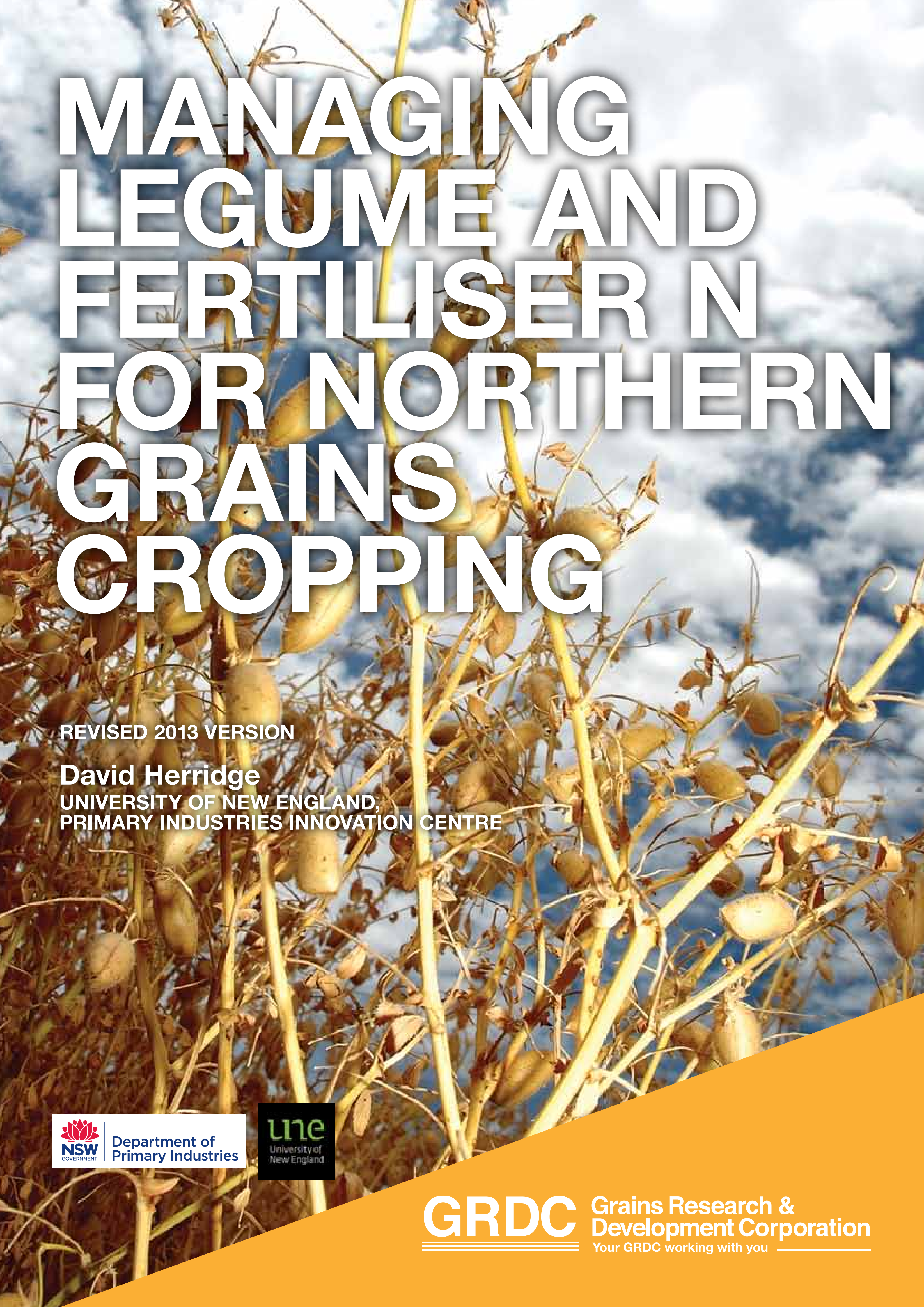

MANAGING LEGUME AND FERTILISER N FOR NORTHERN GRAINS CROPPING

REVISED 2013 VERSION

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Title: **Managing Legume and Fertiliser N for Northern Grains Cropping**

GRDC Project Code: **UNE00014**

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Published October 2011
Update published January 2013

ISBN 978-1-921779-33-6

In submitting this report, Professor Herridge has agreed to the GRDC publishing this material in its edited form.

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Design and production:
Coretext, www.coretext.com.au
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> ‘…Major leaps in the productivity of agricultural systems rarely arise from interventions related to single factors, but rather from synergistic interactions among many interventions working together…’

Source: Watt M, Kirkegaard JA, Passioura JB (2006) Australian Journal of Soil Research 44, 299–317.

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FOREWORD

The purpose for writing this manual was twofold. First, it was to provide an update of current information on fertiliser and legume nitrogen (N) in broadacre cropping in Australia's northern grains region, with particular emphasis on the legume N. Second, the manual was written to provide instructions, underpinning technical information and background science for 'NBudget' – the web-based (CropMate™) calculator for estimating the fertiliser N requirements of cereal and oilseed crops and dinitrogen (N_2) fixation by legumes. The manual's target audience is likely to be the private and government agronomists, consultants and advisers who work with farmers to make decisions about N, rather than the farmers themselves. The manual may also provide useful material for tertiary-level education and training.

Data and concepts that underpin the manual and calculator were sourced from the many published and unpublished experiments conducted primarily by the farming systems and plant nutrition programs of the NSW and Queensland government agencies during the past 30 years. I have interpreted an reported not only the data but also the knowledge and insight of the Australian and international scientists who have worked and published in the fields of soil and plant N. The contributions of (the late) Harry Marcellos, Warwick Felton, David Doyle and Ian Holford of the former New South Wales Department of Agriculture (Primary Industries) and Wayne Strong, Ram Dalal, David Freebairn and Greg Thomas of the former Queensland Department of Primary Industries are greatly acknowledged.

Why focus on N? Plant-available (mineral) N is a major driver of agricultural productivity and profitability. Nitrogen is a component of chlorophyll, the green pigment found in almost all plants. It is responsible for photosynthesis in which carbon from carbon dioxide in the atmosphere is fixed by the plant into sugars in the presence of sunlight. Photosynthesis is the source of almost all of the energy for animal and human life. When plants are N-deficient they lack chlorophyll (termed chlorotic), appear yellow and are unthrifty. For grain crops, N deficiency means reduced yield and low grain proteins.

Mineral N in the soil is also required for the formation of humus (stable soil organic matter), necessary for soil health and land sustainability. Nitrogen in one of its gaseous forms, nitrous oxide (N_2O), is a potent greenhouse gas and N as nitrate is potentially dangerous to human health when leached into groundwater that is used for drinking. The challenge facing farmers is that they need to supply sufficient N to their plant-soil systems to optimise yields, profitability and soil health, while at the same time minimising the environmental risks associated with greenhouse gas emissions and nitrate pollution of water tables.

There are six chapters plus appendices and references in this manual. Each chapter is self contained although written in such a way that one chapter leads logically into the next.

Chapter 1 provides a brief overview of grain cropping in Australian agriculture. The northern grains region is introduced, to be followed by details of research on N in the region that commenced in the 1960s and which led to the development of N management tools and programs for farmers and their advisers during the 1990s. The N cycle in agricultural systems is examined in terms of how N is added to the soil, how it is moved around and stored in the soil, how it is lost from the soil and, finally, how soil biology makes it all happen.

Chapter 2 defines the problem of declining soil organic matter in grain cropping soils in the region. Variations in nitrate-N concentrations in the root zone are described to provide a sense of how much they vary with cropping and during the post-crop fallow. Potential loss mechanisms – leaching and denitrification – are introduced with brief discussion on their relative significance.

Chapter 3 explores legume N_2 fixation and the farming practices that affect it. Rhizobial inoculants and the inoculation of legumes are also covered. The chapter examines the rotational benefits of legumes, defined by their ability to fix N, improve the mineral and organic N contents of soils in which they grow and to act as a break for soil- and stubble-borne diseases of cereals.

Chapter 4 examines mineral and organic fertilisers, particularly related to the efficiency with which the N is utilised by the target crop. The chapter also examines the fate of fertiliser N as it is processed in the soil to a plant-available form and is either taken up by the growing crop, left unused in the soil, lost from the soil or immobilised in the soil organic matter.

Chapter 5 provides a brief overview of 'NBudget' and how it would be used for specific paddocks. Examples are provided of the accuracy with which the tool predicted soil nitrate levels, i.e. validation.

Chapter 6 considers the science that underpins 'NBudget', covering key issues such as the accumulation of nitrate in the soil resulting from mineralisation of native soil organic matter and fresh crop residues, the efficiency with which water is stored in the soil during the pre-crop fallow, to the development of the functions describing legume N_2 fixation.

The appendices contain graphs and tables relevant to 'NBudget'. The cited references constitute the final section of the manual.

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ACKNOWLEDGEMENTS

I wish to acknowledge the support of the late Chris Cole of Industry & Investment NSW. Chris was a great supporter of the concept and provided much-needed impetus at critical times. Special mention should also be made of former colleagues in NSW Primary Industries (NSW DPI), including the late Harry Marcellos, Warwick Felton and Graeme Schwenke. I thank Steph Belfield (HMAg), Wei Chen, Bill Manning and Loretta Serafin (all NSW DPI) for their various inputs and Tracey Farrell (ex-NSW DPI) for her thorough reading of an earlier draft of the manual. Finally, the Grains Research and Development Corporation (GRDC) is acknowledged for providing the financial support to finish this project.

GLOSSARY OF TERMS

Term	Acronym	Description
Ammonia volatilisation		The emission of ammonia gas from soils, nitrogenous fertilisers, standing crops, plant residues and animal urine and manure.
Ammonification		The conversion of organic substances to ammonia and ammonium.
Biological N_2 fixation	BNF	The reduction of atmospheric dinitrogen (N_2) to ammonia (NH_3), catalysed by the enzyme nitrogenase.
Denitrification		The reduction of nitrate by soil microrganisms to the gases nitric oxide (NO), nitrous oxide (N_2O) and dinitrogen (N_2).
Fallow efficiency	FE	The efficiency with which rainfall that occurs during the fallow is stored in the soil.
Fertiliser-N efficiency		The efficiency with which fertiliser N is converted into grain N.
Fertiliser-N equivalence		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		Greenhouse gases are those gases that absorb and emit infrared radiation. In order of abundance in the Earth's atmosphere, the greenhouse gases are: water vapour, carbon dioxide, methane, nitrous oxide and ozone.
Harvest index	HI	The grain yield of a crop as a proportion of total above-ground biomass yield.
Humus		The stable fraction of soil organic matter composed of amino acids, amino sugars, and a complex of other known and unknown compounds.
Humification		The decomposition of plant and animal residues to relatively stable organic matter in which humic and fulvic acids dominate.
Immobilisation		Conversion of an element, e.g. N, from a mineral form to an organic form.
Microbial biomass	MB	Soil microbial biomass is the living part of soil organic matter, consisting mainly of fungi, bacteria and yeasts, protozoa, algae and nematodes.
Nitrification		The conversion of ammonia or ammonium to nitrate. It is a two-step process. In the first step ammonium is converted to nitrite; in the second step the nitrite converted to nitrate.
Nitrogen fixation	N_2 fixation	The biological or chemical reduction of atmospheric dinitrogen gas (N_2) to ammonia.
Nitrogen harvest index	NHI	Defined as grain N as a proportion of total above-ground biomass N.
Nitrogen mineralisation		The conversion of fresh crop residues, animal manure and humus into nitrate – combines the processes of ammonification and nitrification.
Nitrogen-use efficiency	NUE	The efficiency with which soil nitrate-N is converted into grain N.
Percentage of legume N derived from N_2 fixation	%Ndfa	Percentage of legume N derived from N_2 fixation.
Residue N		N contained in total crop residues.
Soil biota (biology)		See microbial biomass.
Urea hydrolysis		The conversion of urea ($CO(NH_2)_2$) in animal urine and fertilisers to ammonia, catalysed by the enzyme urease.
Water use efficiency	WUE	The efficiency with which water, stored in the soil and falling in-crop as rain, is converted by the crop or pasture into biomass or grain.

CHAPTER 1: INTRODUCTION

Total land use for agriculture in Australia is around 440 million hectares, of which 90% is extensively grazed, about 26 million hectares sown to grass and legume pasture, and 22 million hectares used for cropping. More than half of the cropping in Australia occurs in two states – Western Australia (33% of total) and New South Wales (28%) (ABARES 2011).

1.1 Grain cropping in Australia

In all states, the majority of cropped areas has been and continues to be used for cereal production (Figure 1.1). Pasture and grain legumes are important components of cereal-production systems, particularly in the western and southern regions of the grains belt. The pasture legumes have a dual role. They sustain animal production as well as supplying N to the soil for use by subsequent cereal crops. However, such systems are only relatively recent. Prior to the early 1950s, plant-available N, i.e. nitrate-N, was conserved in the soil through bare fallowing. This practice resulted in depletion of organic matter, damaged soil structure and led to large-scale soil erosion. Average wheat yields during this time remained static at around 0.8 t/ha.

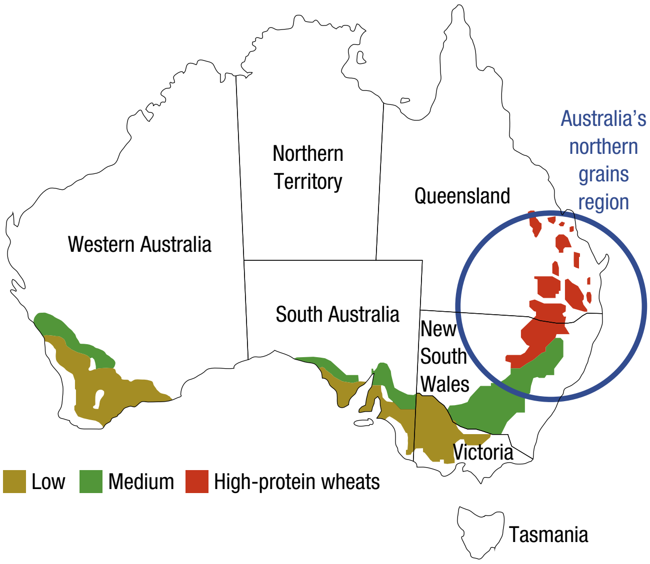
Following the introduction of legume-based pastures in the 1950s, cereal yields increased dramatically to stabilise at around 1.3 t/ha. The increase was almost entirely due to the N benefit of the N_2-fixing legumes. Net increments of soil N under the pasture ranged from 35 to 100 kg/ha and reflected the productivity of the legume (Reeves 1991). Soil structure also benefited from the pasture phase, resulting in enhanced water infiltration and plant root penetration.

