend to be higher where crop rotations include few legumes and large amounts of fertiliser N are applied (Officer et al. 2015). Increased emissions have been found for wheat and canola crops after conversion from pasture to cropping (Harris et al. 2013, Mielenz et al. 2017) and for irrigated maize and barley (Wallace et al. 2015) in south-eastern Australia. Tillage does not seem to increase emissions (Li et al. 2016) and irrigation scheduling may reduce emissions (Jamali et al. 2015).

Nitrification inhibitors block the conversion of $NH_4^+$ to $NO_3^-$ for up to three months by acting directly on the $NH_3^-$ oxidising bacteria (*Nitrosomonas* spp.), therefore slowing the conversion of urea to $NH_4^+$. Nitrification inhibitors remain effective for longer in cool to cold climates. Nitrification inhibitors target losses of N via denitrification directly and leaching indirectly. Examples of products are N-Serve® (Nitrapyrin), Terrazole® and ENTEC® (DMPP) and DCD (dicyandiamide). Using a nitrification inhibitor can reduce losses due to leaching and denitrification, so that some N is preserved for the crop rather than lost to the environment. This can be of particular value for applications to wet soils or where waterlogging is likely, such as in the high-rainfall zone.

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A potential benefit of nitrification inhibitors is the reduction of emissions of $N_2O$. Suter et al. (2011a, 2011c) reported reductions in $N_2O$ emissions of 73 per cent (field) and 19 to 98 per cent (laboratory) when DMPP was added to urea fertiliser. There was a very strong effect of temperature, with the lower reductions associated with higher temperatures. Nitrification inhibitor-coated urea significantly reduced $N_2O$ emissions in all studies, but did not improve grain yields enough to justify the additional cost on an agronomic basis (Bell et al. 2016).

Denitrification is difficult to accurately quantify, although recent Australian research has provided data for sites across the eastern and southern grains regions. Strategies that reduced $N_2O$ emissions were essentially the same as those used to maximise crop yields without exceeding plant N demand. For example, splitting N applications was found to be an effective measure for reducing $N_2O$ loss in the southern region. In higher rainfall environments, such as Victoria's Western District, delaying N fertiliser application in canola until the green bud stage greatly increased fertiliser use efficiency and reduced gaseous losses. Including legumes in crop rotations has also reduced N fertiliser inputs and therefore $N_2O$ emissions (Mielenz et al. 2016).

**Leaching**

Nitrate leaching – the movement of $NO_3$- down the soil profile with water and beyond the crop rooting depth – is directly related to the amount of rainfall, soil $NO_3$- concentration and soil texture. Sands are more prone to leaching than clays because they have a much higher hydraulic conductivity and because they hold less water per volume of soil (Table 6-5). The likelihood of drainage occurring in a given season and soil can be approximated from Figure 6-5, but the amount of $NO_3$- leached would depend on the concentration of $NO_3$- in the soil.

## 6.3 SELECTING THE RIGHT NITROGEN RATE

Determining what fertiliser N rate to use depends on many factors, including the anticipated yield and protein of the crop grown, the likely supply of N from the soil, the type of fertiliser added, where and when it is added, what the N losses are likely to be, the price of the fertiliser relative to the grain price and premium paid for protein, and whether funds spent on fertiliser could be invested elsewhere for a better return. Here we shall deal with the estimation of crop N demand and crop grain N, the supply of N from the soil, and fertiliser type, rate, timing and placement.

| TABLE 6-5  Approximate water storage and saturated hydraulic conductivity of soils. | | | | |
|---|---|---|---|---|
| Soil | Sand (%) | Clay (%) | Water storage to 1m (mm) | Saturated hydraulic conductivity (cm/hour) |
| Sand | >75 | 5 | 140 | >20 |
| Sandy loam | 55–65 | 10 | 180 | 12 |
| Loam | 30–55 | 10–30 | 300 | 2.5 |
| Clay loam | <30 | 30–40 | 340 | 1 |

SOURCE: ROWELL, D. L. (2014). SOIL SCIENCE: METHODS & APPLICATIONS. ROUTLEDGE.

**FIGURE 6-5  Approximate seasonal drainage as a function of seasonal rainfall and soil texture.**
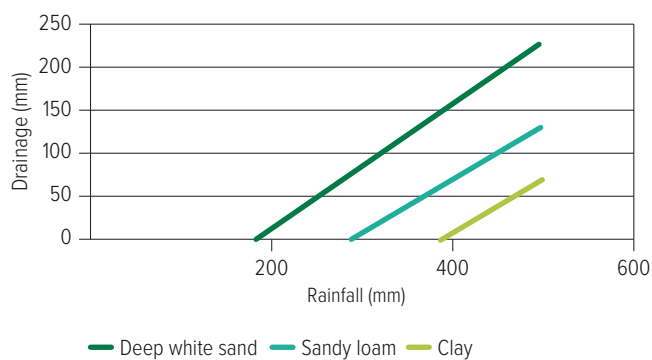


SOURCE: WONG ET AL. 2005

The amount of fertiliser to apply can be calculated as the difference between crop N demand (total N uptake) and the N available from the soil, divided by an efficiency of uptake of both soil N and fertiliser N by the crop. Since crop N demand and soil N supply can only be known at the end of the cropping season, we are required to estimate these as best we can from available information at sowing or during the crop growth period. Soil sampling and analysis at or before sowing can provide information on how much N is available in the soil at that time, but it does not tell us what is going to be mineralised during the crop growth period.

### 6.3.1  Estimating crop nitrogen demand

Decisions on N fertiliser requirements of rainfed crops are made with imperfect knowledge, before seasonal conditions dictate the actual crop growth and N demand. Therefore, crop N demand must be predicted by growers or advisers, based on experience (history), knowledge of present conditions and likely temperature and rainfall conditions in the weeks and months ahead. A simple water use efficiency calculation relating grain yield to growing season rainfall plus soil water stored at sowing is typically used. Potential yield (kg/ha) is often calculated using a French and Schultz (1984)-type model where, for wheat:

$$\text{Potential yield (kg/ha)} =$$

(soil water at sowing + growing season rainfall − 110) x 22

The 110 is an approximation of bare soil evaporation (see Unkovich et al. 2018) and the value 22 is the kilograms of grain produced per millimetre of water transpired by the wheat crop (Sadras and Angus 2006). This would give the potential water-limited grain yield. This figure is often scaled back 10 or 20 per cent by growers since the optimal economic N rate is typically less than the rate required for maximum crop yield, unless a premium can be achieved for higher grain protein. Parameters for barley and canola are given in Table 6-6.

Once a target yield has been established, the N demand is typically determined from an estimated grain protein content, calculated for wheat as:

$$\text{Wheat grain N (kg/ha)} =$$
$$\text{grain protein target}/5.7 \text{ x target yield (t/ha) x 10}$$

This equation would yield 17.5kg N/tonne grain at 10 per cent protein; for other crops the grain protein value is divided by 6.25, rather than 5.75.

The above equation can be simplified to:

$$\text{Wheat grain N (kg/ha)} =$$
$$\text{grain protein target x target yield (t/ha) x 1.75}$$

For other crops multiply by 1.6 instead of 1.75.

This grain N yield is not the total plant N (shoot + root N), because there is also N in the remaining shoots and the roots at harvest, typically about 50 per cent of the crop total wheat N (Angus and Grace 2017). The N concentration in canola seed (4.2 per cent, Norton 2016b) is about double that of wheat, as is the N demand for a given grain yield (see Table 6-7).

**TABLE 6-6  Convenient water use efficiency (WUE) parameters for estimating potential crop yield.**

| Crop | WUE (kg/ha/mm) | Evaporation (mm) |
|---|---|---|
| Wheat | 22 | 110 |
| Barley | 22 | 90 |
| Canola | 12 | 110 |

SOURCE: CSIRO

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## Worked example – canola potential yield

For a canola crop sown in a field with 50mm stored soil water and an average growing season rainfall of 270mm, the estimated potential yield would be:

Potential canola yield = 
(50 + 270 − 110) x 12 = 2520 kg/ha

## A note on nitrogen-to-protein conversion values

For the past 80 years, for all crops other than wheat, a factor of 6.25 has been used to convert grain %N to grain protein. This appears to be incorrect (see for example Mosse 1990). Tkachuk (1969) published N-to-protein conversion values for 18 cereal and oilseed materials (grains, flour, etc.). The range was 5.3 to 5.8. He suggested that the standard of using 5.7 for wheat and 6.25 for the rest was untenable because the factor of 6.25 resulted in an overestimation of protein content. A factor of 5.7 for all the grains would be more accurate. Although we recognise this error, we are forced to adopt the standard conversion factors of 5.7 (wheat) and 6.25 (the remainder) since all current systems are calibrated to these values.

By combining these estimates of grain protein with a crop N harvest index and the N estimated to be contained in the roots and root soil, the total crop N uptake can be estimated. Examples for wheat at a range of grain protein concentrations and grain yields are shown in Figure 6-6.

Estimated crop shoot N of different crops per tonne of grain yield are given in Table 6-7, and from this table the total N required by the crop can be estimated for a given yield.

The N in the shoot does not represent the fertiliser N requirement because some N is supplied from the mineral N in the soil at sowing and additionally from N mineralised during crop growth. However, not all of the N available in the soil is taken up by crops. Experiments in Australia and elsewhere have shown that where both crop husbandry and fertiliser N application are well managed, about 40 to 60 per cent of the fertiliser N applied is recovered in the shoots of a cereal or canola

crop in the year of application (Krupnik et al. 2004, Chen et al. 2008, Norton 2016b). Similar observations have been made for the uptake of soil mineral N.

The N supplied to the crop from the soil is:

N supplied by soil (kg/ha) = 
(soil mineral N at sowing + in crop mineralisation) x 0.5

The value of 0.5 is the fraction of the soil N supply recovered in the crop shoots. The soil mineral N at sowing is readily measured or estimated based on previous experience in a given field, rotation and

**FIGURE 6-6  Wheat total N uptake (including roots) at a range of grain protein concentrations and grain yields. It is assumed that 70 per cent of total plant N is in the shoot at maturity, and that grain N is grain protein/5.7.**
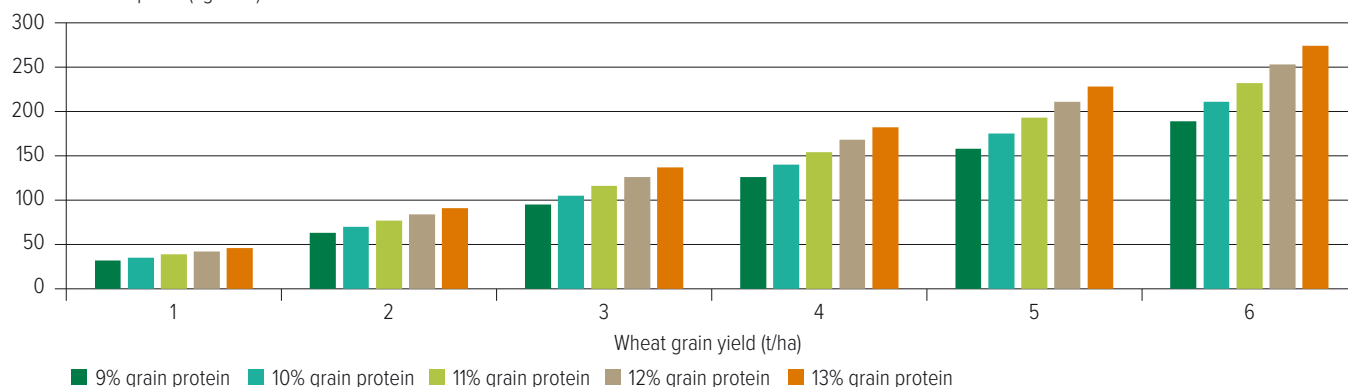
| TABLE 6-7 Crop shoot total N per tonne of grain yield. | | | | |
|---|---|---|---|---|
| Crop | Grain protein | kg N in 1t grain | NHI | Shoot total N (kg/t) |
| Wheat | 10.5 | 18 | 0.70 | 26 |
| Durum | 13 | 22 | 0.70 | 31 |
| Barley | 10 | 16 | 0.70 | 23 |
| Canola | 20 | 32 | 0.55 | 58 |
| Chickpea | 22 | 35 | 0.64 | 50 |
| Field pea | 23 | 37 | 0.64 | 53 |
| Faba bean | 24 | 38 | 0.64 | 54 |
| Lentil | 24 | 39 | 0.60 | 56 |
| Lupin | 32 | 51 | 0.60 | 73 |

NHI = nitrogen harvest index, the ratio of total grain N to total shoot N includes grain.

seasonal conditions (see section 4). The in-crop mineralisation is much more difficult to estimate (see sections 4.1 and 7) and in the absence of robust predictive tools requires site-specific experience.

$$\text{Fertiliser N required (kg/ha)} = \frac{\text{Crop total N} - \text{N supplied from soil}}{0.5}$$

The value of 0.5 is the fraction of the fertiliser N supplied that is recovered in the crop shoots. Most of the rest of the N fertiliser applied nevertheless remains in the soil and in crop roots, with a fraction lost to the atmosphere or leaching (see section 6.2).