During the 1980s, about 30 years after the introduction of the pasture ley system, a number of factors combined to again change the basic cereal production systems from the pasture ley-cereal to a more flexible combination of pasture ley-cereal and grain legume-cereal. These factors included concern for the decline in thrift of pasture legumes, problems of soil acidity, increasing cereal crop diseases (particularly root and crown rots), and the more favourable returns from cropping compared with livestock.

It is worth noting again that these legume systems (both pasture and crop) were really only used in the western and southern parts of the grainbelt. In the northern grainbelt of northern NSW and southern and central Queensland, which for the most part had a more recent history of cropping, legumes were not grown and N was supplied principally through the breakdown of soil organic matter.

During the 1980s grain legume sowings increased dramatically. In the seven years from 1980 to 1987, the grain legume area increased from 0.25 million hectares to 1.55 million hectares, an increase of 560%. By 1995, the area sown to legumes had reached 2 million hectares. The initial expansion in the early 1980s was entirely due to increased areas sown to lupins in WA. During the mid-1980s, both lupin and field pea areas increased. In the late 1980s, chickpea areas expanded.

FIGURE 1.1 Map showing the grainbelt of Australia and the regions producing low, medium and high-protein wheats



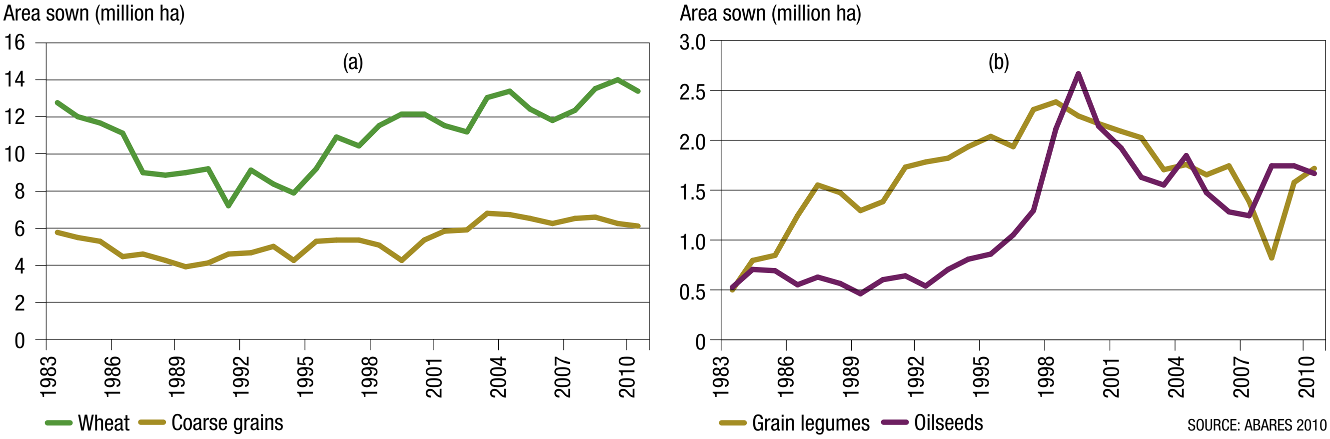
SOURCE: ABARES 2011

Oilseed crops, primarily canola, became popular during the 1990s. By the end of the 1990s, oilseeds were grown on almost 3 million hectares and coincided with the peak of grain legume sowings. Since 2000, the combined area of oilseeds and grain legumes declined from almost 5 million hectares to about 3 million hectares (Figure 1.2).

Thus, the relative areas of cereal and broadleaf crops have changed substantially in recent years. It declined from 20:1 in the 1980s to less than 4:1 in 1999. Since then, the ratio has steadily increased and currently sits at about 6:1. The major factors driving these changes were the expansion then decline in lupin sowings in WA and canola nationally, coupled with the steady increase in cereal sowings.

As has always been the case, cropping on Australia's 25,000 grain farms is dominated by wheat, accounting for about 60% of cereal production and 54% of total crop production (Table 1.1). Almost all of the wheat is rain-fed, with only small areas grown under irrigation. Barley accounts for a further 22% of total crop production. Average yields of the non-irrigated cereals during the period 2002–07 were about 1.6 t/ha, although the period was characterised by below-average rainfall. In the more favourable seasons, average yields were in excess of 2.0 t/ha. Average yields of the legumes were even lower, ranging from 1.0 to 1.9 t/ha. The principal legume crops are lupins and field peas, together accounting for about 70% of legume production.

FIGURE 1.2 Areas (million hectares) sown in Australia to (a) wheat and coarse grains (barley, oats, triticale, sorghum and maize) and to (b) grain legumes and oilseeds during the period 1983 to 2010



SOURCE: ABARES 2010

Statistics on the areas of legumes in pastures, both ley and permanent, are more difficult to access. Australian Bureau of Statistics (ABS) figures indicate that 2.5 million hectares of lucerne and other pasture species, either alone or in mixtures with grasses, were sown during 2000-01. Sowings were mainly in NSW (40% of total), WA (18%) and Victoria (19%). The area of established pastures containing legumes of 21 million hectares was concentrated also in NSW (30% of total), WA (22%) and Victoria (21%).

1.2 The northern grains region

Australia's northern grains region encompasses about 4 million hectares of cropping land between Dubbo in the central-west of NSW and Clermont/Biloela in central Queensland. The region is characterised by relatively high but variable rainfall that ranges between slightly winter-dominant in the south to summer-dominant in the north and high rates of evaporation. Pre-crop fallowing for moisture is the norm. Close to 100% of the region's farmers use no-till or minimum till, coupled with stubble retention, for managing the fallows. Cropping patterns are diverse, incorporating long fallows for summer to winter cropping and vice versa, short fallows for summer to summer or winter to winter cropping, no fallows (double or opportunity cropping) and pasture phases.

The estimated 5000 farmers in the region produce, on average, more than 7 million tones of grain annually, worth about $1.5 billion (Hooper and Levantis 2011a, b, c). This represents about 20% of national production. Principal grain crops are wheat, barley, sorghum and chickpeas, with minor crops being faba beans, maize and sunflowers. Cotton is also a major crop, grown under irrigated and dryland conditions. Consistent with the national statistics above, wheat accounts for 50–60% of grain produced. Additional statistics on grain cropping in the northern region can be found in the ABARES Australian Crop Report series (www.abares.gov.au) and the *2010 GRDC Farm Practices Baseline Report* (Kearns and Umbers 2010).

TABLE 1.1 Area and production figures for cereal and grain legume crops in Australia for 2005–10

Crop	Area sown ('000 ha)	Production ('000 tonnes)	Average yield (t/ha)	Major production states
Wheat	12,875	18,577	1.44	WA, NSW
Barley	4590	7360	1.60	SA, WA
Oats + triticale	1340	1733	1.30	WA, NSW
Sorghum + maize	782	2600	3.32	Queensland, NSW
Rice	30	290	9.67	NSW
All cereals	**19,617**	**30,560**	**1.56**	**WA, NSW**
All oilseeds	**1386**	**1447**	**1.04**	**NSW, WA**
Lupins	715	790	1.10	WA, NSW
Field peas	325	317	0.98	SA, Victoria
Chickpeas	285	316	1.11	NSW, Queensland
Faba beans	151	185	1.23	SA, Victoria
Lentils	147	133	0.90	Victoria, SA
Other legumes*	40	75	1.90	NSW, Queensland
All legumes	**1663**	**1816**	**1.09**	**WA, SA, NSW**

* Estimated. Includes mungbeans, navy beans, cowpeas, peanuts and pigeon peas.

SOURCE: : ABARES 2010, 2011

Soils in the region tend to have a moderate to high percentage of clay and vary in colour from yellow through to red, brown, grey and black. Major soil types are vertosol, dermosol, chromosol, sodosol, kandosol and ferrosol (Isbell 1996; Daniels *et al.* 2002; Cox and Strong 2008). For the most part, the soils were naturally fertile, which meant that farmers could initially produce high-yielding, high-protein crops with little use of either N_2-fixing grain or pasture legumes or N fertiliser. Research conducted during the late 1940s to early 1950s signalled a future problem however, by showing that soil organic N declined with cultivation, that the rate of decline was most severe in the first 10 years of cropping, and that lower soil total N was associated with lower wheat yields (Hallsworth *et al.* 1954; Chapter 2.1).

By the 1970s and 1980s, declining wheat grain protein levels across the region were indicating a widespread problem of N supply, even though R&D on fertiliser N and N_2-fixing legumes at that time pointed to potential solutions. Eventually the Grains Research and Development Corporation (GRDC) commissioned a review of N management in the northern grains region (Henzell and Daniels 1995). The report stated:

> *"…while grain growers recognise the problem of declining soil fertility in the region, and scientific understanding of the problems of nitrogen management has advanced rapidly, it may be that the complexity of the processes involved has stifled the ability of growers to use this understanding for farm decision making…" (Henzell and Daniels 1995, quoted by Lawrence* et al. *2000).*

Almost immediately, and arguably in response to the 1995 report, significant advances were made in the N extension programs in NSW and Queensland with the publication of the 'N and Wheat Production' supplement to Australian Grains magazine (Marcellos and Felton 1994) and the subsequent release of 'Nitrogen in 95/96', a Queensland Department of Primary Industries (QDPI) workshop manual and training package for farmers (Lawrence *et al.* 1995).

The manual/training program was designed to help farmers calculate fertiliser N requirements of their cereal crops while at the same time providing them with basic knowledge of N cycling and the interactions of soil, crop, water and N. Thus, after many years of confusion, growers were provided with training and tools for determining more confidently fertiliser N requirements. In south-eastern Queensland during 1995-96, about 400 farmers participated in the program. The NSW Department of Agriculture produced 'NITROGEN IN 96' and 'Nitrogen budgeting for winter cereals' in 1998 to extend the workshop program into northern NSW (Martin *et al.* 1996; Edwards and Herridge 1998).

Those early paper-based packages, while highly effective for transferring knowledge and as decision aids, had some deficiencies (Lawrence *et al.* 2000). They were not sufficiently accurate in estimating effects of previous crop or pasture on mineralisation of N in the soil, nor were they accurate in calculating the efficiency with which fertiliser N was converted into grain protein. The packages did not provide information on N_2 fixation of the legumes and effects of the fixed N on soil N balances.

At the same time, far more complex computer-based decision-support programs – APSIM, *WhopperCropper* and Yield Prophet® – were developed and released (see for example, McCown *et al.* 1996; Cox and Strong 2008; Carberry *et al.* 2009; Hochman *et al.* 2009b). All of the tools for N management essentially relied on the same budgeting approach; that is, the supply of plant-available N for a paddock is determined prior to sowing together with the amount of N needed to grow the crop, i.e. N demand. The shortfall between N demand and supply is the fertiliser N requirement.

Farmers use various approaches to determine N supply including deep coring for nitrate or mineral N, calculating on the basis of soil organic carbon levels and back-calculating on the basis of previous yield x protein outputs, i.e. N replacement. Nitrate testing is the most direct method and should provide the basis for good decisions about fertiliser N requirements. The proviso is that sampling is well done, i.e. adequate number of cores per paddock, and the samples are quickly transported to the testing laboratory. Each year, some paddocks in the northern grains region will be deep cored for nitrate. If the past is any guide, however, the percentage tested will likely be less than 30% (see for example, GRDC 2010). The majority of paddocks will not have any testing, leaving farmers to make the N budgeting decisions with little of the required information.

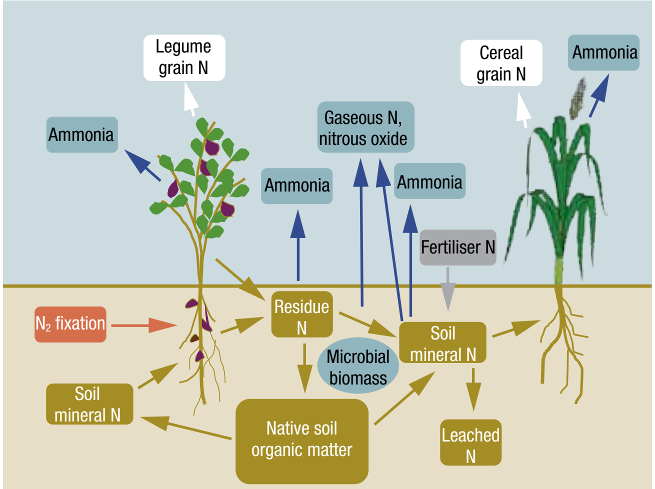
The problem is that the current N-management tools are not relevant to the majority of paddocks because they are not soil tested. What is needed is a tool that does not rely on soil testing for nitrate at sowing, yet at the same time provides estimates of the fertiliser N needs of next season's cereal and oilseed crops. 'NBudget', an N calculator, was developed in response to that need (see Chapter 5).

1.3 Nitrogen cycling in agricultural systems

In land-based systems, N is continually cycled between the atmosphere, where it exists in an unreactive state as gaseous N_2, and the soil. In natural (non-agricultural) systems, almost all of the N moves through growing plants. In disturbed agricultural systems, some of the N is lost from the soil before the plants have had the opportunity to use it. The major loss pathways are erosion, denitrification, ammonia volatilisation and leaching.

Between 150 and 200 million tonnes of N are added to the world's agricultural soils and crops each year to be balanced by the processing of N into soil organic matter, the removal of N in harvested products, and losses. In Australian agriculture, inputs of N are 3 to 4 million tonnes annually (Smil 1999; Angus 2001; Unkovich 2002; Herridge *et al.* 2008).

FIGURE 1.3 The N cycle in grains cropping, in this instance involving a legume-to-cereal sequence, showing transformation processes, pathways and sinks. Losses of N through erosion are not shown



At first glance, the N cycle appears to be a complicated jumble of boxes and arrows (Figure 1.3) and unrelated to on-farm or in-paddock decision making about N. The commonly asked questions about N in farming – for example, how much N do legumes fix, how much N is mineralised during a fallow, what is the efficiency of fertiliser-N application, how much N is lost through leaching or denitrification from soil – may all be more readily answered with a basic understanding of the N cycle, coupled with real values that quantify the transformations (arrows in Figure 1.3) and pools (boxes in Figure 1.3) in the cycle.

In the following sections, the N cycle is defined in terms of its major functions: adding N to the soil, moving N around the soil, harvesting N and losing N from the soil. Note that pasture systems with grazing animals are also important in grain cropping. When animals are present, less plant N is harvested as product and substantial amounts of the plant N are recycled back into the soil as animal dung and urine (see Chapter 3.3.2).

1.3.1. Adding nitrogen to the soil

Nitrogen can be supplied to a system either as mineral or organic fertilisers, through N_2 fixation by bacteria associated with legumes and other plant species or free living in the soil, and through deposition from the atmosphere.

Fertilisers

Globally, in excess of 100 million tonnes of fertiliser N, in both mineral and organic forms, are used each year in agriculture (Jensen and Hauggaard-Nielson 2003). The amount for Australia is about 1 million tonnes (see Chapter 4).

Following application, the various forms of nitrogenous fertiliser undergo transformations, resulting in the N being incorporated into the soil mineral N pools (ammonium and nitrate), microbial biomass, plants or lost via the various loss pathways. As there are a number of pathways in which fertiliser N may go, the efficiency of incorporation of the N into the soil mineral pools and then into the growing crop may vary substantially and may sometimes be quite low (see Chapter 4). A rule of thumb is that 80% of fertiliser N is converted into plant-available nitrate N.

Converting 50% of fertiliser N into cereal grain N is regarded as highly efficient. The fertiliser N does not only make grain proteins, it is also used to grow the rest of the plant, including the roots. Efficiencies with which fertiliser N is converted into grain N are usually in the range of 25 to 50% (Strong 1995).

Biological nitrogen fixation

Biological N_2 fixation is the reduction of atmospheric dinitrogen (N_2) to ammonia (NH_3), catalysed by the enzyme nitrogenase. It occurs most intensively in the root nodules of legumes (termed symbiotic N_2 fixation) inhabited by a soil bacteria, rhizobia. The rhizobia actually fix the N with the legume using almost all the fixed N for their own growth. Some other types of bacteria can fix N 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 1.4). The most important system for agriculture, however, is the legume-rhizobia symbiosis (see Chapter 3).

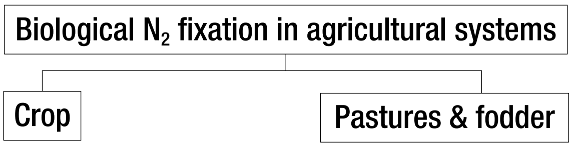
$$N_2 + 8H^+ + 8e^- \rightarrow 2NH_3 + H_2$$

(N_2 – gaseous N; H^+ – hydrogen ion; e^- – electron; NH_3 – ammonia; H_2 – hydrogen)

In N_2-fixing legumes, the ammonia is quickly converted into amino acids and other N-rich compounds in the nodules, to be then transported to the shoot and utilised in growth.

Globally, agricultural legumes fix about 40 million tonnes annually (Herridge *et al.* 2008). The figure for Australia's legumes is close to 3 million tonnes annually,

FIGURE 1.4 Biological N_2-fixing agents in agriculture



Plant-associated
- legumes-rhizobia (symbiotic)
- *Azolla*-cyanobacteria (symbiotic)
- grasses/cereals-associative bacteria
- grasses/cereals-endophytic bacteria

Free-living
- cyanobacteria
- heterophic bacteria
- autotrophic bacteria

Plant-associated
- legumes-rhizobia (symbiotic)
- grasses-associative bacteria
- grasses-endophytic bacteria

Free-living
- cyanobacteria
- heterophic bacteria
- autotrophic bacteria

more than 90% of which is fixed by pasture species (Angus 2001; Unkovich 2002). On a unit area basis, the amounts fixed can be substantial. An amount of 600 kg N/ha/year is quite realistic for a very high-yielding grain legume crop or pasture. More commonly, amounts are in the order of 100 kg N/ha/year (see Chapter 3).

Atmospheric deposition

Small amounts of nitrogen, 5 to 10 kg/ha/year in Australia but as much as 40 kg N/ha/year in parts of Europe and North America, can also be introduced via ammonia and nitrous oxide (N_2O) assimilation by plants and through deposition on the soil surface of N in rainfall (as nitrate (NO_3^-) and ammonium (NH_4^+)), nitric oxide (NO) and nitrous oxide and dust (Goulding *et al.* 1998; Angus 2001).

1.3.2 Moving nitrogen around the soil

Nitrogen can be found in different components (pools) in the soil, depicted by the boxes in Figure 1.3, and moves between the pools via a variety of transformation processes. This section does not include the harvesting and loss processes.

POOLS

Plants

Nitrogen is present in plants as proteins, transport and storage compounds, structural compounds and genetic material. Cereal and oilseed crops have a high demand for N, which is met through uptake of soil mineral N, principally nitrate. With legumes there are two sources of N supply: N_2 fixation and soil mineral N. Typically, wheat will extract N from the top 1.2 metres in well-structured soils; depth of extraction of N by the grain legumes may be slightly less, i.e. about 1 m.

The N demand of grain crops in non-drought seasons is commonly 100 to 150 kg N/ha for wheat and about 150 to 200 kg N/ha for grain legumes, such as faba beans and chickpeas. Those amounts will be distributed between above-ground (shoot) and below-ground (root) parts. With wheat and faba beans, about 30% of N is below ground. In the case of chickpeas and the pasture legume lucerne, the percentage below ground is closer to 50% (see for example, Unkovich *et al.* 2010).

Residues – above and below ground

With grain crops, above-ground (straw, shoots, fallen leaves) and below-ground (roots, nodules) residues remain after grain harvest. Typically, the N contained in these residues may range from 10 to 50 kg N/ha for the above-ground and 30 to 100 kg N/ha for the below-ground material.

Recent research using the isotope of nitrogen (^{15}N) as a tracer has shown that the N contained in below-ground parts was usually underestimated in the past and that these residues represent a larger source of N for the soil than the straw, shoots and fallen leaves.

Dung and urine of grazing animals

Between 5 and 25% of the N of grazed pasture and fodder plants ends up in the body of the grazing animal, with the remaining 75 to 95% expelled as dung and urine (Fillery 2001).

Soil organic matter – humus, charcoal & active fractions

Soil organic matter is a heterogeneous mixture of plant and animal litter in various stages of decomposition, microbial biomass and its detritus and charcoal (Skjemstad *et al.* 1998). Broadly, its composition is 70 to 90% stable humus material and 10 to 30% active or labile material (Gregorich *et al.* 1997). Humus is composed of amino acids, amino sugars, and a complex of other known and unknown compounds. It is mineralised slowly to ammonia and ammonium by soil microorganisms, to be converted to nitrate by other microbes. The active or labile fraction of soil organic matter is mainly in the form of readily decomposable plant and animal residues, with 20 to 40% as microbial biomass.

In natural systems, amounts of soil organic N (humus, microbial biomass, plant residues and dung) tend to be stable, although they will vary according to soil type, rainfall, and air and soil temperatures, in turn affecting the landscape vegetation. The ratio of humus to labile material also tends to be higher.

With cropping, organic N declines exponentially, so that levels after 30 years' continuous cropping may be anywhere between 40 and 80% of the original levels (Chapter 2). Thus, typical organic N levels in the NSW grainbelt soils may be 1 to 2 t/ha in the top 10 centimetres and 5 to 8 t/ha in the top 1m of soil.

Microbial biomass

Soil microbial biomass is the living part of soil organic matter (Dalal 1998), consisting of fungi (about 50% of total), bacteria (30%) and yeasts, protozoa, algae and nematodes (20%) (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 (also termed soil biota and soil biology). They 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 cm of the soil. Typical amounts of microbial biomass N are 30 to 80 kg N/ha in the top 10 cm of soil, equivalent to 1 to 2 t/ha biomass. More comprehensive descriptions of microbial biomass (soil biology) can be found in Chapter 1.3.5. Readers are referred also to Dalal *et al.* (1998) for a review of factors affecting the size of the microbial biomass in soils and the significance of its measurement.

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

In agricultural soils, nitrate is the most important form of mineral N. It is usually in far higher concentrations than ammonium, particularly in the root zone, and it is the form of N that plants utilise for growth. In most agricultural soils, microbial conversion of ammonium to nitrate proceeds quickly and efficiently. This process will be slowed in highly acid soils, resulting in a build-up of ammonium. Typical soil tests for wheat paddocks may show nitrate levels of 50 to 100 kg N/ha in the top 1m of soil, with ammonium levels less than 5 kg N/ha.

Nitrate is very soluble in water and moves principally with water movement (i.e. mass flow). Nitrate can also move in soil by diffusion, from an area of high concentration to an area of low concentration. Nitrate is also quite stable in soil and, in the absence of growing plants and conditions that are conducive to the pathways of loss, can accumulate to high levels, that is, more than 300 kg N/ha to 1.2 m depth (more details of stability of nitrate in soil in Chapter 2). Nitrate can also be immobilised into soil microbial biomass and be lost from the soil through leaching, denitrification and erosion.

NITROGEN TRANSFORMATION PROCESSES

All of the soil processes associated with organic matter decomposition and N transformations are optimised in warm, moist soils, i.e. 30°C and close to field capacity (Stott *et al.* 1986; Summerell and Burgess 1989), with good contact between the substrate, e.g. crop residues, and the soil (Douglas *et al.* 1980; Summerell and Burgess 1989). Such conditions are found in cultivated soils in which crop residues are incorporated.

Urea hydrolysis

An important nitrogen transformation is the conversion of urea ($CO(NH_2)_2$) in animal urine and fertilisers to ammonia, catalysed by the enzyme urease.

$$CO(NH_2)_2 + 2H_2O \rightarrow (NH_4)_2\,CO_3 \rightarrow 2NH_3 + CO_2 + H_2O$$

($CO(NH_2)_2$ – urea; H_2O – water; $(NH_4)_2CO_3$ – ammonium carbonate; NH_3 – ammonia; CO_2 – carbon dioxide)

This 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.

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 secreted by either living or dead soil organisms into the soil matrix (particularly associated with humic colloids and clay minerals). 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 eaten 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 eaten by microfauna predators (see Figure 1.4). Eventually, the residues will have been processed to the point that they are relatively stable as humic substances (humic and fulvic acids and other compounds). Humus, to a large extent, represents the recalcitrant compounds of the original residues and the faeces and dead bodies of the soil organisms

Ammonification

Ammonification is the conversion of organic substances in the soil to ammonia and ammonium 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, i.e. 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.

Nitrification

Nitrification is the conversion of ammonia or ammonium to nitrate. It is a two-step process. In the first step, ammonium is converted to nitrite (NO_2^-) by the soil bacteria, *Nitrosomonas*. The second step, carried out by *Nitrobacter* bacteria, sees the nitrite converted to nitrate (NO_3^-). Thus:

$$NH_4^+ + {}^3\!/\!_2\,O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

and

$$NO_2^- + {}^1\!/\!_2\,O_2 \rightarrow NO_3^-$$

(NH_4^+ – ammonium; H_2O – water; O_2– oxygen; NH_3 – ammonia; H^+ – hydrogen ion; NO_2^- – nitrite ion; NO_3^- – nitrate ion)

Nitrification occurs under much the same conditions as ammonification. An additional requirement, though, is for neutral to alkaline soils. Nitrification is inhibited in acidic soils (pH less than 6.0).

The processes of ammonification and nitrification are together termed mineralisation. Fresh crop residues, animal manure and humus are all subjected 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 by soil management practice (generally higher for cultivated soils) (Powlson 1980).

Immobilisation

Incorporation of both nitrate and ammonium into microbial biomass, called immobilisation, occurs when plant residues with high C:N ratios are being broken down in the soil by the soil biota (Bradbury *et al.* 1993). Humus and the bacteria and fungi that are key to its creation all have low C:N ratios, about 11:1 or less. Thus, amounts of additional N required for microbial activity and humification will decline as the C:N ratios of residues declines (see Chapter 6 for more detail). In acidic soils (pH less than 6.0), ammonium is preferentially immobilised, whilst in alkaline soils (pH greater than 7.0), nitrate is immobilised in preference to ammonium (Rochester *et al.* 1992).

Net immobilisation of the mineral N will normally be transitory (days to weeks) and, once the C:N ratio of the residues have been reduced sufficiently, will be followed by the release of and net increase in mineral N in the soil. Immobilisation of fertiliser N can be more permanent if the fertiliser is applied in close proximity to residues with high C:N ratios.

Generally, residues with C:N ratio greater than 30 will immobilise mineral N. Residues with C:N ratio less than 20 will release mineral N, and those in between will have a neutral effect on soil mineral N.

1.3.3 Harvesting nitrogen

Grain

With crops, substantial amounts of N are transferred out of the system with the harvested grain. Nitrogen concentrations in grain vary from about 1.4% (8% protein) for sorghum and biscuit wheats, to 2.3 to 2.6% (13 to 15% protein) for prime hard wheats, to about 3.5% (22% protein) for chickpeas, to greater than 6% (38% protein) for soybeans.

Thus, amounts of N removed in the harvested grain may range from as little as 20 to 30 kg N/ha to more than 100 kg N/ha. Typically, grain N harvested from crops in the northern grains region would be 50 to 80 kg N/ha.

Shoot biomass cut for hay, silage

Infrequently, the decision will be made to cut the crop or pasture for hay/silage, rather than take it through to grain harvest (crop) or graze it (pasture). With grain crops, this is usually because the crop is damaged by extremely dry or wet weather and unlikely to yield much grain.

Meat and wool

In grazing systems, the harvested products are meat and wool. Amounts of N transferred out of the system are typically 5 to 50 kg N/ha/year (Fillery 2001; Peoples and Baldock 2001).

1.3.4 Losing nitrogen from the soil

Substantial amounts of N can be lost from the soil during a season, either in one of the number of gaseous forms or leached as nitrate. Nitrogen can also be lost through erosion (not shown in N cycle (Figure 1.3) but discussed below).