Research has shown that as N supply increases relative to crop demand, the efficiency of uptake decreases, so fertilising with high rates of N (>200kg/ha) might mean a decreasing percentage of the applied fertiliser would be taken up by the crop. This is discussed further in section 8.2.

**Optimising grain protein in cereals**

The idea of using grain protein concentration to assess the likelihood of N responsiveness of wheat in cropping systems in South Australia was described more than 50 years ago (Russell 1963). The work suggested that yield responses were most likely when grain protein concentration was <11.4 per cent. An analysis of more recent trials in South Australia and Victoria (Figure 6-7) would indicate that this general conclusion still appears valid. In all trials where the grain protein concentration of the unfertilised control was <8.5 per cent, wheat was responsive to N fertiliser and gave a mean yield response of 14 kilograms

of grain per kilogram fertiliser N applied, although the magnitude of the yield response varied considerably. When grain protein concentration was >11.5 per cent, only 32 per cent of the trials were responsive to N and the mean yield response was zero.

While this relationship cannot be used to make in-season N decisions, it may be useful in helping to assess the degree of N stress during the previous season and in making post-harvest assessments of N management strategies, which can help with future planning. It is also useful for setting a target protein and yield for fertiliser N planning. Most analyses conducted in the southern region (for example, Browne et al. 2011) indicate that it is not usually profitable to try to fertilise for high protein (>11.5 per cent) since the cost of the additional fertiliser N required is not justified by the likelihood of achieving the higher grain protein content and protein payment premium, which is usually not high, relative to yield. It is clear that growers are best served by aiming to optimise grain yield rather than grain protein and supplying sufficient N to support a near water-limited target yield at about 11 per cent protein.

## Worked example – canola N uptake

For the canola crop with an estimated potential grain yield of 2520kg/ha, the N requirement is calculated as:

Canola N uptake = 2.52 x 58 = 146kg/ha

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## Worked example – fertiliser requirement

If our 2520kg/ha canola crop requiring 146kg N (58kg N/t) was sown into a field with 90kg mineral N at sowing and an additional 50kg of N was mineralised during crop growth, the fertiliser N requirement would be:

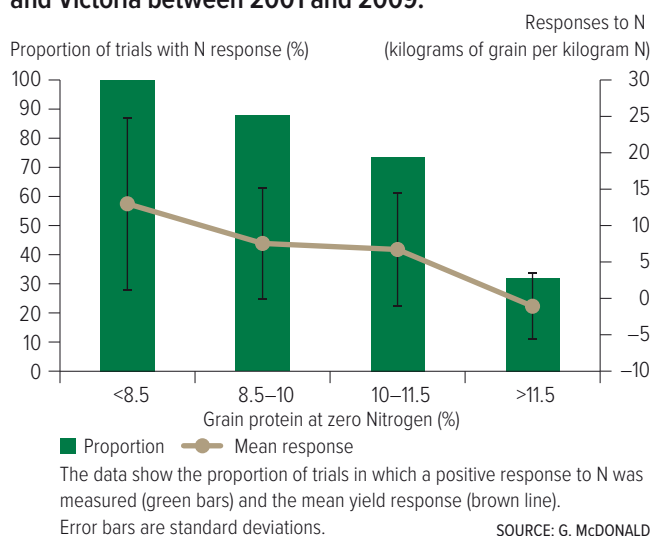N supplied from soil = (90 + 50) x 0.5 = 70kg N/ha

$$\text{Fertiliser N required (kg/ha)} = \frac{146 - 70}{0.5} = 152\text{kg N/ha}$$

### Optimising nitrogen in canola

Norton (2016b) recently reviewed N management for canola production in Australia and this, along with Norton (2013b), provides a valuable guide for canola cropping in the southern region. As for cereals, the maximum N demand for canola crops is during stem elongation. Increasing N supply to canola results in larger leaves and plants and a longer crop duration with extended flowering. Crop N uptake and photosynthesis in canola can persist longer than in cereals, and so photosynthesis and N uptake through grain fill can contribute substantially to grain yield and to protein, while mobilisation of stem or root reserves is generally of lesser importance.

Canola has a higher N concentration in grain (19 to 23 per cent), shoots and probably also in roots than wheat and thus requires more N to be taken up for each tonne of seed produced (40 to 44 per cent oil). This means that in higher yield potential (rainfall) environments, considerable fertiliser N may be required. Rates of 200kg fertiliser N/ha or more were required to achieve 4t/ha canola grain yields in the high-rainfall zone in Victoria when soil N supply was estimated to be 350kg N/ha (Riffkin et al. 2012). However, such high rates of N fertiliser should not be applied with the seed because (i) seed damage will occur, especially in dry sandy soils with narrow points and wide rows (Roberts and Harapiak 1997), and (ii) more fertiliser can be applied later when seasonal yield potentials can be better assessed. Nevertheless, problems with seed damage can be avoided by side banding or deep placement of fertiliser.

**FIGURE 6-7** The relationship between the grain protein concentration of wheat and the response to N fertiliser applied (kilograms of grain per kilogram fertiliser N) at sowing or later based on trial results from South Australia and Victoria between 2001 and 2009.



The data show the proportion of trials in which a positive response to N was measured (green bars) and the mean yield response (brown line). Error bars are standard deviations.

SOURCE: G. McDONALD

Generally, a supply of 40 to 50kg N/ha should be sufficient for the crop up until stem elongation, at which time N can be applied as required. There appears to be no yield penalty associated with splitting N fertiliser applications in canola (Norton 2016b). Delaying part of the application also reduces soil nitrate concentrations and the likelihood of losses to denitrification or leaching in higher rainfall environments.

Application of N at the stem elongation stage requires some knowledge of the N status of the crop. Significant N deficiency is most readily recognised through the yellowing and chlorosis of older leaves, which may also display some purple colouration, but it is more difficult to identify emerging and sub-acute N deficiency. Tissue (petiole nitrate) analysis was developed to identify N sufficiency and deficiency in canola (Hocking et al. 1997), but this technique has not been maintained for current varieties and farming systems. Consequently, estimates of potential yield and N supply at stem elongation provide the most useful indicator of N requirement, although N-rich test strips and crop sensors can also provide valuable insight (see sections 7.4 and 7.5).

Canola also has a significant sulfur requirement compared with other crops and S deficiency can reduce N-use efficiency. Hence, ammonium sulfate ($(NH_4)_2SO_4$) is often used to supply N and S for canola crops. Where more N is required, ammonium sulfate and urea can be blended to achieve the required sulfur and N mix. While additional N can increase canola protein concentration at the expense of oil, the effect on oil concentration is usually small and typically compensated by the increased total grain yield (Norton 2016b).

## 6.4 SELECTING THE RIGHT NITROGEN TIMING

Early N application or availability can contribute to increased shoot and tiller growth, and therefore potential yield, while applications after stem elongation can also contribute to yield as well as contributing to grain protein. In most of the southern region, unless spring growing conditions are good to very good, there will be little yield benefit from N applied after booting, although there may be a protein response. However, in higher rainfall environments yield responses have been observed with fertiliser N applications until just before flowering (Midwood 2014). The effectiveness of applying N to increase grain protein rapidly diminishes after flowering. In low-rainfall areas or in drier seasons, rainfall may be too low or variable to get consistent results from delayed N application.

Early fertiliser applications that help to increase tiller number can also help crops to compete better with weeds. However, in cereals it may be prudent to constrain early crop growth so that the development of crop leaf area does not exceed that which can be supported with the likely soil water supply during the grain fill period (Zhou et al. 2017). If the leaf area is too high to be sustained by the water supply then haying-off can occur and grain yield can be less than what could have

been achieved with a smaller crop canopy (van Herwaarden et al. 1998a). Seeding rate and tiller number influence crop biomass and early water use. There has been some research in Western Australia demonstrating that the optimal number of tillers in wheat is equivalent to 1/m²/mm growing season rainfall (Zhang et al. 2010).

It may not always be possible to apply all of the required N fertiliser at sowing because (i) the quantities of N required may cause crop damage (Norton 2016b), (ii) it may be logistically unfavourable to apply N through an airseeder when seeding time is critical, (iii) it may increase the likelihood of gaseous or leaching losses of N, and (iv) in cereals excess early N supply might produce a canopy that is unable to be supported by the amount of water available later during seed fill. Furthermore, applying all of the N at sowing assumes that one knows how much N will actually be required, but this cannot be predicted accurately in rainfed systems because the unfolding seasonal conditions play a large part in determining the final yield and thus N demand.

Field trials in SA and Victoria, (Figure 6-8a) show that delaying N applications to GS31 does not have a substantial effect on yield but delayed applications are more reliable when yields are >3t/ha (Figure 6-8b). Note that the risk of a negative response to N increases as yields decline due to there being insufficient soil water in mid to late spring to support high crop biomass in dry years.

For canola there also appears to be no advantage of late application of N fertiliser (Ramsey and Callinan 1994, Farlow et al. 2014), although split applications appear to be reliable and, importantly, allow growers to make decisions based on developing seasonal conditions (Norton 2016b).

In environments with low yield potential, N fertiliser decisions and applications can sometimes be made at sowing because (i) expected yields and

N applications rates are lower, and these amounts can readily be applied at seeding, (ii) it would not be cost-effective to apply small amounts of top-up N later, and (iii) dry surface soil conditions later in the season may prevent fertiliser N from being available for uptake and also increase the likelihood of NH$_3$ losses.

Conversely, in higher yielding situations, consultants and growers are increasingly splitting N applications because (i) as yield potentials increase, the financial risk associated with variable seasonal conditions and high rates of N application increase, (ii) high rates of N applied at sowing can be toxic to crops (see Table 6-9) and also increase the likelihood of N losses through leaching and denitrification, and (iii) yield potentials and therefore N demand cannot be reliably predicted, but knowledge later in the season may give greater confidence as to whether an N application will be cost effective. There is therefore a demand for information about both the mineralisation of N in soil as seasonal conditions change and, in higher rainfall environments, the availability of fertiliser N as soil water contents vary.

One of the risks of delaying N applications after seeding may be that trafficability problems arise on wet soils where growers are unable to apply N at optimal times or have to resort to more expensive application techniques (for example, aeroplane). This may be less of an issue where controlled traffic is used. In the case of N deficiency associated with waterlogging, additional N fertiliser should be applied as soon as the soil drains and becomes aerobic. The use of controlled release (polymer-coated urea) fertiliser has been shown to be of benefit in improving N-use efficiency and yield of wheat under waterlogged conditions, but the additional cost of the product over and above standard urea may not be balanced by the increased efficiency compared with using a higher rate of urea (Kisaakye et al. 2017).