Gaseous nitrogen – ammonia (NH_3), dinitrogen (N_2), nitric oxide (NO), nitrous oxide (N_2O)

Gaseous N is present in the soil-plant-air system as ammonia, dinitrogen (N_2), nitric oxide and nitrous oxide. By far the most common is N_2, which makes up about 80% 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 N cycle (ammonia in volatilisation; nitric oxide and nitrous oxide in nitrification; N_2, nitric oxide and nitrous oxide in denitrification). Globally, there is 10,000 times more N in the atmosphere than in soil organic matter.

Denitrification

Denitrification is the reduction of nitrate by soil microrganisms to nitric oxide, nitrous oxide and N_2. The soil microbes use the nitrate and nitrite ions, ie NO_3^- and NO_2^-, in place of oxygen as terminal electron acceptors for respiration. Thus:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\uparrow \rightarrow N_2O\uparrow \rightarrow N_2\uparrow$$

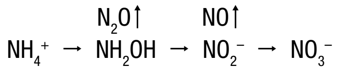
(NO_3^- – nitrate ion; NO_2^- – nitrite ion; NO – nitric oxide; N_2O – nitrous oxide; N_2 – dinitrogen)

The process requires an energy source (carbon), the substrate (soil nitrate) and appropriate conditions (saturated soil, moderate to high soil temperatures). 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 agriculture and in the irrigated systems than in the dryland agriculture of the southern and western grainbelts. It can be a problem of the vertosols (black, cracking clays) in the northern grainbelt because of their low hydraulic conductivity when wet and high-rainfall events.

The process is difficult to accurately quantify. Estimates for global denitrification and nitrification losses of nitric oxide, nitrous oxide and N_2 associated with agriculture vary substantially, from 4 to 5 million tonnes annually (Jenkinson 2001; Freney 2002; Minami 2002) to 13 to 30 million tonnes annually (Smil 1999).

Nitrification

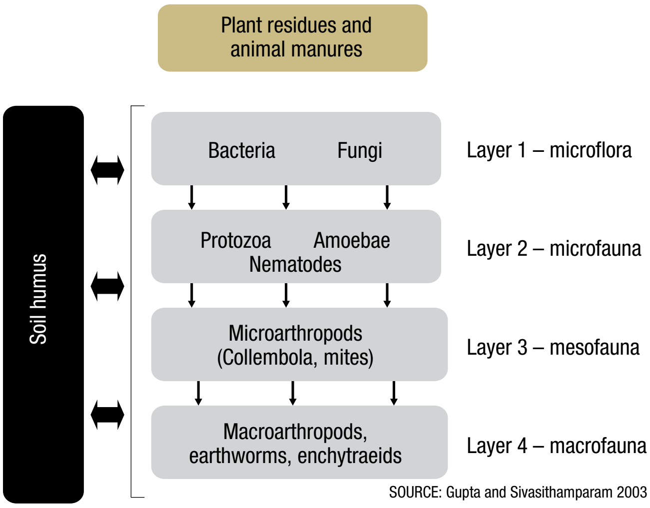
In aerobic soils, N can be emitted as nitric oxide and nitrous oxide as by-products of nitrification, the process in which ammonium is converted to nitrate.



$$NH_4^+ \rightarrow \overset{N_2O\uparrow}{NH_2OH} \rightarrow \overset{NO\uparrow}{NO_2^-} \rightarrow NO_3^-$$

(NH_4^+ – ammonium; NH_2OH – hydroxylamine; NO_3^- – nitrate ion; NO_2^- – nitrite ion; NO – nitric oxide; N_2O – nitrous oxide)

FIGURE 1.5 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

The major issues with gaseous emissions of N via denitrification and nitrification are the cost to the farmer of the loss of potentially plant-available N from the soil and the contribution of nitrous oxide to greenhouse gases. The latter is discussed in more detail in Chapter 2.

Volatilisation of ammonia

Total global ammonia volatilised has been estimated at 50 million tonnes annually, with 22 million tonnes from domestic animal manures and 9 million tonnes from nitrogenous fertilisers. Growing crops and burning of crop residues account for a further 6 million tonnes annually (Asman *et al.* 1998; Smil 1999).

Volatilisation of ammonia from standing crops is about 5 kg N/ha/year, which increases with elevated temperatures, stress conditions of growth and high tissue N contents (Jenkinson 2001; Jensen and Hauggaard-Nielson 2003). Emissions from crop residues during decomposition are generally low but may be significant with N-rich materials under certain circumstances. With burning of plant residues, 90% of plant N will be volatilised. The ammonia does not remain in the atmosphere for long and can be returned to the soil close to where it was emitted (Jenkinson 2001).

The transformation in soil of the more stable ammonium to the volatile ammonia increases with increasing pH, temperature, soil porosity and wind speed at the soil surface. It decreases with increasing water content and rainfall events following application. Consequently, ammonia volatilisation can be high following surface application of urea and ammonium fertilisers, for example ammonium sulfate, to alkaline soils.

Leaching

With efficient management of soil and crops, leaching of nitrogen should be a minor pathway of loss in most soils, and particularly so in the clay soils of the Australian grainbelt. Leaching losses may be significant in coarse-textured (sandy) soils in high-rainfall areas or during protracted periods of high rainfall.

Erosion

One loss pathway that is not shown in Figure 1.3 is erosion. In certain circumstances, this can be substantial, for example on sloped, cultivated land. Natural rates of erosion are usually less than 1 t/ha/year, whereas losses in agricultural soils are more likely 5 to 20 t/ha/year (Elliot 2002), but can be as high as 100 t/ha in a single storm event (Boardman 2002).

Dalal and Probert (1997) suggested that erosion was insidious in its effect on land productivity in that the process selectively removed organic matter and fine soil particles and left behind coarse particles. Each tonne of soil may contain 1 kg N, mainly in organic form. The soil erosion losses of 50 t/ha equate to nitrogen losses of 50 kg/ha. Total global losses of N from leaching and erosion combined have been estimated at 2 million tonnes annually (Mosier 2001).

Management has a large effect on erosion losses, particularly when related to the management of crop stubble and soil surface cover (Thomas *et al.* 2007b). For example, Wockner and Freebairn (1991) reported 3, 6, 16 and 49 t/ha/year soil loss for no-till, stubble mulch cultivation, stubble incorporation cultivation and cultivated bare fallow, respectively, in a wheat production system in southern Queensland.

1.3.5 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 or soil biology. Soil biology is the living part of soil organic matter. Soil organic matter is a component of the soil – commonly 1 to 5% by weight in the top 15 cm – and is composed of living and dead animal and plant material and soil organisms and their excretions. The soil organisms (biology) comprise about 5% of soil organic matter. However, their presence and activity has a huge effect, not only on N cycling, but also on the general health of the soil (see Chapter 2).

Soil biology is best described as a network of organisms, linked to each other and linked to the two main sources of food: plant residues and animal manures and soil humus (Figure 1.5). It has been described conceptually as a detritus food-web (Gupta and Sivasithamparam 2003).

The first layer is composed of the smallest organisms, the microflora, comprising 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 0.05 millimetres), they exist and are protected in very fine pores in the soil.

The second layer is composed of slightly larger organisms, the microfauna, comprising protozoa, amoebae and nematodes. These organisms also have many functions. They decompose humus and residues and feed on (predate) 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 0.1 mm.

The third layer is composed of even larger organisms, the mesofauna, comprising the microarthropods (collembola and mites). The mesofauna 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 10 mm.

The top layer of the food-web comprises the macrofauna. The macrofauna (earth worms, etc) are the major biological agents of fragmentation and redistribution of residues in soil. They also predate the organisms in the layers below. Their range of size is 1 to 150 mm. The whole process is dynamic, with decomposition of soil humus and fresh residues and manures occurring simultaneously with synthesis of new humus.

The numbers of organisms in soil are mind-boggling, particularly in the case of the microflora (bacteria, fungi and algae) (Table 1.2). The numbers of the individual groups of organisms and total soil 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 inputs than impoverished soils). It is interesting to note that the biomass of the soil biology (up to 2.5 t/ha) can far exceed the biomass of grazing sheep (about 0.5 t/ha).

There is also a staggering diversity of thousands of species in the soil with a large range of capabilities (Paul 2007). It has been estimated that the organisms in a typical soil might contain 50 to 60 different enzymes that facilitate all manner of reactions and processes, such as breaking down cellulose to hydrolysing urea to ammonia to producing plant-growth-promoting hormones (King and Pankhurst 1996). It has been estimated that 80 to 90% of the biological activity in a typical soil is associated with the bacteria and fungi.

The majority of the enzymes are located within living soil organisms, but they may also be located within dead cells and cell debris. They may also have leaked from living and dead cells to be absorbed into clay particles and humic colloids (Nannipieri and Landi 2000). What essentially drives this vast array of life and activity is energy, i.e. carbon.

If energy (carbon) is the major driver, it is actually soil temperature and moisture that moderate levels of activity. Peak activity is around 25°C to 30°C, falling away to nil activity as the temperature approaches zero on one hand and 60°C on the other (Paul 2007).

Although the temperature of surface soils fluctuate substantially during the course of a day, temperatures below the surface are far more moderated. Thus, diurnal fluctuations of 35°C at the surface are reduced to fluctuations of about 10°C at 10 cm depth and just 2°C at 20 cm depth. During the hottest and coldest months, temperatures at 10 to 20 cm depths might be near optimum for soil biology activity.

TABLE 1.2 Typical numbers of the various groups of biota in soil

Soil biota group	Numbers/kg surface soil	Numbers/ha
Bacteria	Up to 10 billion	Multiply all of those numbers (hyphal length in the case of the fungi) by 1 million
Fungal hyphae	Up to 100 km	
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 at field capacity (FC) and falling away as the soil becomes drier. Significantly, activity remains at around 40% of maximum at permanent wilting point (PWP), when plants have essentially stopped growing. In a clay soil, PWP coincides with a volumetric moisture content of 20 to 25%, with the water held in micropores, available for the soil organisms but not for plants. The significance of this is the fact that during a drought when crops cannot be planted, other processes continue, such as the decomposition of crop residues and humus (see Chapter 2.5.2.)

Most of the biological activity is in the top part of the soil profile. Fierer *et al.* (2003) showed that 82% of total microbial activity is in the top 25 cm, together with 57% of microbial biomass and 40% of soil organic carbon, the major energy source of the soil organisms. The composition of the soil biology 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 20 cm 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 C-limited than surface organisms.

CHAPTER 2: NITROGEN IN NORTHERN GRAINS REGION SOILS

Research on N in northern grains soils and farming systems during the 1960s through to the end of the century followed a number of themes. First was research on nitrogenous fertilisers during the 1960s to the 1990s (see for example Colwell and Esdaile 1966; Strong 1981, 1982, 1986, 1995; Doyle and Shapland 1991; Doyle and Leckie 1992). The comprehensive studies of Ram Dalal and colleagues during the 1980s on long-term cropping effects on soil fertility and quality (Dalal and Mayer 1986a, b) built on previous research in southern Queensland (see for example Martin and Cox 1956). Finally, farming systems research examined the role of legumes and fertiliser N in cereal cropping during the 1980s through to the end of the century (see for example Dalal *et al.* 1995, 1997a, 1998; Strong *et al.* 1996; Felton *et al.* 1998; Marcellos *et al.* 1998; Herridge *et al.* 1998).

2.1 Organic matter in soil

Before discussing the critical role that organic matter has in delivering N to growing crops, it may be useful to first define soil organic matter and its role in agricultural soils. 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. It is, on average, 57% carbon (C) and about 5% N. To convert soil organic carbon (SOC) to soil organic matter (SOM), multiply the former by 1.75.

FIGURE 2.1 The level of organic matter in soil affects how well the soil functions. High levels enhance soil structure, help to ameliorate toxicities and facilitate efficient nutrient cycling to growing crops and pastures

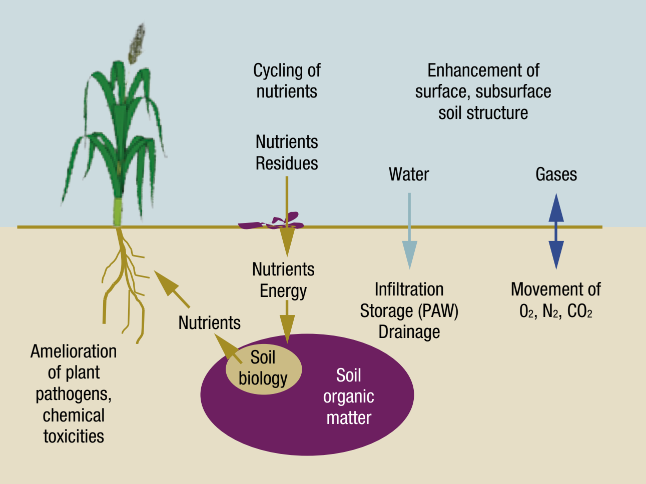


TABLE 2.1 Percentages and weights of whole soil, soil C and soil N in the top 10 cm depth

Fraction	%	Mass (tonnes)	
		BD = 1.0	BD = 1.5
Whole soil	100	1000	1500
Soil C	1	10	15
Soil N	0.1	1	1.5

Organic matter is composed of various fractions, usually in the ratios of 70 to 90% stable humus material and charcoal and 10 to 30% active or labile material. Humus is composed of amino acids, amino sugars, and a complex of other known and unknown compounds. The labile fraction of soil organic matter is mainly in the form of readily decomposable plant and animal residues, with 20 to 40% as microbial biomass.

Microbial biomass, also termed soil biota or soil biology, consists of fungi, bacteria, yeasts, protozoa, algae, nematodes and earthworms, among a host of other 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 soil microbes.

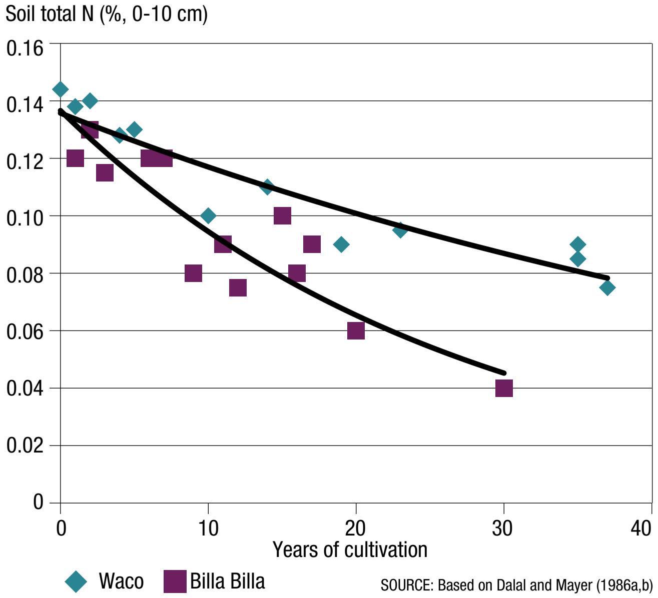
Organic matter has a fundamental and necessary place in soils (Figure 2.1). It helps to ameliorate or buffer the harmful effects of plant pathogens and chemical toxicities. It enhances surface and deeper soil structure, with positive effects for the infiltration and exchange of water and gases and for keeping the soil in place, that is, reducing erosion. It improves soil water-holding capacity and, through its high cation-exchange capacity, prevents the leaching of essential metal cations. Finally, and perhaps most importantly, it is a major repository for the cycling of nutrients and their delivery to crops and pastures (Skjemstad *et al.* 1998).

How are the levels of organic C and N measured in soils and what do the test results mean? Until a few years ago, C and N were measured in soils using the Walkley–Black and Kjeldahl digestion methods, respectively. Now, the preferred method for both is by dry combustion using a Leco analyser. Note that the Walkley–Black method (Walkley and Black 1934) only measures about 80% of the C in the soil and results cannot be directly compared with those determined by dry combustion, i.e. Leco test (Merry and Spouncer 1988; Chan *et al.* 2011). The weights of C and N in hypothetical soils to a depth of 10 cm, with bulk densities of either 1.0 or 1.5, and organic C of 1% and total N of 0.1%, are shown in Table 2.1.

2.2 Declining soil organic matter in the northern grains region

Dalal and Chan (2001) reported that effects of land clearing and cropping to reduce soil organic matter levels resulted from changes in soil temperatures, moisture

FIGURE 2.2 Graph showing decline in soil total N with years of cropping. The decline was greater for the Billa Billa soil (clay content of 34%) than the Waco soil (74% clay)



SOURCE: Based on Dalal and Mayer (1986a,b)

fluxes and aeration, increased soil loss through erosion, reduced inputs of organic materials, increased export of nutrients in harvested product and exposure of protected organic matter with cultivation.

Dalal and co-workers had previously published a series of papers showing effects of years of cultivation and cropping on soil properties, including soil N, in south-eastern Queensland (Dalal and Probert 1997). The average loss of soil N for the 83 paddocks after 16 years of cultivation was 34% (range 25 to 45%). The authors found the rate of soil N loss decreased as the clay content increased and concluded that the clay protected organic matter from mineralisation.

Declines in soil total N with years of cultivation for two of the soil types are shown in Figure 2.2. The annual rate of loss for the Waco soil (74% clay) was 31 kg N/ha and for the Billa Billa soil (34% clay) was 50 kg N/ha. Interestingly, the Waco soil was used more for summer cropping and was supplied with fertiliser N at annual rates of 33 kg N/ha, whereas the Billa Billa soil was used predominantly for winter cropping and was not fertilised with N. To a large extent, the losses of soil N could be explained by net export of the grain product.

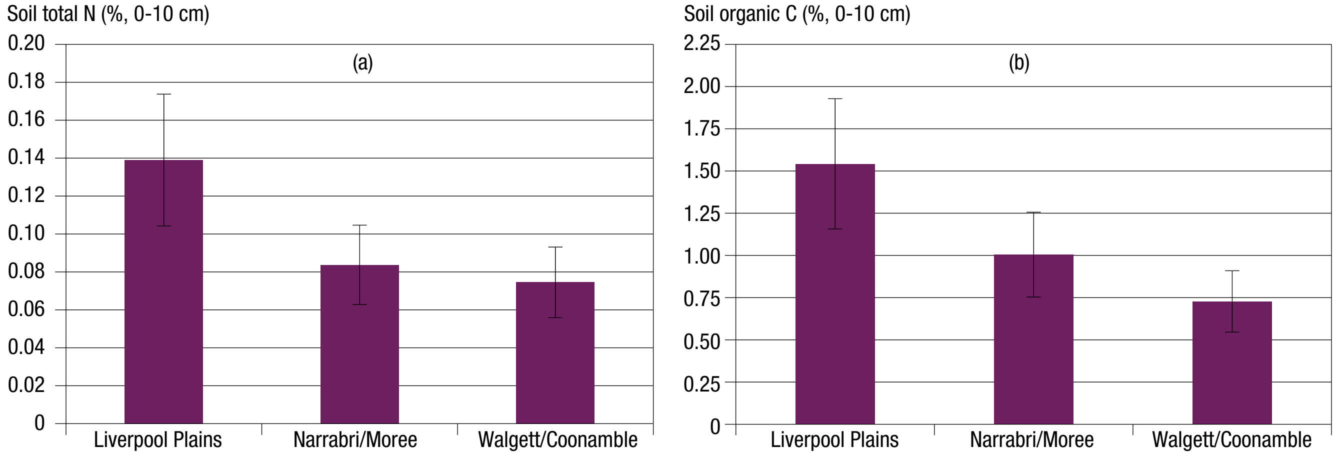
In a later study in the western fringe of the grainbelt of southern Queensland that had been long dominated by mulga (*Acacia aneura*), Dalal *et al.* (2005a, b) found that just 20 years of cropping resulted in losses from the top 30 cm of soil of 35% of soil C (equivalent to 4.7 t/ha) and 23% of soil total N (430 kg/ha). The authors questioned the sustainability of cleared mulga land in this part of the grainbelt, irrespective of whether it was used for cropping or for grazing.

Declining levels of soil organic matter have implications for soil structure, soil moisture retention, nutrient delivery and microbial activity (see Figure 2.1). Arguably, the single most important effect is the decline in the soil's capacity to mineralise organic N to plant-available N. In the original 83-paddock study of Dalal and co-workers, N mineralisation capacity was reduced by 39 to 57%, with an overall average decline of 52%. This translated into reduced wheat yields when crops were grown without fertiliser N.

2.3 The current situation

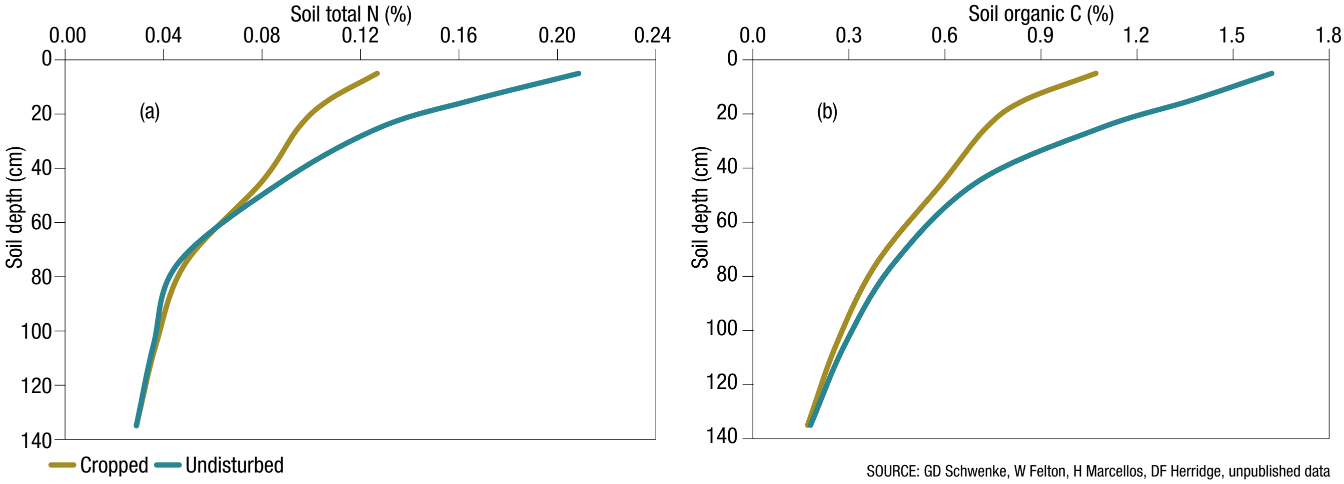
Current organic C and N levels in northern grains cropping soils reflect previous land use and management, as well as other factors such as rainfall, ambient temperature and soil type (Dalal and Mayer 1986b). There will be substantial within-paddock and paddock-to-paddock variation in a specific location, as well as variation across the whole northern region. In fact, differences between the extremely low and high values for particular localities can be as much as 4-fold. As a result, it may be near impossible to categorically state benchmark values for localities and/or soil types without sifting through masses of archived soil-testing data, with the inherent problems of which technique was used for measurement, or embarking on a new comprehensive testing program.

FIGURE 2.3 Values for (a) total N and (b) organic C for soils from three regions of the northern NSW grainbelt. Standard deviations are shown as the vertical bars



SOURCE: Schwenke *et al.* (1998) and GD Schwenke (unpublished)

FIGURE 2.4 **Profiles of total N and organic C in soils at the NSW DPI long-term farming systems site at Croppa Creek showing effects of about 40 years of cropping**



SOURCE: GD Schwenke, W Felton, H Marcellos, DF Herridge, unpublished data

Data for total N and organic C of cropping soils in the localities of the Liverpool Plains, Narrabri–Moree and Walgett–Coonamble are presented in Figure 2.3 to provide a guide for what might be considered as typical values. The data are aggregated from two on-farm surveys conducted by NSW DPI scientists in the 1990s. There was substantial variation within each locality and between localities. For example, for the 51 Moree–Narrabri soils, total N and organic C varied in the ranges 0.05 to 0.15% and 0.6 to 2.1%, respectively.

Measurements of soil organic C and N are normally done on surface soils, i.e. the top 10 or 15 cm. Concentrations of C and N are greatest near to the surface of the soil and progressively decline with depth. Commonly with cropped soils, 15 to 20% of the C and N of the root-zone (1.2 m depth) are in the top 10 cm (Figure 2.4). In the case of undisturbed native soils, the figures are more like 18 to 25%.

About 2.1 t N/ha and 26.5 t C/ha were lost or exported from the soil during the 40 years of cropping at the NSW DPI long-term farming systems site at Croppa Creek (Figure 2.4). All of the losses were in the top 60 cm.

2.4 Options for reversing the decline in soil organic matter

Reversing the decline in soil organic matter can be achieved by increasing organic inputs and, at the same time, reducing losses (Table 2.2).

Arguably, the most direct, effective means of increasing soil organic matter levels is through the use of legume-based pastures. The rotation experiments of Holford and colleagues at Tamworth, NSW, (Holford 1981; Holford *et al.* 1998) and Dalal and colleagues in south-eastern Queensland (Dalal *et al.* 1995; Strong *et al.* 1996) provide good evidence of this. An example is given in Table 2.3.

Greatest gains in soil C and N, relative to the wheat monoculture, were made in the four-year grass/legume ley, with increases of 550 kg total N/ha and 4.2 t/ha organic C. The chickpea–wheat rotation fared no better than the continuous wheat system. The shorter (1 to 2 years) lucerne and annual medic leys resulted in marginal increases in soil organic C and N. Additional details of the rotational benefits of pasture legumes are provided in Chapter 3.

Clearly, time and good sources of both C and N are required to build up soil organic matter, which is exactly what the four-year grass/legume ley provided (Dalal *et al.* 1995; Hossain *et al.* 1996a). Nitrogen was supplied via N_2 fixation by the lucerne and annual medic in the pasture, with most of the carbon supplied by the grasses purple pigeon grass and Rhodes grass (Hossain *et al.* 1995). There were no inputs of fertiliser N in any of the treatments in Table 2.3.

So what impact do fertiliser N inputs have on soil organic matter? In short, if the rates of fertiliser N are sufficiently high, the effects can be positive. In the Warra experiments, both soil organic C and total N increased

TABLE 2.2 Practices to increase soil organic matter

Increase organic inputs by:	Reduce losses of C and N by:
Increasing frequency of well-managed, highly productive pasture leys	Eliminating stubble burning
Increasing crop yields	Minimising fallowing
Retention of all crop residues	Taking measures to reduce erosion
Application of manures and recycled organic materials to the soil	Reducing tillage because excessive tillage leads to greater rates of soil OM decomposition and erosion losses

SOURCE: Adapted from Schwenke 2004, Chan *et al.* 2010

TABLE 2.3 Effects of different rotations on soil total N and organic C

Rotation	Wheat crops	Soil total N (t/ha)		Organic C (t/ha)	
		0–30 cm	Gain	0–30 cm	Gain
Grass/legume ley 4 years	0	2.91	0.55	26.5	4.2
Lucerne ley (1–2 years)	2–3	2.56	0.20	23.5	1.2
Annual medic ley (1–2 years)	2–3	2.49	0.13	23.1	0.8
Chickpeas (2 years)	2	2.35	0.00	22.0	0.0
Continuous wheat 4 years	4	2.36	–	22.3	–

SOURCE: Hossain *et al.* 1996a

marginally (3 to 4%) over an eight-year period when no-till continuous wheat, fertilised at a rate of 75 kg N/ha, was grown. This is in contrast to decreases of 10 to 12% in soil organic C and N in the non-fertilised continuous wheat and chickpea–wheat plots. The story was much the same in the NSW DPI experiments in northern NSW. At the Warialda site, for example, soil organic matter increased during fives years of cropping, but only where fertiliser N had been applied to the cereals (Figure 2.5).

It is clear from the examples above that N is required to build soil organic matter. It works in two ways – first, the fertiliser or legume N produces higher crop/pasture yields and creates more residues that are returned to the soil. These residues are decomposed by the soil microbes, with some eventually becoming stable organic matter or humus. The humus has a C:N ratio of about 10:1, that is, 10 atoms of C to 1 atom of N. If there are good amounts of mineral N in the soil in which the residues are decomposing, the C is efficiently locked into microbial biomass and then into humus. If on the other hand the soil is deficient in mineral N, then more of the C is respired by the soil microbes and less is locked into the stable organic matter.