## 6.5 SELECTING THE RIGHT NITROGEN PLACEMENT

The application method and N placement is a complex decision involving the row spacing, the crop, the amount of soil disturbance and the type of crop. The International Plant Nutrition Institute has developed a calculator to assist (IPNI 2018). Safe urea application rates are given in Table 6-9 and depend upon the soil type, row spacing and spread of seed and fertiliser in each row. Toxicity is most likely on clay soils and wide row spacings with a narrow spread of seed and fertiliser. While

**FIGURE 6-8** (a) Grain yield of wheat in response to N application at sowing or delayed until GS31 in field trials in SA and Victoria, and (b) grain yield of wheat fertilised at GS31 as a percentage of the yield obtained with N applied at sowing.



SOURCE: G. MCDONALD (UNPUBLISHED)
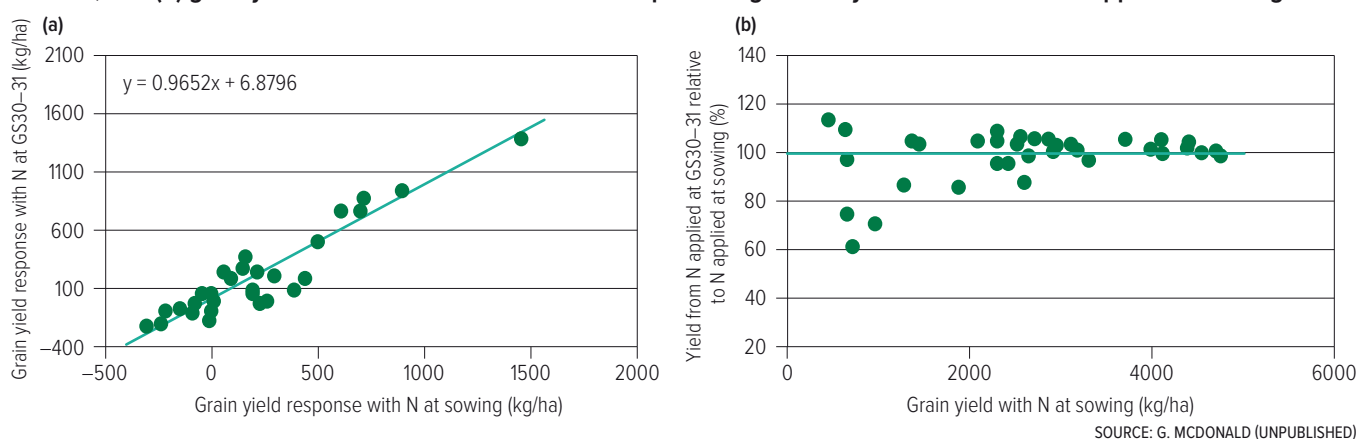
**TABLE 6-8  Key N fertiliser decision points for cereal crops.**

| N decision point | Action |
|---|---|
| Pre-sowing | Soil sample and analyse for available N if possible. |
| Sowing | Apply sufficient N for modest yield potential, or higher yield potential if good stored soil moisture at sowing. |
| Tillering | Reassess yield potential, check tiller number in relation to current estimate of yield potential, apply N to increase tiller number if required. |
| Stem elongation | Reassess yield potential and tiller number based on seasonal rainfall and outlook, apply fertiliser N if required to match potential yield and grain protein target. |
| Booting | If yield potential has increased significantly, may need additional N to maintain protein >10%. |
| Harvest | Assess grain protein and N yield, keep record, assess likely extent of unused fertiliser N and reflect on fertiliser strategy used and final outcome. |

**TABLE 6-9  Approximate safe urea N (kg N/ha) application with seed for different row spacings and seed spread (point width) and soil types.**

| Seed spread | 2.5cm (1") | | | 5cm (2") | | |
|---|---|---|---|---|---|---|
| Row spacing (cm) | 18 | 23 | 30 | 15 | 22 | 30 |
| Light (sandy loam) | 20 | 15 | 11 | 40 | 30 | 22 |
| Medium-heavy (loam to clay) | 25 | 20 | 15 | 50 | 40 | 30 |

SOURCE: NORTON AND DESBIOLLES 2011

low rates of urea drilled in with the seed might cause seedling toxicity, these can be banded either below or to the side of the seed at much higher rates with little risk. Fertiliser applied in a band below the seed may reduce the availability of N to weeds, compared with broadcast fertiliser, and therefore assist with weed management.

Otherwise N can be broadcast and incorporated before or at sowing at higher rates. There may be several benefits from mid-row banding of urea using a 'skip-row' arrangement such that high concentrations of urea are placed between every second row (Sandral et al. 2017b).

The advantages of this may include:

- delayed conversion of ammonium to nitrate and therefore lower likelihood of denitrification, leaching and immobilisation;

- delayed plant N uptake, reducing the likelihood of haying-off;

- root proliferation around the fertiliser band and increased fertiliser use efficiency; and

- the ability to apply at a higher rate without damage to seedlings.

Further advice on fertiliser placement can be found at IPNI (2013).

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# 7 NITROGEN DECISION SUPPORT TOOLS

While a range of tools has been developed for estimating available N in crop rotations in Australia, there is no single universal tool (yet) for making N fertiliser decisions. Available N decision support tools include simple rules of thumb, Excel spreadsheet models, standalone mineralisation models for computers, paper-based models incorporating wheels or slide rules, applications (apps) built for smartphones or tablets, and web-based tools such as YieldProphet®, based on the APSIM platform (Hunt et al. 2006, Hochman et al. 2009). Valuable information is gained from soil and plant tissue analysis, N fertiliser 'test strips', sensors that measure how green and dense a crop canopy is, and historical grain yield and protein data at the paddock or sub-paddock scale.

Most of the tools for estimating in-crop N mineralisation were developed when legume-based pastures significantly boosted soil fertility in rotations; tools developed in such systems may not be as relevant to current intensive cropping systems. Many of these tools also operate on an annual time step and provide little insight into in-crop N management decisions. Annual time-step tools may be inadequate, as growers need to reassess on a weekly basis and adjust an N fertiliser decision in-season, depending on rainfall conditions and weeds, disease and pests, which might alter yield potential substantially or increase the likelihood of urea volatilisation, denitrification or leaching losses. None of the currently available tools appear to provide field and season-specific information about N mineralisation on a useful time step, although we have not been able to assess tools and systems used by private fertiliser companies to estimate N fertiliser application strategies. Complex models requiring detailed parameterisation, such as YieldProphet®, require a substantial investment of time but can provide valuable guidance.

## 7.1 MEASURES OF SOIL-AVAILABLE NITROGEN

Testing for plant-available N in the soil through a laboratory certified by the Australasian Soil and Plant Analysis Council (ASPAC) remains a critical part of fertiliser N and crop rotation decision-making. Knowledge of the available N (ammonium and nitrate) in the soil at crop sowing assists in making informed N fertiliser decisions. While it is not practical to sample every paddock each year, regular sampling across years, crop rotations and soil types will provide a basis on which to make rational decisions informed by data and experience, rather than just 'gut feel'.

Protocols for appropriate soil sampling can be found in Dalgliesh and Foale (2000) and Rayment and Lyons (2011). Soil samples should be sent to the laboratory for analysis as soon as possible, where they will be dried immediately at 40 to 70oC. Significant mineralisation is likely if wet samples are in transit for a week or more before drying, especially if temperatures are high. If this is likely, it is recommended to store samples in a fridge before transport. Measures of available N should include both ammonium and nitrate, not just nitrate. Water extracts should not be used because these do not include mineral N bound to soil and organic matter particles and can grossly underestimate mineral N availability. The standard measure of plant-available N from soil samples in Australia is potassium chloride–extractable N, which approximates currently available N but does not provide insight into what might become mineralised in the weeks or months ahead.

In-paddock measurement of available N is possible with new techniques, but these are yet to be proven reliable in the absence of site-specific calibration. It is anticipated that in the future real-time measurement of soil-available N will become available and reliable.

An example of the way in which growers use soil N testing to assist in N decision-making can be found in case study 9.5.

## 7.2 PRAGMATIC APPROACH TO NITROGEN FERTILISER APPLICATION

If growers do not use N calculator tools or Yield Prophet® to help make decisions about N management in wheat, there are some general recommendations that can be followed.

• Target a yield potential at the start of the season, whether it is based on soil water at sowing, average wheat yield or average plus a bit, depending on your optimism.

• Estimate the amount of N available from the soil, based on soil testing or on guidelines established from several years of paddock histories and local experience.

• Calculate the amount of N required to reach your target (see section 6.3.1).

• Apply 70 to 80 per cent of the N required between mid-tillering and mid-stem elongation. Adjust the timing of the application depending on initial soil N and factors such as time of sowing.

• The remaining N can be applied later, up to flag leaf emergence, to maintain or boost grain protein, depending on seasonal conditions and soil moisture availability. The rates of N can be adjusted in response to seasonal conditions.

## 7.3 RULE OF THUMB FOR ESTIMATING AVAILABLE NITROGEN

A rule of thumb used for continuous cropping on the black soils of the Wimmera for estimating in-crop N mineralisation is organic C percentage x 0.15 x growing season rainfall (mm) (Armstrong et al. 2016). Using such a calculation could return in-crop mineralisation from 12 to 142kg N/ha, depending on soil C percentage and growing season rainfall. It is unlikely that this rule of thumb would be portable to other soils, systems or regions.

## 7.4 VISUAL SYMPTOMS OF CROP NITROGEN DEFICIENCY

In cereals, by the time visual symptoms of N deficiency become apparent, some yield potential may already be lost. However, N deficiency can be rectified if identified early enough in crop development. Nitrogen-deficient cereals are pale green and of ill thrift, and they will have few tillers if they are up to that stage. Nitrogen deficiency first appears in the older leaves, which will have transferred their N to younger leaves. Stems may be pale pink. Symptoms may be worse on light (sandier) soils where there is very low organic matter or on waterlogged soils. At harvest, grain protein will be less than 10 per cent.

Although crop tissue N concentration is a useful guide to N sufficiency, it has been shown to be more robust to use the combination of tissue N concentration and crop biomass (Fitzgerald et al. 2010, Neuhaus et al. 2017). Although regional and seasonal variations might need to be taken into account, these are yet to be articulated.

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**FIGURE 7-1 Approximate change in N concentration of wheat shoots during the life of an N sufficient crop. The value of 1 on the X-axis equates to crop maturity.**
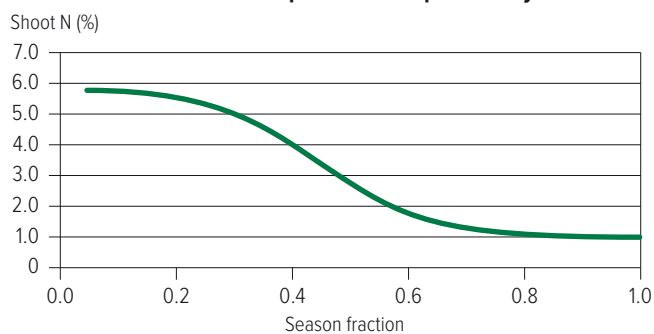


SOURCE: M. UNKOVICH (UNPUBLISHED)

### Using nitrogen-rich strips

When establishing a crop, it may be useful to set up some test strips in the paddock to examine the response to improved crop N nutrition. These strips can be established before or after sowing by applying an additional amount of N (or other) fertiliser in a long strip across the paddock. Choose an area representative of the paddock, or a long strip that cuts across changes in topography and soil type. These N-rich strips then provide a guide or reference point for examining possible crop responses to additional N. Strips can be established with a combine, airseeder or boom spray if applying fluids. A four-wheel motorbike with a boom spray can be a quick way to set these up, possibly with overlaps for more than one N rate. Nil N strips can also be informative.

The location of the test strips must be clearly recorded and marked in the field, or perhaps placed using global positioning system (GPS) guidance. Probably the best time to examine N responses is at the start of stem elongation, a critical time for fertiliser application (see section 6.4). The N-rich strip can be visually inspected for differences between it and the remainder of the paddock, using handheld or vehicle-mounted sensors or satellite imagery. If the N-rich strip appears to be healthier and the yield potential looks significantly higher, then it provides strong evidence that there is likely to be an economic N response in the remainder of the paddock. If additional N is applied to the paddock, also add it to the N-rich strip as this could still provide a useful point of reference and learning at harvest.

Examples of the way in which growers use N-rich strips can be found in case studies 9.3 and 9.4.

## 7.5 THE ROLE OF PRECISION AGRICULTURE AND VARIABLE-RATE TECHNOLOGY

Information (data) at fine (sub-paddock) scale, either in real-time or historical, can be used to assist in farm, crop and N fertiliser management and to improve fertiliser use efficiency. Fertiliser N is often the primary target for variable-rate approaches because it is needed in large amounts, is relatively costly and can be applied strategically during the season. There are emerging opportunities in the use of real-time sensors for soil and crop analysis in paddock, and for grain yield and grain quality. Satellite imagery is improving in quality, scale and accessibility (see case study 9.2).

Advances in the use of auto-steer machinery and precision agriculture (PA) technologies are continuing apace but are beyond the scope of this manual. General guidance on precision agriculture technologies can be found in Leonard (2009) and detailed information in Leonard and Price (2006) and Nicholls and McCallum (2012). These latter two publications also include case studies highlighting some of the different opportunities that precision agriculture brings to N management. Further case studies are included in section 9 of this manual.

Evaluation of variable-rate N technologies on grain farms in Western Australia showed that variable-rate application of N was generally profitable and set-up costs returned within two to five years (Robertson et al. 2007). However, this excludes the many other benefits of PA and, when these are included, costs might be recovered much quicker, especially where there is significant variability in soils and/or grain yields within individual paddocks.

An example of the way in which growers use precision agriculture and variable-rate technology can be found in case study 9.4.

## 7.6 SATELLITE IMAGERY AND CROP SENSORS

Information on the N status of crops can also be obtained via satellite, from sensors mounted on vehicles or unmanned aerial vehicles (drones). These primarily work on the principle that the concentration of chlorophyll in leaves changes the ratio of the absorption of red and blue light to the reflectance of near infra-red light. Such data can be obtained at fine (≤1m) spatial scale and can therefore be incorporated into precision agriculture management systems, although a scale of 2 to 25m is perhaps more readily obtainable.

In addition to such sensors giving an indication of the greenness of the crop, they can also estimate crop biomass and crop vigour and provide guidance on crop N requirements in real time. The technicalities of these systems are beyond the scope of this manual but guidance on crop sensors is provided in Whelan (2015) and example applications in Poole (2009) and Cammarano et al. (2014). Satellite imagery is not effective on cloudy days, a problem not encountered with vehicle or drone-mounted sensors and this can be an issue in some areas (for example, case study 9.6).

It should be stressed that poor crop growth as indicated by remote sensors may not be due to N nutrition but can be confounded by water stress (Tilling et al. 2007), diseases, pests or other factors. Most field assessments will need an N-rich strip for in-field calibration.

Examples of the way in which growers use sensors can be found in case studies 9.3 and 9.4, and satellite imagery in case study 9.2.

### 7.6.1 Grain protein sensors

Near infrared sensors fitted to the grain elevator on a harvester can provide on-the-go grain protein sensing at fine spatial scale across a paddock. Combined with yield data, this information can be used to examine the interactions between yield, protein and soil type across the paddock and assist in future N fertiliser decisions. While areas of low protein might be expected to require greater N inputs in future crops, experience has shown that lower grain yield is not always associated with lower grain protein (Whelan et al. 2009). In fact, the reverse is often the case.

Spatial data on grain protein might be more useful for managing the quality of grain delivered to the silo as it provides an opportunity for tactical in-paddock blending or segregation of grain to ensure that a target protein can be met. Blending or segregation of grain in-paddock can return substantial financial benefits. However, protein sensors may not always provide reliable results, so some in-field checks against laboratory-analysed samples are recommended to establish the reliability of your sensor system (Whelan et al. 2009, Bramley 2012).

An example of the way in which growers use grain protein sensors can be found in case study 9.1.

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## 7.7 APSIM AND YIELD PROPHET®

APSIM (Agricultural Production Systems Simulator) is a computer modelling system developed in Australia to simulate biophysical processes in farming systems and the outcomes (economic and biophysical) of management practice in the face of climatic risk (Keating et al. 2003). It has been shown to be able to realistically simulate commercial grain crop yields, provided that the specific soil properties and management practices are well characterised (Carberry et al. 2009). It was developed as a research tool and as such requires both considerable user experience and detailed soil, crop and management information before reliable results can be obtained. The need for detailed and specific soil and management data and a steep learning curve make it less attractive for advisers or grain growers. However, a simplified web-based version (Yield Prophet®) and subscription service is available (Hunt et al. 2006).

Yield Prophet® is able to estimate virtual crop growth and potential yield in real time, based on actual daily rainfall and temperature and simulated soil N mineralisation. It can provide grain growers with up-to-the-minute advice on current crop growth and the possible effect of management interventions on crop yield and quality. Some grain growers are using Yield Prophet® to match N fertiliser input to crop requirements at various times during growth. This modelling approach can help to reduce grower uncertainty about yield prospects and the potential effects of management options on grain production and profit. The Yield Prophet® service is typically used in an iterative fashion during a cropping season, providing feedback on management interventions and seasonal climatic conditions at critical points in the cropping cycle. The platform is also able to be integrated with a range of real-time information from soil and crop sensors or other relevant information (for example, economic indicators).

More detail can be found at the Yield Prophet® web portal.

# 8 ECONOMIC CONSIDERATIONS

## 8.1  INTRODUCTION

Fertiliser N decisions are influenced by numerous factors, and for some grain growers the economic considerations are secondary to other factors. For example, some growers like simple crop management packages and therefore have pre-determined fertiliser rates for all wheat crops on the farm regardless of history and seasonal conditions. Some may have a fixed fertiliser budget, and opportunities for post-emergent N applications to exploit favourable growing conditions are not considered if the budget is exhausted. In some regions and years, supplies of fertiliser are exhausted and not available, even if growers want to apply N during the season. In other areas, waterlogging may limit opportunities for N application. For this section of the manual, economic considerations are discussed on the assumption that the grower is motivated to achieve the best economic outcome from their investment in fertiliser, while considering risk, and has the ability to apply N fertiliser in-season on a paddock-by-paddock basis in response to growing conditions.

There are some key principles of farm economics relevant to the use of fertiliser N on crops. This chapter outlines some of the principles that are important in grower or adviser decision-making on the use of N in cropping systems. These key principles of farm economics are:

- the whole-farm approach – the combination of all things;
- the marginal principle – diminishing marginal returns to additional input;
- equi-marginal returns and law of the minimum;
- opportunity cost;
- farm inputs as an investment;

- the principle of increasing financial risk; and
- risk creates return and intensification increases both return and risk.

The first principle, the 'whole-farm approach', holds that solutions to problems of parts of the farm system are not necessarily solutions to problems of the whole. The whole-farm approach involves analysis to determine if a change to a farming system is likely to be beneficial, considering the farmer's goals such as building wealth through extra profit, extra cash flow, and with acceptable implications for risk, while helping to meet other important goals of the farm family. The whole-farm approach recognises that the operation and performance of a farming system is the result of the combination of all parts. All inputs come into consideration when thinking about changes to the farm system to help achieve farm family goals.

The second principle, related to the first, is the marginal principle: 'a bit more of this, a bit less of that, am I better off?' This requires farm analysts to think 'at the margin', knowing the principle of diminishing marginal returns to an additional input with other inputs unchanged is at work and applies to all the inputs used in the farm system.

Related to the principles about a farming system being the combination of all components and the principle of diminishing marginal returns is the idea formally called the 'principle of equi-marginal returns'. A farm is operating at its best when all inputs are 'equally limiting'. An additional unit of one input to reduce a constraint to output and profit cannot add more to output or profit than another unit of any other input; that is, the extra return from an extra unit of an input is equal to the extra return from an extra unit of another input. Related to this idea is the 'law of the minimum'. This holds that, while dealing with nutrition of crops and pasture, production will be constrained

by the nutrient that is 'most limiting'. This limiting condition is removed by adding more of the limiting factor, until another plant requirement becomes the limiting factor.

The concept of opportunity cost is a corollary of the principle of equi-marginal returns. Opportunity cost is the net benefit that is given up by doing one thing, such as using one input to increase production, instead of doing some other thing, such as using a different input in production.

Another matter when investing in inputs is to consider the likely return on that investment. If money must be borrowed to finance an input, then the likely return will need to repay that money and cover the (interest) cost of that capital. But for grain growers there may be an extra return (over and above the cost of capital) needed to provide a return to their entrepreneurial management and give a margin for the riskiness in yield response.

Another important principle of farm finance is known as the principle of increasing financial risk. This principle holds that as more debt is incurred in a farm business, the chance to grow wealth more rapidly increases. At the same time, the chance (risk) of eroding wealth increases more rapidly.

In farming, benefits and risk are related. Low risk means only low benefits are on offer, higher risk means higher benefits can be generated. This is because risk creates benefit. Without risk, farming would not be worth doing. If investing to improve the performance of farm business increases the average profit, it also involves increasing the volatility of annual profit. This means managing more risk than was previously the case, but, on average, from a base of an increased profit. Thus, change that successfully lifts the average performance of the farm business, such as intensification, increases both the mean and volatility of farm returns.

Each of these principles about farm performance and farm analysis come into play when considering investments in fertiliser inputs to production: which fertiliser to use on different crops in different areas of farming systems, how much to use, and when to apply. To answer these fertiliser questions, the costs and benefits and risks are analysed, informally or formally, on the basis of the plant–fertiliser response function that the decision-maker expects to be at work on the area of crop being fertilised.

A biological response function is the relation between the amount of an input applied and the amount of output that results, with all other inputs not limiting. The interest for the farm decision-maker is the amount of extra output and the value that can be expected to result from incurring the cost of adding an extra unit of an input. More precisely, it is the extra cost of an extra unit of input and the extra benefit – yield multiplied by price – that is created. If the extra benefit exceeds the extra cost, then extra profit is created, along with extra risk. This thinking is used keeping in mind that an extra unit of another input could create an even greater extra benefit and risk. If this is the case, the principle of equi-marginal returns tells that the input that adds the most extra benefit minus extra cost with acceptable risk should be used.

Farm production is about combining all inputs of which N is just one input; the actual yield response in any particular paddock of crops and pasture to additional N is uncertain. The price of the extra yield too is usually uncertain. Despite the lack of information and uncertainty about extra yield and extra revenue that will be achieved from applying extra N, farmers make generally sound decisions about using N and all the other inputs that add to their whole-farm profit. So how do they do it?

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When a truckload of grain or other produce leaves a farm, this production is a result of the decisions the grower has made about combining all the inputs under their control: fixed inputs such as land, permanent labour, plant and machinery, and variable inputs such as fuel, fertiliser, seed, chemicals and water, as well as the inputs the grower does not have total control over in broadacre farming systems such as rainfall, temperature, frost, drought and so on. These decisions are made under conditions of uncertainty. The decisions that growers make about combining all the inputs involved in running their farm businesses are of three types:

- day to day;

- tactical (within season, within crop); and
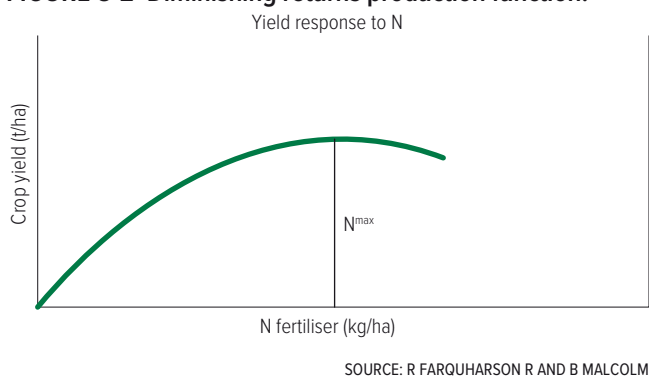
- strategic (medium term, with implications beyond a year).