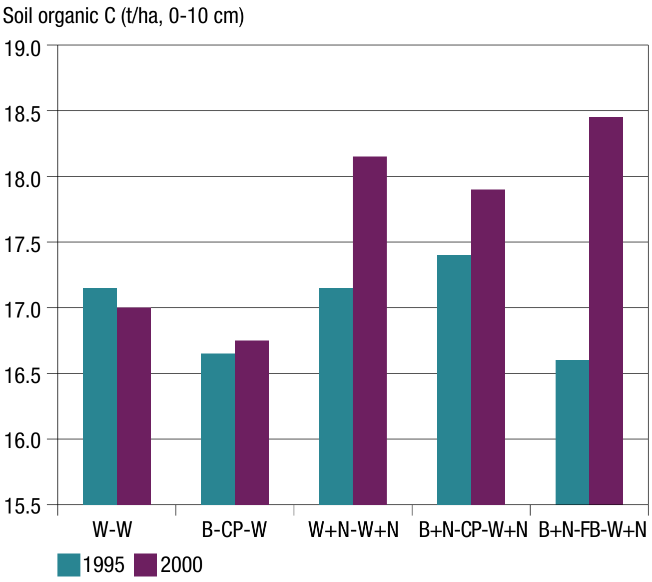
There is published evidence that applied fertiliser N enhances residue decomposition and its conversion into humus (see for example Moran *et al.* 2005). A number of the possible mechanisms are summarised by Baldock and Nelson (2000). Certainly the effects of fertiliser N inputs on the build-up of soil organic matter levels in the NSW and Queensland farming systems experiments appear to support this.

2.5 Plant-available (nitrate) N in the root zone

Nitrogen in the plant-available, mineral form is a major driver of crop production. In the northern grains region, almost all the N taken up by crops is in the form of nitrate. The other mineral form, ammonium, is present in most soils at low levels and very little, if any, is used directly by crops. Nitrate levels in the root zones of soils across the northern region vary substantially in both space (that is, amongst paddocks) and time (from season to season). In the following section, some of these variations are presented.

Throughout this book, the root zone for the annual crops is considered to be the top 1.2 m of soil. This is an average value, supported by the very large number of soil water and nitrate determinations of the NSW and Queensland nutrition and farming systems experimental programs of the past 20 years. In some soils, subsoil constraints will limit the root zone to less than 1 m (GD Schwenke, personal communication). In others that are particularly well structured, the root zones of long-season or particularly vigorous crops such as cotton and sorghum can be as deep as 1.8 m (Dalgliesh and Foale 1998).

FIGURE 2.5 Effects of applied fertiliser N in the cropping sequence on accumulation of soil organic C in the top 10 cm of soil



W-W = continuous wheat, no N fertiliser
B-CP-W = barley – chickpeas–wheat, no N fertiliser
W+N-W+N = continuous N-fertilised wheat
B+N-CP-W+N = chickpeas – N-fertilised wheat and barley
B+N-FB-W+N = faba beans – N-fertilised wheat and barley

SOURCE: GD Schwenke, W Felton, H Marcellos, DF Herridge, unpublished data; Schwenke et al. 1998

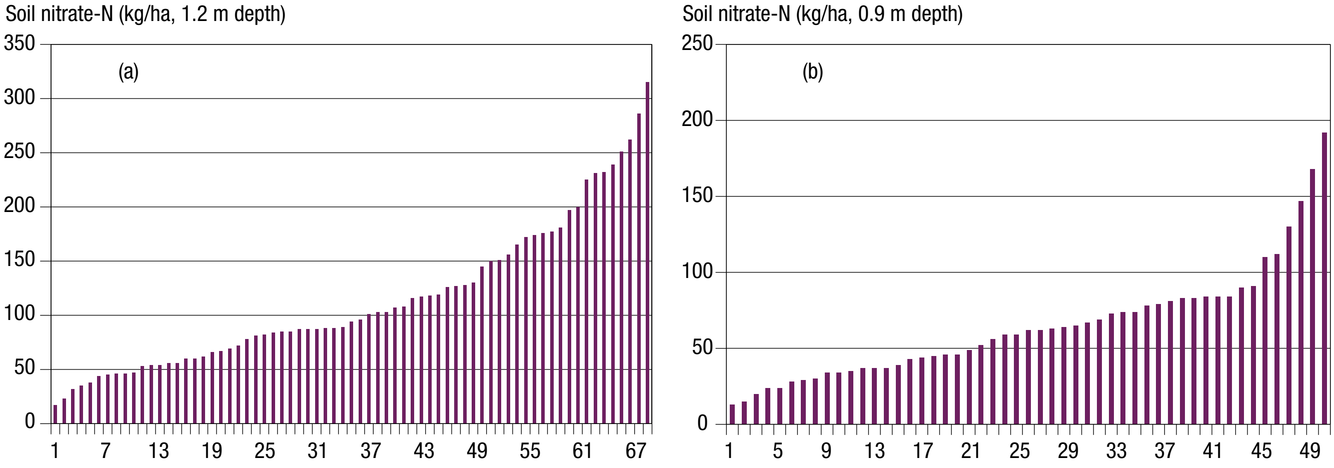
2.5.1 Nitrate variations with cropping and fallowing

Knowing how much nitrate is in the top 1.2 m of the soil in a particular paddock is a challenge for farmers. However, that information is critical for the farmer to then make a decision about how much fertiliser N to add. Each time assessments have been made of soil nitrate levels in commercial paddocks, the story has been the same. Soil nitrates vary enormously amongst paddocks, even though the paddocks may have then been used to grow identical crops. This is a management problem (see Chapters 5 and 6).

Data for two surveys of sowing soil nitrates are shown in Figure 2.6. One involved 70 paddocks that were sown with wheat, the second 51 paddocks that were either sown with chickpeas or faba beans. Ranges of nitrate levels in the two studies were large, 17 to 315 kg nitrate-N/ha in the 70-paddock wheat study and 13 to 192 kg nitrate-N/ha in the winter pulse study. Such large variations clearly provide challenges for farmers, such as how much additional N to add as fertiliser in the wheat paddocks and how to deal with the suppressive effects of the high nitrate soils on nodulation and N_2 fixation of the pulses.

In the normal cropping cycles of the northern grains region, nitrate accumulates during crop-free fallows to be used for crop growth during the cropping phase. We call the accumulation of soil nitrate N net mineralisation because it is really the balance of N released into the soil (mineralisation) during a particular period minus

FIGURE 2.6 Variations in soil nitrate levels in (a) 70 commercial paddocks in northern NSW two to three months prior to wheat sowing in 1996 and (b) 51 commercial paddocks in northern NSW just prior to sowing chickpeas or faba beans in 1994 and 1995



SOURCE: W Felton, H Marcellos, D Herridge, G Schwenke, unpublished; Schwenke *et al.* 1998

the N immobilised and lost through gaseous emissions (see Chapter 7 for more detail). Mineralisation is the conversion of organic N contained in humus and residues of plants and animals into the mineral forms – nitrate and ammonium. Immobilisation is the reverse. Both processes are associated with the soil microbes.

Figure 2.7 shows the accumulation of nitrate in the root zone soil during the summer fallow at the Breeza, NSW, long-term farming systems site following chickpeas, faba beans or barley (Khan *et al.* 2003). Accumulation of nitrate-N (net mineralisation) was 110 kg N/ha after the two legumes and 35 kg N/ha after barley. That equated to average net mineralisation rates of 0.2 to 0.5 kg N/ha/day following legumes and 0.1 to 0.2 kg N/ha/day following wheat (Marcellos *et al.* 1998; Dalal *et al.* 1994; Strong *et al.* 1996).

Note that there would have been substantial immobilisation associated with the decomposition of the barley residues, possibly as much as 40 to 50 kg N/ha. On the other hand, about 30 kg N/ha would have been released into the soil (net mineralisation) from decomposition of the chickpea and faba bean residues.

Figure 2.8 provides a snapshot of the depletion, accumulation and depletion of nitrate in a chickpea–summer fallow–wheat sequence. Data are the means of 6 tillage and soil fertility treatments from the NSW DPI medium-term farming systems site at Windridge in northern NSW. Chickpeas yielded 2.8 t/ha and the following wheat 3.5 t/ha.

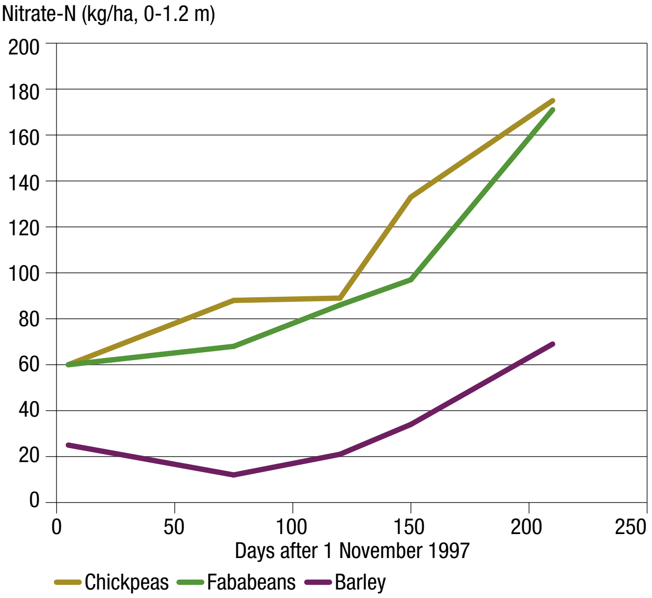
The first graph (a) shows the depletion of nitrate-N by the 1989 chickpea crop. The second graph (b) shows the replenishment of soil nitrate during the 1989-90 summer fallow to be followed by (c) depletion by the following 1990 wheat crop. In this case, only very small amounts of nitrate below 90 cm depth were used by either chickpeas or wheat.

The accumulation and depletion of water in the soil is, to a large extent, in concert with that of soil nitrate (Figure 2.9). The two are very closely linked and one should not be considered without the other.

2.5.2 Nitrate leaching

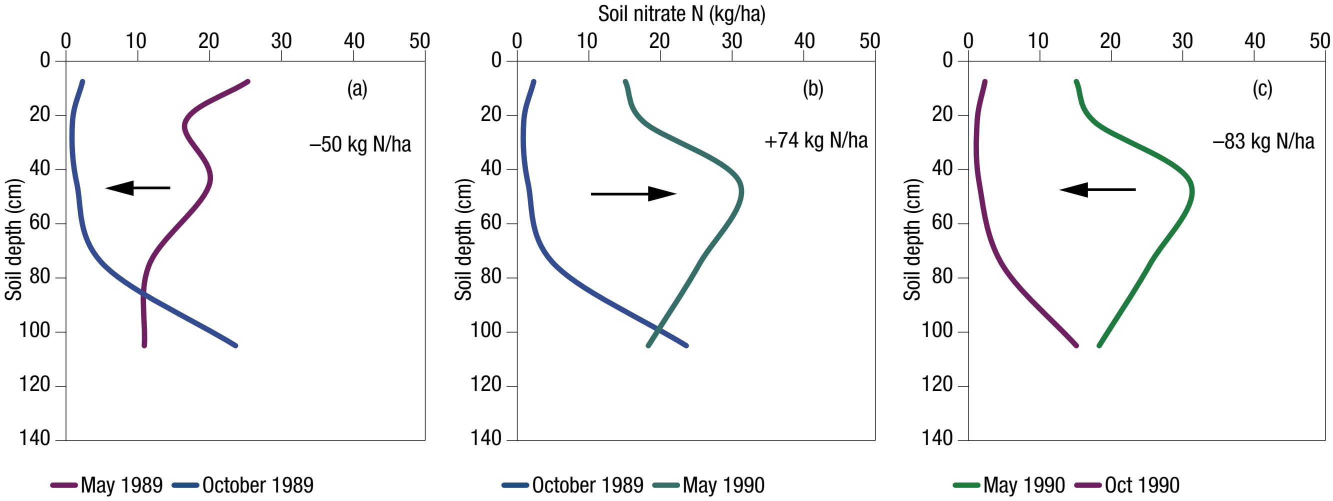
The question is often asked about the stability of nitrate in soils. In some environments, nitrate is readily leached beneath the root zone and lost. It is an important question because cropping in the northern grains region involves long (12- to 15-month) fallows as cropping moves from summer to winter and vice versa. As well, droughts might

FIGURE 2.7 Accumulation of nitrate in the root zones of soils following chickpeas, faba beans or barley. The experiment was at the NSW DPI Breeza long-term farming systems site during the 1997-98 summer fallow.



Note that the amount of nitrate in the old barley plots was less at the start of the fallow, reflecting nitrate sparing by the pulses, and actually declined during the first part of the fallow because of nitrate immobilisation.
SOURCE: Khan *et al.* 2003

FIGURE 2.8 Graphs showing the (a) depletion of nitrate-N in the root zone soil (1.2 m depth) by chickpeas, (b) accumulation of nitrate during the post-chickpea summer fallow and (c) depletion of nitrate by the following wheat crops



SOURCE: W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data

well be considered as enforced long (18- to 20-month) fallows.