Decisions about how much N fertiliser to use, on which crop or pasture and when, are tactical and day-to-day decisions. The use of legumes to contribute N to the farming system and the management of soil organic matter to provide mineralised N is a strategic decision.
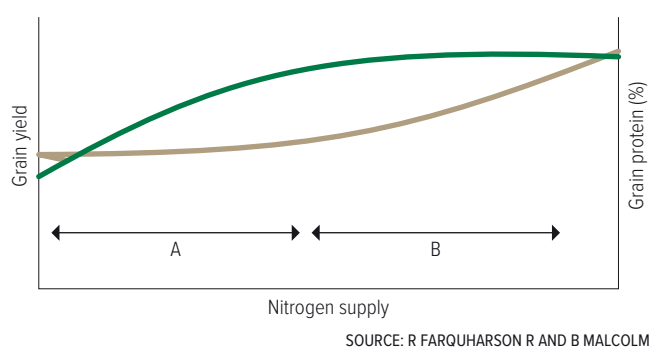
## 8.2 IN THEORY

Plant production is a multiple-input, multiple-output process. For wheat, the economically important outputs are crop yield (Y) and protein content. The inputs to wheat production are nutrients (N, phosphorus (P), potassium, sulfur and micronutrients) and rainfall and moisture. The most important inputs to wheat production in the southern region are N and moisture.

We are interested in 'how much' questions, from a grower viewpoint: how much N fertiliser should I apply to grow a wheat crop according farmer objectives?

### Biophysical considerations

We need to know the likely crop yield (and protein) outcomes for alternative N decisions (N rates). Increases in yield and protein content both occur with N from any source and a stylised representation of this process, adapted from McDonald and Hooper (2013), is in Figure 8-1. At low levels of N supply (section A of the curve), yield increases but protein does not change much with added N, whereas at higher N rates (section B of the curve), yield shows no further increase but grain protein does.

Rainfall is obviously important in rainfed (dryland) agriculture and yield responds to both N applied and climate (mainly rainfall). Providing there are no other major limitations, yield increases as more N is added, but the increase is at a decreasing rate (Figure 8-2).

Typically, these yield response shapes are increasing at a decreasing rate (diminishing returns). This type of response is based on agronomic principles of Liebig's law of the minimum (Harmsen 2000), and diminishing returns to additional inputs are often observed. The yield response shown in Figure 8-2 is to additional fertiliser. In this chapter the fertiliser decision is set in terms of yield responses while acknowledging the yield protein interactions of Figure 8-1.

**FIGURE 8-1  General response of yield (green line) and protein content (brown line) to N fertiliser.**



SOURCE: R FARQUHARSON R AND B MALCOLM

**FIGURE 8-2  Diminishing returns production function.**



SOURCE: R FARQUHARSON R AND B MALCOLM

**FIGURE 8-3  Small changes in crop yield response.**



Yield response – diminishing returns

SOURCE: R FARQUHARSON R AND B MALCOLM
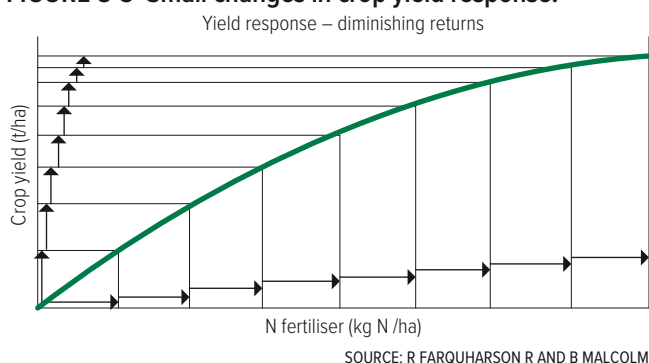
### Economics and the nitrogen decision

The production economics framework has long addressed the economic 'how much' question arising from Figure 8-2. This involves a marginal economic analysis of benefits and costs from considering small (incremental) N decisions, starting from the lowest N level, as shown in Figure 8-2. This production information can be turned into a decision framework as follows.

### (i) Marginal product (MP) and marginal revenue (MR)

The marginal product (MP), shown in Figure 8-4, is the change in yield from incremental additions of N and is estimated from the production function (Figures 8-2 and 8-3). For each incremental N application, the corresponding yield gain can be measured or estimated. For the diminishing returns yield response, the incremental change in yield is initially relatively large and declines to zero at the maximum yield (Figure 8-4). The MP is multiplied by the crop price to develop the marginal revenue schedule (Figure 8-4).

The MR shows what each incremental unit of N is worth in terms of the value of crop yield increases. It shows what the grower would be willing to pay for additional units of N in growing the crop. The MR depends on the yield response relationship to N and the crop price.

Apart from the price of wheat, payments to growers also depend on protein percentage. Typically, a base protein is specified for each grade. Because of the relatively small premiums or discounts due to differences in grain protein, adjustments for protein content are not included here.

### (ii) Include marginal cost (MC) for the nitrogen decision

Now the cost of adding extra fertiliser can be included. For each extra unit of N added, this is the price of N fertiliser. The marginal cost (MC) of N fertiliser is compared with the MR to find the 'best' economic fertiliser outcome (N*), see Figure 8-5a. The 'best' economic rate of N is where MR = MC.

From Figure 8-5 the 'best' economic level of N to use (N*) is lower than the fertiliser level for the maximum yield ($N^{max}$). Why? Because the MR is less than the MC as more N is added between N* and $N^{max}$. The fertiliser decision can also be seen on the yield response where the change in yield (MP) equals the price ratio of fertiliser/crop (Figure 8-5).

### (iii) Risk aversion

If we now consider the possible yield responses that could be associated with increased variability, then decision-makers might be averse to increased risk (increased variance in crop income). Thus, risk-averse growers may apply even less than the 'best' economic amount (N*), where MR = MC. The risk-averse decision for fertiliser N input is shown as $N^{risk}$ in Figure 8-6.

**FIGURE 8-4  Change in (a) yield (marginal product) and (b) marginal revenue with incremental N fertiliser.**



a) Marginal product

b) Marginal revenue

SOURCE: R FARQUHARSON R AND B MALCOLM
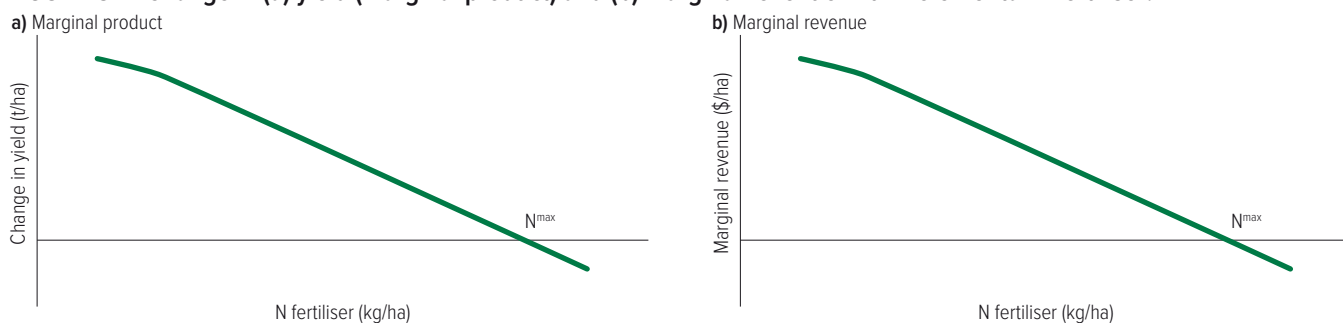
**FIGURE 8-5  Marginal revenue, marginal cost and the fertiliser decision.**

**a)** MR and MC



**b)** MP and price ratio
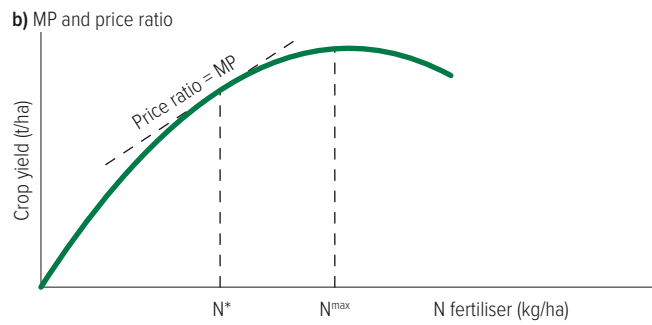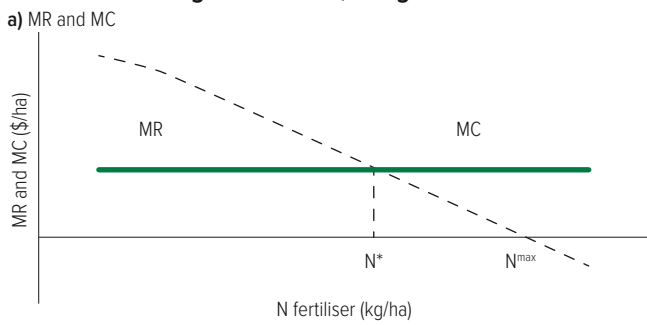


SOURCE: R FARQUHARSON R AND B MALCOLM

### (iv) Flat economic responses

Economists have further considered the shape of these economic responses in making fertiliser decisions. It has been found that the economic payoff function to fertiliser is in fact relatively flat for a range of fertiliser rates near the agronomic maximum and economic 'best' rates. Figure 8-6 is redrawn as a 'profit' function in Figure 8-7.

The wide range of N rates with at least 90 per cent of the maximum crop gross margin (GM or net fertiliser profit) means that it makes little sense to be ultra-precise with fertiliser N inputs over the flat economic response part of the curve.

## 8.3  THE REAL WORLD

In the real world, do cereal producers explicitly consider marginal economic costs and revenues in making their decisions? Not explicitly, for the above reasons of flat economic responses and yield variability. They know their own soils, paddocks and climate and they intuitively include these factors in making their fertiliser decisions.

Is there any use in thinking about the economics of fertiliser decisions to support growers? What about cereal producers who are using fertiliser at lower rates than the flat economic response range? In Australia there is concern that dryland cereal producers are under-fertilising. There may also be cases of over-fertilising, when N loss can be important.

**FIGURE 8-6  Agronomic ($N^{max}$), economic ($N^*$) and risk averse ($N^{risk}$) fertiliser decisions.**
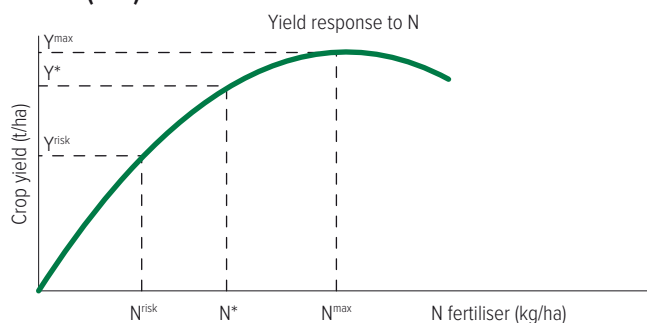


SOURCE: R FARQUHARSON R AND B MALCOLM

**FIGURE 8-7  Flatness of economic response.**
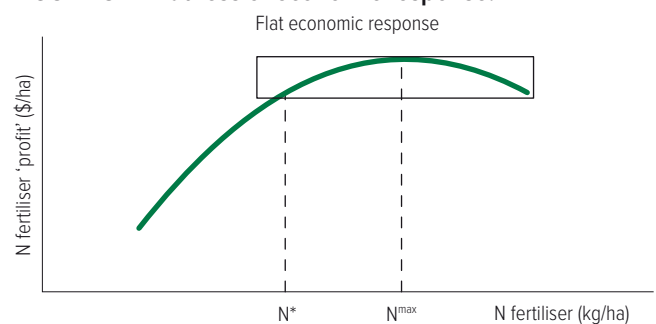


SOURCE: PANNELL 2006

### Where to from here?

The expenditure on fertiliser is an investment on which growers need a return. Requiring a return on that marginal capital investment is a way to extend the fertiliser decision framework to account for the variability in yield responses and risk-averse decision-makers (Figure 8-6). If the money to buy fertiliser is borrowed and involves an interest cost, or the capital has a significant opportunity cost, then covering the cost of capital is an important benchmark to apply in considering fertiliser decisions.

An even higher hurdle could be to require returns to cover twice the cost of capital. If the interest cost of capital on farm is 8 per cent and the opportunity cost is, for example, up to 15 per cent, then the rate of return required could be 16 per cent up to 30 per cent in recognition of all the risk and unknowns in the decision. If $1 is borrowed for fertiliser, then a $1.30 net return allows the $1 to be paid back and $0.30 (30 per cent) is the return on marginal capital for the $1 borrowed. The effect of imposing a 30 per cent minimum return is shown in Figure 8-8.

In Figure 8-8, if the MC (price) of N is $1/kg then a 30 per cent return to marginal capital requirement will reduce the 'best' N level from N* to N30. Imposing a hurdle requirement for marginal capital in making any N recommendation to growers attempts to provide the grain grower with more certainty about the MR and being able to repay the loan. However, this means that fertiliser application rates will remain relatively conservative. These decision support processes that attempt to improve fertiliser decision-making are likely to make recommendations that are more acceptable to grain growers.

The individual grower's own beliefs about yield responses to added fertiliser (their subjective probabilities) are most important. If decision support tools are developed, such tools are better able to help grower decisions if the grower decision-makers are at the centre of the considerations. If growers are considering adding more fertiliser, the amount of extra yield that they expect to achieve is the most important factor in their decision, as well as the relative prices of crop and fertiliser.

**FIGURE 8-8  Fertiliser decisions with a hurdle rate of return.**

SOURCE: M UNKOVICH UNPUBLISHED
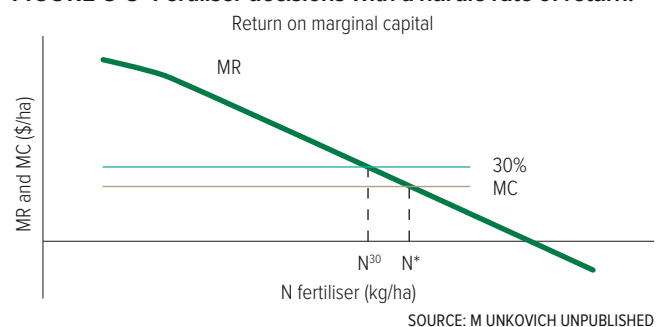
## 8.4  IN PRACTICE

In reality, farm production is about combining all inputs of which N is just one; the actual yield response in any particular paddock to additional N is uncertain; the price of the extra yield, too, is uncertain. Despite the uncertainty about extra yield and extra revenue that will be achieved from applying extra N, growers make decisions about using N and all the other inputs that they believe add to their whole-farm profit. So how do they do it?

In deciding whether to add N fertiliser to a farm activity, the decision-maker knows that the extra yield resulting from the additional N input into a farm system depends on the availability of all the other inputs required to produce yield. Therefore, the extra yield from extra N depends on the extent to which any other inputs limit the potential of the plants that are fertilised to use the extra N to produce extra yield. Other limiting inputs could be soil moisture, lime, P, K, S and trace elements. Apart from N, the biggest driver of yield is soil moisture. If other plant requirements are not limiting, the extra yields that result from different amounts of extra N in any paddock cannot be assumed for two reasons.

First, the N-responsive status of the soil and crop may not be well known. Second, the condition regarding the weather (rainfall, frost and heat) and markets after the N is applied is unknowable. The information that the grower or adviser has and can draw on in making the decision about adding N to a crop activity is what they have learned and understand about the effects on crop yields of fertiliser from previous experiences. Commonly this knowledge is of an average response that

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appears to have occurred. For example, we put 100 kg/ha of N on and yields seemed to increase about a tonne; an average response of 10kg of output per kg of N. This 'average thinking' is often misplaced.

The economic theory about profit-maximising rates of N to use is all about marginal (extra) responses, not average responses. The law of diminishing marginal returns to extra variable inputs, with other inputs held constant, dictates that beyond a certain rate of N, the extra yield from extra N diminishes, which lowers the average of all the inputs of N. Basing a decision on an extra yield expected to be the same as the average yield response to total N often overstates the true extra yield that will be grown if there are diminishing returns to additional N.

Another guide to thinking about how much more N to add is the question: Will more N bring in more revenue than it costs, and how much revenue will I forgo if I don't add the extra N? Further, given the uncertainty about the extra yield that will result from extra N and what it will be worth, how much worse off am I if I use more N than is theoretically the most profitable level, compared with how much profit I forgo if I add too little N? That is, given that getting right the profit-maximising rate of N that would apply could only happen by luck or coincidence under the real-world (uncertain) conditions, how much is profit affected if 'too much' or 'too little' N is used?

## 8.5  SUMMARY

Farm management economics emphasises considerations of whole-farm analysis and the production economics framework in making farm-level decisions. A foundational basis for the decision framework is accounting for the observed law of diminishing returns in crop yields and the resulting need for marginal thinking in decision making.

The economic framework incorporates flat economic responses over a range of N rates around the theoretical yield and profit-maximising fertiliser levels. It incorporates the likely effects of risk aversion on the part of cereal grain decision-makers. The economic framework includes the capacity to incorporate a hurdle rate of return on investment to account for the opportunity cost of capital.

Cereal growers and advisers may not explicitly incorporate the marginal economic framework in fertiliser decision-making, but they may incorporate these factors, together with their subjective expectations of yield responses, implicitly in their decisions. If the grains industry is concerned by apparent low rates of fertiliser use, then the economic framework and factors discussed here may provide an understanding for decisions.

# 9 CASE STUDIES

Given the range of environments, soils and farm businesses, there is no single best way to manage N in farming systems, but if you follow something like the 4R strategy, then you will at least be increasing the efficiency of the N fertiliser applied. There are, however, many other factors, both on and off farm, that can influence N management strategies and the focus of N management for a particular grower. The following case studies provide useful examples of how different growers deploy some of the available tools and how they allocate resources in their N management strategies.

## 9.1 GRAIN PROTEIN INFORMS SEASONAL NITROGEN DECISIONS

**Grower:** Ashley Wakefield

**Farm location:** Central Yorke Peninsula, South Australia

**Size of farm:** 1200ha

**Annual rainfall:** 400mm average

**Soil types:** grey mallee loam (pH 5 to 8)

**Enterprises:** 100 per cent cropping

**Main crops:** wheat, canola, lentil, chickpea

Investing in a near-infrared grain protein monitor has enabled Yorke Peninsula grower Ashley Wakefield to make more informed nitrogen decisions across his 1200ha cropping enterprise.

The Wakefields initially began protein monitoring to select high-protein grain feed for their on-farm piggery. "With the piggery gone we now use the protein monitoring to try and get a handle on what causes low and high grain protein so we can better manage our nitrogen inputs," Ashley says.

The CropScan protein monitor is the same as those used at grain receival sites and Ashley finds it very straightforward to use. "It attaches to the grain elevator and scans the grain using near infrared light as it falls into a small chamber," Ashley says. "The results are then sent directly to the computer in the harvester."

Ashley's consultant agronomist converts the protein readouts into a nitrogen-removal map of the farm and, along with deep soil nitrogen tests, is used to determine how much nitrogen to apply the following season.

Percentage protein can vary by as much as two percentage points within the same paddock so, when logistically possible, Ashley segregates harvested grain to ensure he meets specific quality targets.

"Last year was a wet harvest and we had time to mix grain to ensure we met the APW [Australian Premium White] grade but this year we've been under the pump time wise and haven't had a chance to segregate."

Ashley says they are still in the early days of translating the protein monitoring into dollars and it will take time to quantify how much the system is worth in more effective nitrogen management.

"At this stage, we are focused on getting a better handle on nitrogen use, so that we can increase inputs on areas of the farm we think we can improve and reduce inputs on areas that have no chance of yield or quality improvements.

"As we gain a better understanding of what's happening with protein and nitrogen, we'll start fine-tuning the system."

Ashley says the inherent variability associated with nitrogen mineralisation and soil moisture makes nitrogen management difficult. "Some seasons you

just have to throw the dice and make a judgement on whether it's going to be wet enough to justify an extra nitrogen application."

To help with nitrogen decisions, the Wakefields have soil moisture probes installed across the farm. "The monitors give us an indicator of whether we've got enough soil moisture to add some nitrogen but if it's on the dry side we hold back because it's likely to be a waste of money."

Getting nitrogen management wrong can cost thousands of dollars in nitrogen or forgone grain yield and quality. "This year we didn't put out a final nitrogen application because it wasn't moist enough, but the spring turned out wet and we are now only just scraping into APW, so with hindsight we could have done with that extra urea application."

Ashley says a valuable spin-off with the protein monitor he uses is that it is also very useful for measuring grain moisture.

"Our farm is quite close to the coast and we struggle with moisture issues during harvest," he says. "Being able to measure grain moisture with a 0.2 per cent accuracy means we gain valuable harvest time because we can start harvest in the morning as soon as the grain is dry enough and stop when the moisture starts to rise again at the end of the day."

Ashley has no doubt the $20,000 cost of the grain protein monitor is worth it. "I wouldn't do without it now especially with the added advantage of the moisture monitoring. I'm confident that with time we will be able to extract more yield and protein out of our paddocks by being more focused with our nitrogen inputs."

## 9.2 DRIVING NITROGEN DECISIONS FROM SPACE

**Grower and consultant:** Ed Hunt

**Farm location:** Wharminda, eastern Eyre Peninsula, South Australia

**Growing season rainfall:** 230 to 280mm (two properties)

**Soil types:** white sands (up to 20 per cent) through to sandy loams and some clay. Non-wetting soils on both properties.

Normalised difference vegetation index (NDVI) satellite imagery calibrated to soil and crop nitrogen could be the ultimate nitrogen management tool for eastern Eyre Peninsula grower and consultant Ed Hunt.

"If we could be assured of quality imagery during the cloudy months the technology holds real promise of delivering the real-time nitrogen status of crops," Ed says.

In 2016, Ed embarked on an intensive project to calibrate NDVI imagery of his wheat crop with deep soil nitrogen and tissue tests throughout the season.

"We segmented the satellite imagery and then measured site-specific, deep-soil nitrogen along with nitrogen in total plant tops and from this we calculated a total nitrogen supply and calibrated it with the NDVI images."

Ed says the ultimate aim is to develop a calibrated system that relies predominantly on the satellite imagery to quantify the nitrogen status of his crops in real time – with ongoing ground-truthing using soil and plant nitrogen tests.

The 2016 exercise indicated that, given the available soil moisture, there was enough nitrogen in the soil and the crop to deliver 4t of wheat. "And that's what we got," Ed says.

Frustratingly, excessive cloud cover meant the reliability of the images at the critical time of the season was poor. "We really need to be able to penetrate the cloud cover or have access to a cost-effective drone system that can operate

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underneath the clouds, as this would deliver reliable images of the crop in late winter and early spring."

Ed matched his measurements of total nitrogen supply to what he terms the 'finish-ability' of soil zones across the farm. "We divided the paddock into zones of soil moisture capacity so that we could get a feel for the ability of the soil to hold on to moisture to finish the crop."

He entered the data into the FarmWorks software system to generate a variable-rate nitrogen plan for the paddock. "We loaded the variable-rate data into our spreader so we could automatically adjust the applied nitrogen – it was a very valuable process."

Ed acknowledges that the nitrogen sampling process he undertook in 2016 was very intense and is not a viable option each season.

"We need to get to a point of knowing that a particular NDVI image means a particular amount of nitrogen," Ed says. "There's still a lot of learning and calibrating to be done and we certainly haven't got it sorted but there's lots of potential there."

Ed is not a fan of nitrogen calculators, which he says waste too much effort trying to predict what nitrogen might do within an inherently variable and complex system.