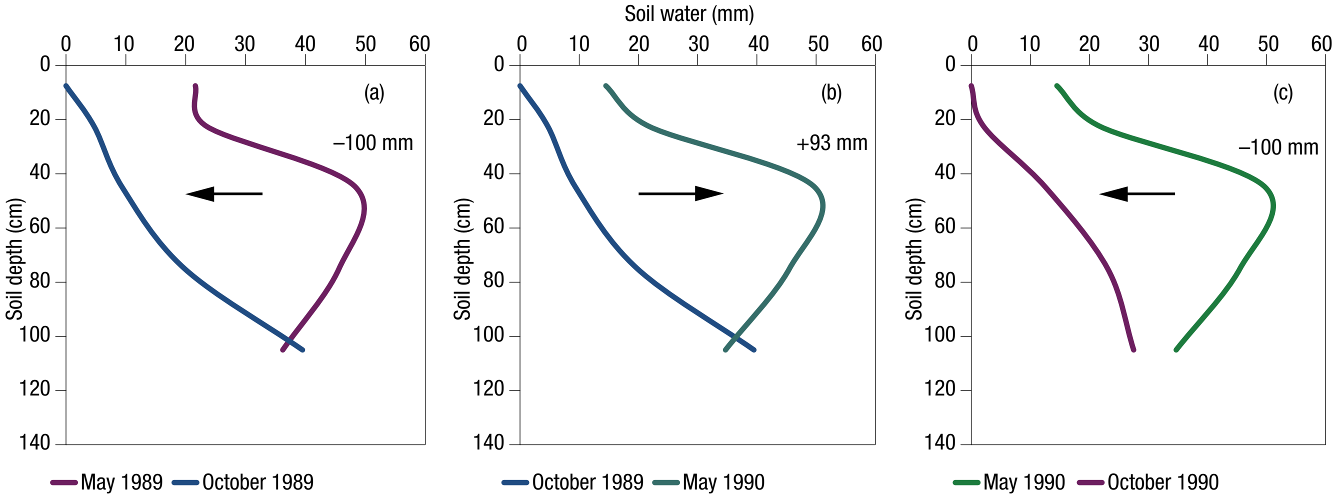
Nitrate certainly keeps accumulating during long fallows. During the 20 months of drought-enforced fallow from November 1990 to May 1992 at the Warra farming systems site, root-zone soil nitrate levels increased by between 89 (following wheat) and 282 kg N/ha (following a four-year grass/legume ley) (Hossain *et al.* 1996b). Values were intermediate for the other treatments – lucerne, annual medic and chickpeas.

These data would suggest that the nitrate was stable in the soil and was not subjected to large losses and probably would have kept increasing with time. Eventually however, nitrate would be pushed further and further down the profile, beyond the bottom of the root zone.

Was there any evidence of nitrate leaching out of the bottom of the root zone during this 20-month fallow? Figure 2.10 shows soil nitrate levels to 1.5 m depth at sowing of the 1990 (June 1990) and 1992 wheat crops (June 1992). Data are from the chickpea–wheat plots. The 1990 crop was sown after the normal eight-month fallow and the 1992 crop sown after a drought-extended 20-month fallow. Total rainfall during the extended fallow (October 1990 to June 1992) was about 850 mm.

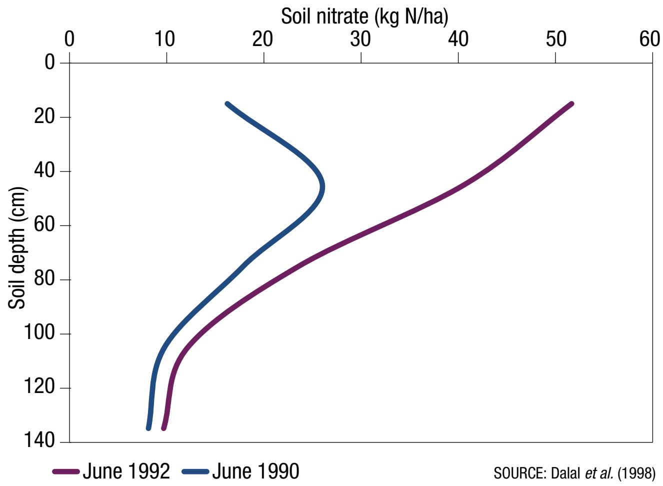
During the 20-month fallow, virtually all the nitrate accumulated in the top 90 cm of the profile, with very little below 90 cm. If leakage of nitrate had occurred or was to occur, there should have been higher nitrate levels in the 90 to 150 cm part of the profile. In a coarse-textured soil, more of the nitrate would be expected to leak beyond 90 cm. Other data sets from the NSW farming systems experiments are consistent with the Warra data. We can conclude that, in well-managed paddocks, leaching of nitrate beyond the root zone would be minor for the clay

FIGURE 2.9 Graphs showing the (a) depletion of water in the root zone soil (1.2 m depth) by chickpeas, (b) accumulation of water during the post-chickpea summer fallow and (c) depletion of water by the following wheat crops



SOURCE: W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data

FIGURE 2.10 Soil nitrate levels to 1.5m depth at sowing of the 1990 (June 1990) and 1992 wheat crops (June 1992) in the Warra field experiments, south-east Queensland



SOURCE: Dalal *et al.* (1998)

soils of the northern grains region. This may not be the case for coarse-textured soils.

2.5.3 Denitrification and gaseous N emissions – greenhouse gases

Nitrogen is emitted from the soil as volatilised ammonia (NH_3) and as part of the biologically mediated processes of nitrification and denitrification (Chapter 1.3.4). Ammonia losses can be substantial with surface-applied nitrogenous fertilisers and manures (see Chapter 4 for more detail). Gaseous N losses associated with denitrifaction can also be substantial, i.e. as much as 50% of applied fertiliser N in high-rainfall situations (W Strong, personal communication). More often, denitrification losses are of the order of 10 to 15% of applied N (Cox and Strong 2008), equivalent to about 10 kg N/ha/year.

With nitrification and denitrification, N is emitted as dinitrogen (atmospheric N_2 gas) or as one of the oxides of N – nitrous oxide (N_2O) or nitric oxide (NO). Nitrous oxide is of particular significance as it has a greenhouse warming potential about 300 times greater than that of carbon dioxide (Dalal *et al.* 2003). Nitrous oxide emissions become more of an issue as the temperature increases (maximum at about 30ºC), in neutral to acidic soils with high nitrate and carbon contents, and at high, but not saturated, soil moisture contents.

At the national level, Dalal *et al.* (2003) reported that agricultural soils account for 58% of nitrous oxide in Australia's National Greenhouse Gas Inventory. Of that, 32% is attributed to emissions from nitrogenous fertilisers and 38% from soil disturbance. About 70% of the fertiliser N is applied to cereals.

Emissions of the greenhouse gases CO_2 and N_2O are not restricted to the paddock but are also associated with manufacture and transport of farm inputs, particularly fertiliser N. Thus, it would be logical to conclude that greenhouse gas emissions from the full inventory of activities associated with grains cropping are reduced with inclusion of N_2-fixing legumes in cropping systems and associated reduction of fertiliser N inputs. A number of reports from North America support this conclusion (see for exmample Robertson *et al.* 2000; Mosier *et al.* 2005, Gregorich *et al.* 2005; Lemke *et al.* 2007; Lupwayi and Kennedy 2007). Lupwayi and Kennedy (2007), in a review of many of these studies, separated out the major sources of the emissions in broadacre cropping as fertiliser N, residues, fertiliser-N application, fertiliser-N manufacture and transport. For three of the four sources, emissions were reduced in the legume-cereal rotation.

In the northern grains region, experimental research (for example Schwenke *et al.* 2010) and simulation modelling (Huth *et al.* 2010) indicate 15 to 75% reductions in nitrous oxide emissions from legume–cereal rotations compared with cereal–cereal and oilseed–cereal rotations with reductions associated with reduced inputs of fertiliser N.

CHAPTER 3: LEGUMES IN ROTATIONS

Grain and pasture legumes are valued components of Australian agricultural production systems. More than a century ago, Thompson (1895) summarised their worth in rotations as contributing to:

- more economical use of manures;
- more economical use of nutrients in the soil;
- improved distribution of labour on the farm;
- improved weed control;
- improved soil conditions through the benefits of deep-rooted and air-feeding crops;
- improved productivity of following cereal crops;
- improved management of plant pathogens and insects;
- improved management of livestock; and
- spread of economic risk.

Nothing much has changed. Farmers still grow legumes as rotation crops because it helps them to spread risk and manage disease, weeds and pests in the production system. A number of the pulses, in particular, are valuable crops in their own right, attracting high prices for good-quality grain. Arguably, however, the most attractive feature of legumes is their ability to form a mutually beneficial (symbiotic) association with rhizobia, a soil bacteria, and fix atmospheric N_2. The 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 N_2 into ammonia (NH_3), which is then largely used by the legume for growth. In return, the legume provides the rhizobia with nutrients, energy and habitat.

The principal beneficiary of N_2 fixation is the legume itself. Because it is self-sufficient in N, it can grow in essentially any soil without inputs of fertiliser N. The legume also produces N-rich residues that remain in 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. Thus, legumes have a role in supplying N to the cropping system following their harvest.

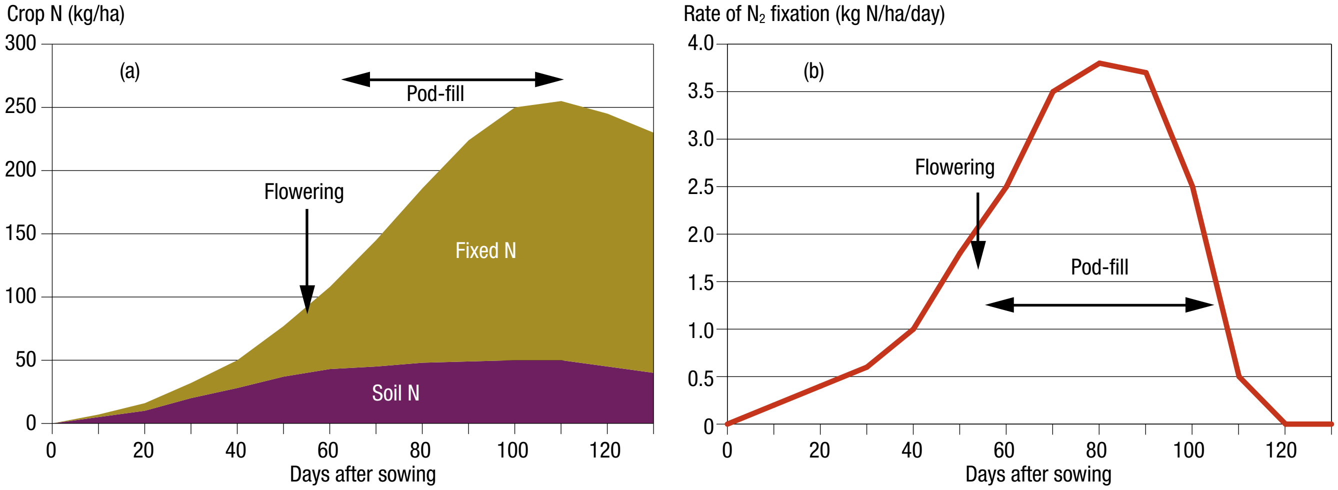
The value of legumes in agricultural systems is strongly influenced by how well they grow and fix N_2. High grain and biomass yields mean high economic returns to the farmer and potentially more N added to the system via the N-rich residues. However, legumes should be grown in soils that are low in plant-available mineral N, otherwise nodulation and N_2 fixation are suppressed.

Optimising legume yields can only be achieved through the use of elite, high-yielding varieties that are not constrained by poor agronomy, insects, disease, weeds and nutrient deficiencies. Nodulation must also be optimised, either through inoculation or by growing the legume in soils that are known to contain high numbers of effective, compatible rhizobia. This chapter examines legume N_2 fixation within global and Australian contexts, the management of legume N_2 fixation at the paddock level including inoculation and, finally, the rotational benefits of legumes and legume N in production systems.

3.1 Legume N_2 fixation

Agricultural legumes fix a lot of N. Globally, the 185 million hectares of crop legumes and more than 100 million hectares of pasture and fodder legumes fix about 40 million tonnes of N annually (Herridge *et al.* 2008). This represents a huge saving of fertiliser N that would otherwise need to be applied and has positive economic and environmental consequences. Assuming 80% conversion of fertiliser N into plant N, the 40 million tonnes

FIGURE 3.1 **Typical patterns of N accumulation and N_2 fixation by annual crop legumes. In (a) total crop N is shown to have two sources – soil N and fixed N – and the bulk of N accretion occurs after flowering. In (b), rates of N_2 fixation are shown to peak at 4 kg N/ha/day during mid pod-fill, then decline as the crop matures**



SOURCE: Data aggregated from Zapata *et al.* 1987a,b; DF Herridge, unpublished of biologically fixed N has a fertiliser-N equivalence of 50 million tonnes, or about 50% of current global inputs of nitrogenous fertilisers. The nominal annual value of the fixed N is about $63 billion (assuming a cost of fertiliser N of $1.25/kg).

The situation for Australian agriculture is equally impressive. The 23 million hectares of legume-based pastures are estimated to fix about 2.5 million tonnes of N annually, based on average production of 3.0 t/ha legume biomass and rates of N_2 fixation of 110 kg N/ha (see Tables 3.3 and 3.4). Nitrogen fixation by the crop legumes is estimated at less than 0.2 million tonnes annually. Using the same assumptions above, the economic value of the N fixed by legumes in our agricultural systems is more than $4 billion annually.

As we shall see later in this chapter, legume N_2 fixation is strongly related to legume growth. Rates of N_2 fixation are low during early growth when the crop is small, then increase substantially during and after flowering (Figure 3.1). Rates remain high until the crop starts to senesce during late pod-fill. During early growth, much of the legume N is taken up from the soil. As the crop grows and the soil N is depleted, progressively more of the crop's N is derived from N_2 fixation. In high-nitrate (fertile) soils, relatively more of the crop N is derived from the soil and less from N_2 fixation.

There is a common misconception that the highest rates of N_2 fixation in annual crop legumes occur prior to flowering and the bulk of the crop's N is fixed also during that period. This could not be further from the truth. At the time of flowering for the average crop legume, rates of N_2 fixation are still increasing and only about 25% of the total crop N will have been assimilated (Figure 3.1).

3.1.1 Do all legumes fix the same amount of N?

Not all legumes grown by Australian farmers have the same capacity for N_2 fixation as shown in Table 3.1. Of the crop legumes, navy beans are weak, fixing only about 20% of their needs with the remainder supplied from soil and fertiliser sources. At the other end of the scale are faba beans, lupins and soybeans that have good capacity for N_2 fixation. In between the two extremes are field peas, peanuts, lentils, mungbeans and chickpeas.