Nitrogen supply depends on soil moisture and the rate and extent of nitrogen mineralisation, but Ed says both these factors are impossible to predict with any accuracy. "The current calculators also don't take account of short-term organic matter breakdown, which can be substantial following a legume rotation," Ed says.

"We need to stop trying to predict what will happen with nitrogen and start measuring plant response to nitrogen in real time. The plant is the best thing to measure because it can tell us immediately if it has enough nitrogen or not."

Ed's clients span 250 kilometres up and down the Eyre Peninsula from the high-rainfall, acidic soils of Port Lincoln in the south through the highly alkaline soils of Cummins and Lock in the centre and up to the low-rainfall areas of Darke Peak in the north.

According to Ed, grower knowledge about yield and soil zones across a farm is often underestimated and that information would make

a valuable adjunct to yield maps. "I think if you sat a farmer down with a map and asked them to draw their high, low and medium-yield zones, I don't think they'd be that far off the mark and they'd certainly be close enough to make valuable decisions about those areas. I just don't think we've got close enough yet to really use all the PA data intelligently enough to be useful and at a value that the farmer is prepared to pay."

## 9.3 TEST STRIPS AND GREENSEEKER® FOR IN-CROP FERTILISER DECISIONS

**Grower:** Andrew Slater

**Farm location:** Central Yorke Peninsula, South Australia

**Farm size:** 640ha

**Growing season rainfall:** 330mm

**Soil types:** two-thirds of farm is grey mallee loam (shallow grey soil over calcrete lime) and one-third of farm is shallow red soil over exposed limestone

**Soil pH:** 8.3 (surface) 8.9 (30cm)

**Enterprises:** cropping (625ha), permanent pasture (16ha)

**Main crops:** wheat and lentil

For the past few seasons, more soil nitrogen than predicted by nitrogen calculators has been generated underneath long-term, no-till cropping paddocks in Andrew Slater's 625ha cropping enterprise on the central Yorke Peninsula in South Australia. The extra mineralisation has resulted in significant savings on applied nitrogen.

"In 2017, we applied half the nitrogen that the calculators said we needed because our nitrogen-rich strips and GreenSeeker® readings were telling us otherwise," Andrew says. "And we generated better yields than we predicted, too, which sent the water use efficiency figures for our wheat beyond 80 per cent."

Placing trust in his in-paddock nitrogen strips saved Andrew tens of thousands of dollars and he wants to unravel what is happening with nitrogen in his system so he can continue to take advantage of the extra nitrogen and make more reliable fertiliser decisions into the future.

According to Andrew, "lentils are king" on his alkaline (pH 8.3) grey mallee-loam soil. Canola and wheat are effectively used as a break crop to clean up the paddocks for subsequent lentil crops. "We are fortunate that the legume in our system also generates our highest returns and contributes a significant agronomic benefit to the wheat and canola crops in the rotation."

Andrew has used a no-till stubble-retention system for nearly 30 years with lentils part of the mix for the past two decades. He suspects that the extra nitrogen in his system has been generated by a shift in soil biology brought about by reduced tillage, stubble retention and fixed nitrogen delivered by the lentils.

"I believe we are on the cusp of a management change in our no-till system," he says. "We no longer need to put on as much nitrogen because instead of the 60 to 70kg N/ha of mineralised nitrogen we used to anticipate at the start of each season, we have been getting more like 100 to 120kg N/ha in recent years."

The phenomenon of extra soil nitrogen is not peculiar to Andrew's property, with other no-till lentil farms in the district also measuring more mineralised nitrogen at sowing.

Andrew tests for deep soil nitrogen and plant-available water across his property at the end of March each season.

In addition, he establishes zero-nitrogen and double-nitrogen test strips in-crop to monitor the nitrogen needs of his crops throughout the season.

In March 2017, soil testing indicated he had about 100kg N/ha of mineralised soil nitrogen. To achieve the yield he obtained in 2017, he should have added a further 250kg N/ha of nitrogen to the cropping system. "But our zero-nitrogen strips weren't showing up any different from our double-nitrogen strips, which meant there had to be extra nitrogen in the system."

Based on the nitrogen strips and GreenSeeker® information, Andrew decided to apply only about half the amount requested by the calculators and in the process saved himself $40,000. Retrospective calculations suggested another 70kg N/ha of mineralised nitrogen might have been generated in-season, bringing the total amount of 2017 nitrogen mineralisation to 170kg N/ha.

"What I really want to be able to do is get a handle on nitrogen mineralisation in real time throughout the season so I can more accurately adjust nitrogen inputs as the season progresses rather than examining things retrospectively once the yields are in," Andrew says.

Andrew uses 25 years of crop records to calculate water use efficiencies for each of his crops under the average, wet and dry rainfall possibilities for his region. "We then use the plant-available water measurement from the end of March along with the season's rainfall prediction and our target yield to estimate the nitrogen needs of each of our crops," he says.

As the season unfolds, the nitrogen rates are adjusted accordingly. "We apply 80kg DAP at seeding and split this so that two-thirds goes deep and one-third with the seed."

About half of the predicted nitrogen requirement for the season is applied at GS31. After this, further nitrogen additions depend on the season. "We generally add some more two to three weeks after GS31 and might add some more again a couple of weeks after that; it just depends on rainfall and our nitrogen strip monitoring.

"What we need to do now is manage the changing system to our advantage so that we can accurately predict how much nitrogen we need in July and August to generate high-quality wheat and canola crops."

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## 9.4 PRECISION AGRICULTURE INVESTMENT BOOSTS BOTTOM LINE

**Grower:** Mark Branson

**Farm location:** Stockport, South Australia

**Farm size:** 1200ha

**Growing season rainfall:** 350 to 400mm (two properties)

**Major soil types:** red brown earth, dark-brown cracking clay

**Enterprises:** cropping (1000ha) and pasture (200ha) in rotation

South Australian farmer Mark Branson has been using precision agriculture to optimise grain yield and quality and save on input costs for more than a decade.

"Our PA journey has been challenging to implement but we are now saving upwards of $50 per hectare on nitrogen and phosphorus inputs as well as achieving better weed and soil pH management," Mark says.

The Bransons' wheat yield potential has also benefited from a combination of PA and no-till approaches, with average yields now sitting at 4.5 to 5.0t/ha and crop water use efficiencies well above average.

Mark started yield mapping 20 years ago but it wasn't until he spent time at Oklahoma State University in 2006 as part of his Nuffield Scholarship that he was able to take PA to the next level on his property.

"The other important thing has been my association with SPAA (Society of Precision Agriculture Australia), which has enabled me to work closely with other farmers and work out how to make money out of PA."

The first step on his PA journey involved lots of soil testing, which the Bransons then used to develop management zones across their paddocks and farm. "While dividing the soils into management zones was a good exercise, we didn't have the

application technologies to translate this into variable rate until I bought my first in-cab computer console in 2002.

"But it wasn't until after the Nuffield Scholarship in 2006 that I gained the confidence to produce decent maps myself."

Variable-rate nitrogen was the first cab off the PA rank with Mark using deep soil nitrogen testing, nitrogen-rich strips and GreenSeeker® technology to generate seasonal nitrogen application maps across his 1000ha cropping program.

He was an early adopter of the GreenSeeker® technology, spending "a fortune" on one of the first machines, which needed to be mounted onto an all-terrain vehicle to operate. "Just over a decade later I now use a handheld Trimble® to achieve the same job," Mark says.

Investment in GreenSeeker® technology has well and truly been worth it, with the Bransons saving about $34/ha each season in nitrogen inputs across their 1000ha property by using variable rate rather than a blanket application.

The nitrogen-rich strips play a critical role in the Bransons' nitrogen management because they allow in-season nitrogen mineralisation and yield potential to be taken into account as the season unfolds.

"I apply 70 per cent of the predicted nitrogen needs up front at seeding and then assess the nitrogen-rich strips regularly to determine how much more the crop needs as the season progresses."

Mark does not add any more nitrogen to the crop until GS30–32 unless the nitrogen strips tell him otherwise. If the nitrogen strips are ahead of the crop he knows he needs to apply more nitrogen and uses CropSpec sensors mounted on his tractor to assess crop biomass and determine the nitrogen rates to apply across the farm.

Sorting out the variable-rate phosphorus system took Mark a bit longer and he wishes now he had got on to it earlier on his PA journey. "We now save about $16 per hectare applying variable-rate phosphorus but it took me a while to get on top of what needed to happen."

Mark uses his seasonal yield map to determine the amount of phosphorus removed at harvest. "I then apply a calculation across the yield map to develop a variable-rate phosphorus application to account for the phosphorus removed."

The goal is to maintain optimum phosphorus in the soil and, according to Mark, the cheapest way to do this is to replace what comes off each season. "If I was starting out on the PA journey again, I'd move straight into phosphorus as well as nitrogen," Mark says. "But just because you've got a nice coloured yield map that tells you where your yield differences are doesn't mean you know how to make money out of it. It took us a lot of research, a lot of tools and a lot of scientists coming here to get it right."

Mark says his biggest challenges with variable-rate nitrogen revolve around the season. "If it's a dry spring like it was this year then my system can mean we miss out on yield and protein potential because there isn't enough moisture to deliver the nitrogen to the crop at the critical growth stage." But with the good and consistent rainfall that falls in the Bransons' southern South Australia region, it is a rare year that variable-rate nitrogen does not make them money.

Mark is now moving into using PA for weed management and lime applications across the property.

"We're using drone technology to identify problem weed areas so that we can develop weed maps for the farm and apply herbicides only where they are needed."

With increasing yield potential and nitrogen application, soil acidity is now becoming an issue; Mark has started mapping the pH across his paddocks using Veris technology. He then applies variable-rate lime accordingly.

"Even within the same paddock, we can have areas that are fine for pH and areas that are down to pH 4.5, so variable rating lime is really a no brainer."

## 9.5 DEEP SOIL NITROGEN TESTING CENTRAL TO NITROGEN DECISIONS

**Grower and consultant:** Ian Delmenico

**Farm locations:** Victorian Mallee region (Swan Hill) through to southern NSW

**Farm types:** rainfed and irrigated (no-till)

**Main soil types:** sands through to sandy loams and loamy clays

**Soil fertility:** 0.3 to 1.5 per cent organic carbon

**Growing season rainfall:** 220mm

**Main crops:** wheat, lentil, field pea, vetch, chickpea

Ian Delmenico relies heavily on deep soil nitrogen testing when developing variable-rate recommendations for his cropping clients. "Each February we carry out about 430 deep soil nitrogen tests in the Victorian Mallee region and across the border into southern New South Wales," Ian says.

The farms cover a range of rainfed and irrigated cropping systems. All nitrogen decision-making is done before the start of the season. "We need to have the soil test information available to us before the start of the season so we can make up all the variable-rate inputs on time."

Ian does not do any in-season nitrogen testing. "We tried it a few times, but it was just too difficult."

Each of the nitrogen tests is done in two depths: 0 to 20cm and 20 to 60cm.

"This helps us establish how much nitrogen we need to put up front and how much we can delay; if there's a bit further down in the profile you know the crops will hit it later in the season."

Ian runs a 100m transect across each soil zone and pulls four 60cm cores. "We keep all our nitrogen and yield data so we can graph changes across individual farms and paddocks and pick up on other issues such as disease or frost."

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A proportion of the recommended nitrogen is applied using variable rate at seeding, followed by a top dressing at the three to four-leaf stage. "We might do a further top dressing beyond this growth stage depending on the season and rainfall."

Over the past 20 years of testing, Ian has noticed a drop in deep soil nitrogen at the start of each season and is having to add more nitrogen each year. "We were consistently getting about 80kg N/ha nitrogen from our soil testing a couple of decades ago but now we are getting more like 50 to 60kg N/ha."

Ian suspects the drop is due to the tighter rotations of recent times (up to 65 per cent of crops are cereals) with fewer legumes and fallows. "Stubble retention could also be playing a part if the nitrogen gets tied up as the stubbles are broken down."

For the nitrogen testing, Ian breaks each cropping paddock into soil-type zones. "We sample every cereal and canola paddock going into crop, because this allows us to make the most informed decision for the client."

Ian has designed his own nitrogen management model, which he uses each season to develop his client nitrogen schedules. "The model takes account of the crop type and stubble load and generates a nitrogen tie-up and mineralisation factor based on rainfall." It took Ian and his team about 10 years to develop the model, which he uses across both irrigated and rainfed cropping systems. "Each year we refine it with the season's yield and quality results."

Ian's biggest nitrogen management issue is nitrogen tie-up in the stubbles. "A reasonable stubble load might tie up as much as 25kg N/ha, whereas in a normal year we might only get 15kg N/ha nitrogen mineralisation. So, you can actually go backwards in terms of nitrogen and you need to add more just to keep up."

Nitrogen application rates can range from nothing on some hostile subsoils through to 50kg on the region's loams and up to 100 to 120kg N/ha on lighter soil types.

The main difference between the irrigated and rainfed systems involves factoring in the water and its impact on nitrogen mineralisation. "Irrigated yields depend largely on the client's attitude to risk and the price of water," Ian says.

## 9.6 BUMPER YIELDS BRING NITROGEN CHALLENGES TO HIGH-RAINFALL ZONE

**Grower and private agronomist:** Craig Drum

**Farm location:** Tatyoon, south-west Victoria

**Farm size:** Average farm 200 to 4000ha, most sit around 600 to 1500ha

**Growing season rainfall:** 550mm

**Main soil types:** clay to loamy clay over a sodic subsoil, pH 4.5-6

**Enterprises:** cropping and livestock (80:20)

**Main crops:** wheat, canola

Cropping only came into vogue in the high-rainfall region of south-west Victoria about 15 to 20 years ago. Before this, the area was dedicated entirely to livestock grazing clover-based pastures.

Private agronomist and grower Craig Drum says the region is characterised by regular rainfall, a generally cool, soft finish to the season and, until recently, an abundance of stored soil nitrogen due to the many years of legume pastures.

"Ten to fifteen years ago farmers basically planted a crop, shut the gate and came back at harvest to take off an excellent crop," he says.

With soil organic carbon levels sitting at about three per cent, nitrogen mineralisation rates are high. "Up until four to five years ago farmers in the region were only having to apply about 100kg of urea for the season to grow 4 to 6t crops."

But with the big crop yields over the past few years, soil nitrogen is dropping. "Last year the season was exceptional and many of my clients averaged eight tonnes of wheat to the hectare, so coming into 2017 we knew our soil nitrogen would be low," Craig says.

To match the high yield potential, the region now budgets for about 200 to 300kg N/ha each year, depending on the previous season and the results of deep soil nitrogen testing. "Our soils are heavy enough that we don't tend to lose nitrogen to leaching but we do lose some to waterlogging and denitrification."

Craig is not a fan of inhibitors, which he says are too expensive and have not shown any yield response. "Urea takes a long time to break down and get into the plant during the winter in our part of the world, so we don't need anything inhibiting that process, especially when there's no yield incentive."

Nitrogen is applied in-season over two passes using controlled traffic. "We are not set up to deliver nitrogen at sowing; most of my guys will put their nitrogen out in two passes using a spreader starting at early tillering for wheat and first budding for canola," Craig says.

Most nitrogen used is urea. "We put very little liquid nitrogen out because it's too expensive and doesn't work any better than urea."

Deep soil testing and calculators are the main nitrogen management tools used in the region, but Craig says both tools are problematic.

"Deep N testing in-crop is a nightmare logistically as our soils make trafficability a real hassle and then on top of that the soil in the probe turns to mud, making the testing a really slow and difficult process."

As a consequence, many are discouraged by the process of deep nitrogen testing and opt to use nitrogen budgeting instead. "Some clients use the testing, but many prefer to go by gut feel about seasonal nitrogen needs," Craig says.

Soil nitrogens range from 60 to 200kg N/ha with most around the 100 to 120kg N/ha mark. "But with the huge yields of 2016, our 2017 soil tests were down to 30 to 90kg N/ha."

Craig says he is confident in the modelling they use to estimate nitrogen requirements for the season, but the problem lies in not knowing how much nitrogen mineralisation is going to take place. "The calculators require you to guestimate mineralisation and final yield so in the end many growers prefer to just sit down and work out what yield they are aiming for, and then we develop a nitrogen budget to match the yield expectation based on the deep soil nitrogen test.

"If working back after harvest and yields are known, then the calculator always works!" Craig says. "But going forward we can't develop the perfect nitrogen answer because we haven't got the crystal ball regarding how the season will end."

To simplify nitrogen management, Craig uses crop yields, grain protein and soil nitrogen tests (if available) to divide his clients' paddocks up into low, medium and high ranges in terms of soil nitrogen.

"Instead of trying to calculate an exact amount of nitrogen to apply, I prefer to make decisions based on a paddock's general nitrogen status. The farmer then budgets nitrogen according to the yield they are aiming for."

Only a few of Craig's clients use nitrogen-rich strips, which he says are working well. "Our issue is with satellite imagery because with cloud cover we average only about two reliable satellite images between June and early November, so we just can't get enough information during that critical time of August to September to be of any use to us."

PA is not used in the region as the variability across paddocks is not large enough. "We just don't have enough variability to justify variable-rate nitrogen here."

Craig says the biggest challenge in nitrogen management is the logistics of deep nitrogen testing. "If we had an easier system to test for deep soil nitrogen, we could eventually make use of NDVI via satellite or drone and calibrate this to a soil N level."

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# 10 GLOSSARY AND RESOURCES

## 10.1 GLOSSARY

**Aerobic:** soils in which oxygen is abundant, typical of well-drained soils with good structure.

**Ammonia volatilisation:** the emission of ammonia gas from soils, nitrogen fertilisers, standing crops, plant residues, animal urine or manure.

**Ammonification:** biological process resulting in the release of ammonia or ammonium from organic substances.

**Anaerobic:** an environment deficient in oxygen. Generally occurs in poorly drained or waterlogged soils or microsites within the soil.

**Anhydrous ammonia:** a fertiliser stored under high pressure as a liquid and composed of 82 per cent N.

**Anion:** an ion with a negative charge. Common soil anions are nitrate, sulfate, chloride and bicarbonate.

**Available N:** nitrogen in a form that plants can absorb. Primarily refers to nitrate and ammonium but could also include some ammonia or organic compounds such as urea or amino acids.

**Biological $N_2$ fixation:** see $N_2$ fixation.

**Crop residues:** plant material (roots and shoots) that remain in the field after harvest.

**Denitrification:** the transformation of nitrates or nitrites to nitrogen or nitrogen oxide gases under anaerobic conditions. Primarily mediated by microbes.

**Detritus:** organic matter formed from dead plants and animals and broken down into smaller pieces.

**Diammonium phosphate (DAP):** fertiliser containing both nitrogen and phosphorus (but zero potassium) in a ratio of 18-46-0.

**Diffusion:** the movement of ions or molecules from a higher to lower concentration.

**Fertiliser-N efficiency:** the efficiency with which fertiliser N is converted into grain N, or the fraction of fertiliser N taken up by a crop.

**Fertiliser-N equivalent:** the amount of fertiliser N required to increase the yield of a cereal following a cereal to match that of a cereal following a legume or other broadleaf crop.

**Greenhouse gas:** those gases that absorb and emit infrared radiation, but primarily referring to those produced by industrial activity (carbon dioxide, methane, nitrous oxide and ozone).

**Harvest index (HI):** the grain yield of a crop as a proportion of total above-ground biomass.

**Humification:** the decomposition of plant and animal residues to relatively stable organic matter in which humic and fulvic acids dominate.

**Humus:** the relatively resistant, usually dark brown to black fraction of soil organic matter, peat or compost that forms as a result of biological decomposition of organic material.

**Immobilisation:** conversion of an element from a mineral form to an organic form; for example, assimilation of nitrate by soil microbes or plants.

**Leaching:** the downward movement of dissolved nutrients, chiefly nitrate, in water percolating down through the soil.

**Microbial biomass:** the mass of the microscopic-sized part of the living soil organic matter, consisting mainly of fungi, bacteria, yeasts, protozoa, algae and nematodes.

**Mineral nitrogen:** mineral forms of nitrogen, primarily ammonium and nitrate. Also called inorganic N.

**Nitrogen ($N_2$) fixation:** the biological or chemical reduction of atmospheric dinitrogen gas ($N_2$) to ammonia ($NH_3$).

**$N_2$ fixation – associative:** biologically mediated $N_2$ fixation where a $N_2$ fixing organism associates itself with a plant or animal to obtain nutrients in a low $O_2$ environment; for example, on the outside or near of plant roots.

**$N_2$ fixation – symbiotic:** biologically mediated $N_2$ fixation that only occurs in a complex partnership between two different organisms who receive mutual benefit.

**Nitrification:** the conversion of ammonia or ammonium to nitrate by microorganisms.

**Nitrogen harvest index (NHI):** grain N expressed as a fraction of the total shoot biomass N.

**Nitrogen mineralisation:** the conversion of the organic N in crop residues, animal manure or humus into mineral N by the action of the microbial biomass.

**Nitrogen, organic:** nitrogen compounds originating from living material and still part of a carbon-chain complex.

**Nitrogen-use efficiency (NUE):** the efficiency with which plant-available N is converted into grain N.

**Organic fertiliser:** a fertiliser originating from organic source, typically composts or manures from industrial production systems or urban waste.

**Plant-available nitrogen:** nitrogen in a form available in the soil for crop uptake.

**Residue N:** N contained in total crop residues.

**Rhizobia:** $N_2$-fixing bacteria capable of living in a complex partnership with legumes.

**Soil biota:** any or all of the organisms living in the soil. Includes microbes, animals (protozoa, nematodes, mites, springtails, spiders, insects and earthworms), fungi and plants.

**Soil organic matter:** the organic fraction of the soil excluding undecayed plant and animal residues. Primarily made up of humus.

**Soil texture:** the relative proportions of sand, silt and clay in a soil.

**Synthetic fertiliser:** a fertiliser produced in a factory from inorganic elements.

**Total nitrogen:** the sum of the organic and inorganic forms of nitrogen.

**Urea hydrolysis:** the conversion of urea ($CO(NH_2)_2$) in fertilisers or animal urine to ammonia, catalysed by the enzyme urease.

**Volatilisation:** conversion of a solid or a liquid to a gas. For example, ammonia ($NH_3$) loss to the air from urea, crop residues or leaf surfaces.

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## 10.2 USEFUL RESOURCES

- **Ammonia volatilisation calculator:**
  https://downloads.backpaddock.com.au/tools/Fillery_Volatweb032017/Fillery_Volatweb032017.htm

- **For details on wheat crop development and yield formation:**
  White J, Edwards J, Eds. (2007) Wheat growth and development. Sydney: NSW Primary Industries.

- **For targeting very high (>6 t/ha) cereal yields:**
  Stapper M (2007) High-yielding irrigated wheat crop management, CSIRO, Canberra.

  Lacy J, Giblin K (2009) Growing eight tonnes a hectare of irrigated wheat in southern NSW, Primefact 197. Industries NSW, DPI, Sydney.

- **Legume inoculation:**
  Drew E, Herridge D, Ballard R, O'Hara G, Deaker R, Denton M, Yates R, Gemell G, Hartley E, Philllips L, Seymour N, Howieson J, Ballard N (2013) Inoculating legumes: A practical guide. Canberra: Grains Research and Development Corporation.

- **Crop agronomy:**
  GRDC (2018) GrowNotes™. Canberra: Grains Research and Development Corporation. Available from: https://grdc.com.au/resources-and-publications/grownotes (accessed 21/11/2018).

- **Soils:**
  Chemical, physical and biological iIndicators of soil quality, http://www.soilquality.org.au

  Dalgliesh N, Foale M (2000) Soil matters: monitoring soil water and nutrients in dryland farming. Brisbane: APSRU; CSIRO.

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