Soybeans are shown to fix the most N on an area basis (180 kg N/ha), reflecting the fact that it is a high-yielding crop either grown under irrigation or in the well-watered east-coast areas of the country. The low estimates for mungbeans and, to a lesser extent lentils, essentially reflect low-yielding, water-limited crops. The lowest estimate for navy beans reflects their particular genetic

TABLE 3.1 Estimates of the amounts of N fixed annually by crop legumes in Australia; %Ndfa is the % of legume N derived from N_2 fixation

Legume	%Ndfa	Shoot DM[1] (t/ha)	Shoot N (kg/ha)	Root N[2] (kg/ha)	Total crop N (kg/ha)	Total N fixed[3] (kg/ha)
Soybeans	48	10.8	250	123	373	180
Lupins	75	5.0	125	51	176	130
Faba beans	65	4.3	122	50	172	110
Field peas	66	4.8	115	47	162	105
Peanuts	36	6.8	190	78	268	95
Chickpeas	41	5.0	85	85	170	70
Lentils	60	2.6	68	28	96	58
Mungbeans	31	3.5	77	32	109	34
Navy beans	20	4.2	105	43	148	30

1 DM = dry matter
2 Root N = shoot N x 0.5 (soybeans), 1.0 (chickpeas) or 0.4 (remainder)
3 Total N fixed = %Ndfa x total crop N

SOURCE: Primarily Unkovich *et al.* (2010)

TABLE 3.2 Comparisons of N_2 fixation and yields of chickpeas and faba beans in crop-rotation experiments and on-farm surveys in northern NSW

Crop	Soil (sowing) Water (mm)	Soil (sowing) Nitrate (kg N/ha)	Shoot DM (t/ha)	Shoot N (kg/ha)	N_2 fixation % Ndfa	N_2 fixation Crop N fixed (kg/ha)
Long-term experiments[A]						
Faba beans	171	106	5.56	124	71	123
Chickpeas	171	95	5.21	98	53	105
On-farm surveys[B]						
Faba beans	163	54	4.57	121	60	100
Chickpeas	158	58	3.73	79	38	60

A Means of 18 site/years/tillage treatments; soil water and nitrate to depth of 1.2 m (unpublished data of W. Felton, H. Marcellos, D. Herridge, G. Schwenke and M. Peoples)
B Means of 15 farmer crops; soil water and nitrate to depth of 0.9m (Schwenke *et al.* 1998)

TABLE 3.3 Estimates of the amounts of N fixed annually by the pasture legumes in Australia; %Ndfa is the % of legume N derived from N_2 fixation

Pasture legume	% Ndfa	Shoot DM[1] (t/ha)	Shoot N (kg/ha)	Root N[2] (kg/ha)	Total crop N (kg/ha)	Total N fixed[3] (kg/ha)
Subterranean clover	81	2.8	88	62	150	120
Annual clovers	60	5.8	167	67	234	140
Perennial clovers	72	4.0	128	51	180	130
Annual medics	74	2.6	78	31	110	80
Lucerne	60	4.4	149	149	298	180

1 DM = dry matter
2 Root N = shoot N x 0.7 (subterranean clover), 1.0 (lucerne) or 0.4 (remainder)
3 Total N fixed = %Ndfa x total crop N

SOURCE: Primarily Unkovich *et al.* (2010) and aggregated from 240 individual values. %Ndfa is the % of legume N derived from N_2 fixation

TABLE 3.4 Estimates of the amounts of N fixed annually by pasture legumes in Australia using the published intensities of N_2 fixation for each group

Pasture legume	Shoot DM[1] (t/ha)	kg shoot N fixed/t shoot DM	kg total N fixed/t shoot DM[2]	Total N fixed[3] (kg/ha)
Subterranean clover	2.8	20.2	34.3	95
Annual clovers	5.8	20.0	28.0	160
Perennial clovers	4.0	18.7	26.2	105
Annual medics	2.6	24.3	34.0	90
Lucerne	4.4	18.7	37.4	165

1 DM, dry matter
2 Calculated using root N factor of 0.7 (subterranean clover), 1.0 (lucerne) or 0.4 (remainder)
3 Total N fixed = shoot DM x kg total N fixed/ t shoot DM

SOURCE: Primarily Unkovich *et al.* (2010)

problem (see comments above), coupled with the fact that all commercial crops are fertilised with N. The widely grown crop legumes – narrow-leafed lupins, field peas, chickpeas and faba beans – are estimated to fix in the order of 70 to 130 kg N/ha/year.

The major crop legumes in the northern grains region are chickpeas and faba beans. Local N_2 fixation data for the two legumes are consistent with the national data in Table 3.1. In the NSW DPI long-term farming systems experiments, faba beans fixed about 20% more N than chickpeas (Table 3.2). In on-farm surveys, rates of N_2 fixation were less than in the experimental plots but the differences between faba beans and chickpeas were consistent with faba beans fixing about 70% more N than chickpeas.

Amounts of N fixed annually by the pasture legumes in Australia can be estimated using two different methods. The first method is identical to that used for crop legumes, in which the estimated % crop N derived from N_2 fixation (%Ndfa) value for each pasture legume group is multiplied by the estimated total crop N (Table 3.3). Values for amounts of N fixed range between 80 kg N/ha for the annual medics to 180 kg N/ha for lucerne. Estimates for the clovers are 120 to 140 kg N/ha.

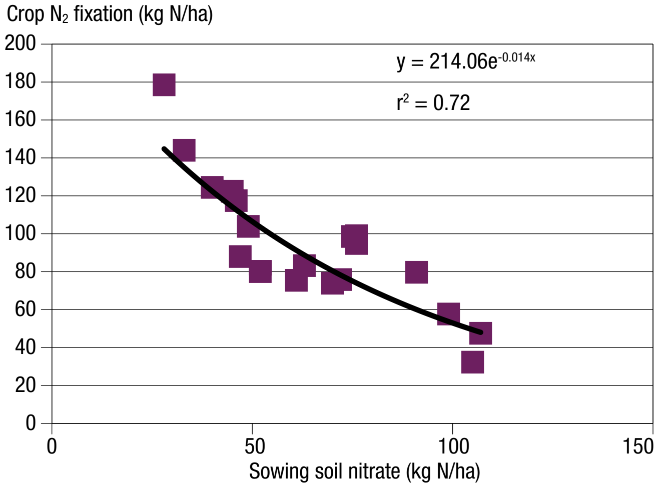
The second method is based on the published relationships for both pasture and crop legumes between shoot dry matter (DM) and the amount of fixed N in the shoot (for example Peoples *et al.* 2008). The rationale here is that the amount of N fixed by the legume is simply a function of the biomass produced. Thus, the updated values, ranging from 18.7 to 24.3 kg shoot N fixed/t shoot DM (Unkovich *et al.* 2010) were used to calculate N_2 fixation by the pasture legumes (Table 3.4). Estimated values for annual N_2 fixation were very similar to those in Table 3.3, varying between 90 kg N/ha for the annual medics and 165 kg N/ha for lucerne, with the clovers between the two. A reasonable overall value for N_2 fixation by the pasture legumes is 110 kg N/ha.

The values in the three tables were derived from very large amounts of data (see Unkovich *et al.* 2010) and provide a broad picture of the average amounts of N fixed by the major crop and pasture legumes in Australian agriculture. They have little relevance to specific crops or pastures. The actual amounts of N_2 fixed by legumes in specific paddocks will vary enormously with site, season and management by the farmer. In the next section, we look at some of the management effects on legume N_2 fixation.

3.1.2 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. Farmers cannot control the weather but they can optimise their management to capture and store the greatest amount of water in the soil, to keep soil nitrate levels as low as possible and to provide the legume with ideal, stress-free growing conditions.

FIGURE 3.2 High soil nitrate levels depress legume nodulation and N_2 fixation. Data are for chickpeas in farming systems experiments in northern NSW



SOURCE: Herridge *et al.* 1998; unpublished data of WL Felton, H Marcellos, DF Herridge, GD Schwenke and MB Peoples

TABLE 3.5 Effects of tillage practice on soil water and nitrate at sowing, chickpea growth and grain yield and N_2 fixation[1]

Tillage	Sowing soil water ( )	Sowing soil nitrate (kg N/ha)	Shoot DM (t/ha)	Grain yield (t/ha)	% Ndfa	Crop N fixed (kg/ha)[2]
No-till	144	71	5.4	2.01	55	107
Cultivated	109	86	4.7	1.83	44	75

[1] Means of 21 site/years of experiments (unpublished data of W. Felton, H. Marcellos, D. Herridge, G. Schwenke and M. Peoples)

[2] Crop N calculated as shoot N x 2

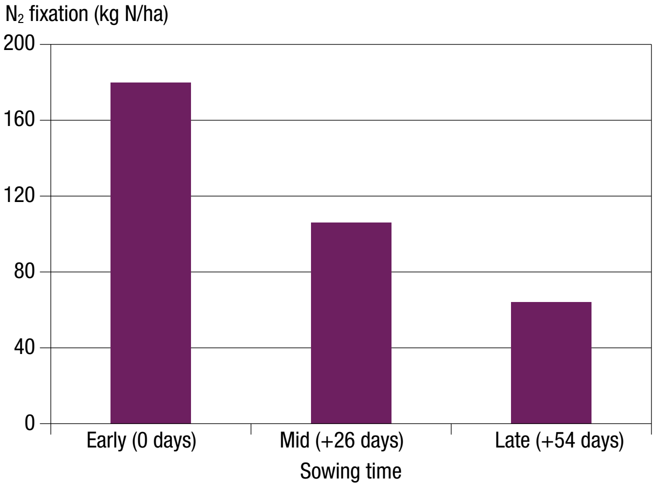
Soil nitrate is a potent inhibitor of legume nodulation and N_2 fixation. At low nitrate levels – less than 50 kg N/ha in the top 1.2 m of soil – the legume's reliance on N_2 fixation is generally high. As soil nitrate levels increase, legume nodulation and N_2 fixation become more and more suppressed. Eventually, at very high levels – greater than 200 kg N/ha – N_2 fixation will be close to zero (Figure 3.2). Faba beans appear to be one of the most resistant legumes to the negative effects of soil nitrate.

Tillage practice

A management practice that has gained popularity in recent years is no-till. Data from farming systems experiments in northern NSW showed a positive effect of no-till on yields and N_2 fixation of chickpeas. The result was increased soil water and reduced soil nitrate accumulation during the summer (pre-crop) fallow. The no-till plots had an average of 35 mm additional soil water and reduction of 15 kg nitrate-N /ha at sowing, when compared with the cultivated soils (Table 3.5).

For cereals under no-till, additional fertiliser N may be required to supplement the reduced soil nitrate. For legumes, however, the lower nitrate levels lead to greater N_2 fixation activity. As a result of the extra soil water and reduced soil nitrate, chickpea shoot DM, grain yield, %Ndfa and total crop N fixed were all higher (Table 3.5).

FIGURE 3.3 **Matching legume species to the soil environment and sowing on time increases N_2 fixation**



Basic agronomy

Optimising the basic 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 (for example, phosphorus), reducing acidity with lime and managing weeds, diseases and insects.

Sowing on time to take full advantage of growing season rainfall and temperatures and to minimise deleterious effects of pest and disease cycles provides options for enhancing N_2 fixation. With field peas in the southern NSW grainbelt, N_2 fixation was increased from 64 kg N/ha to 180 kg N/ha by planting 54 days earlier (Figure 3.3) (O'Connor *et al.* 1993).

Use of narrow row spacing and/or high plant density can increase legume N_2 fixation. In on-farm surveys of 51 chickpea and faba bean crops in the northern NSW grainbelt, Schwenke *et al.* (1998) reported that crop biomass was greatest in narrow rows and that crop dependence on N_2 fixation increased with higher plant density. Increasing lucerne numbers from 5 to 40 plants per square metre more than doubled crop biomass N and N_2 fixation in pasture systems in south-eastern Australia (Figure 3.4) (Peoples *et al.* 1998).

The key messages from the data in Figures 3.3 and 3.4 are that legume N_2 fixation reflects, to a large extent, the efficiencies with which space and time are utilised by the growing crop or pasture.

Soil acidity and phosphorus (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% with P fertiliser and by 120 to 130% with a combination of lime and P (Figure 3.4). Lime increased pH and reduced extractable aluminium and manganese, both of which are toxic to legumes and rhizobia at elevated concentrations (Peoples *et al.* 1995a).

Other soil constraints include salinity, sodicity, and nutrient toxicities and deficiencies. Such constraints need to be addressed if potential legume biomass production is to be realised. Of course, that is not always possible. Research has also 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).

FIGURE 3.4 **Optimising (a) plant density and (b) nutrition increases N_2 fixation**

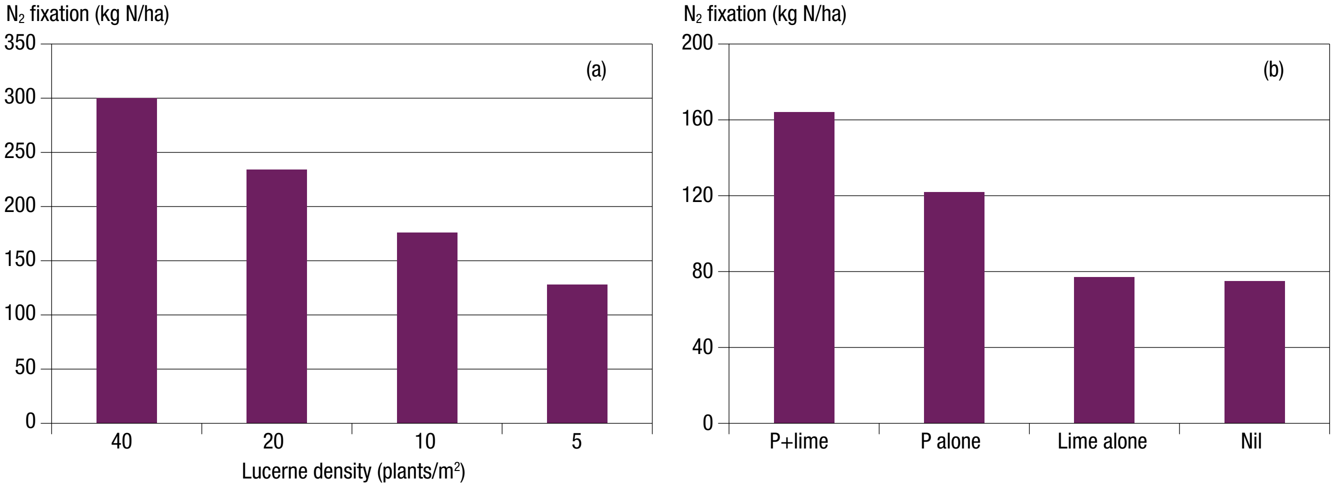
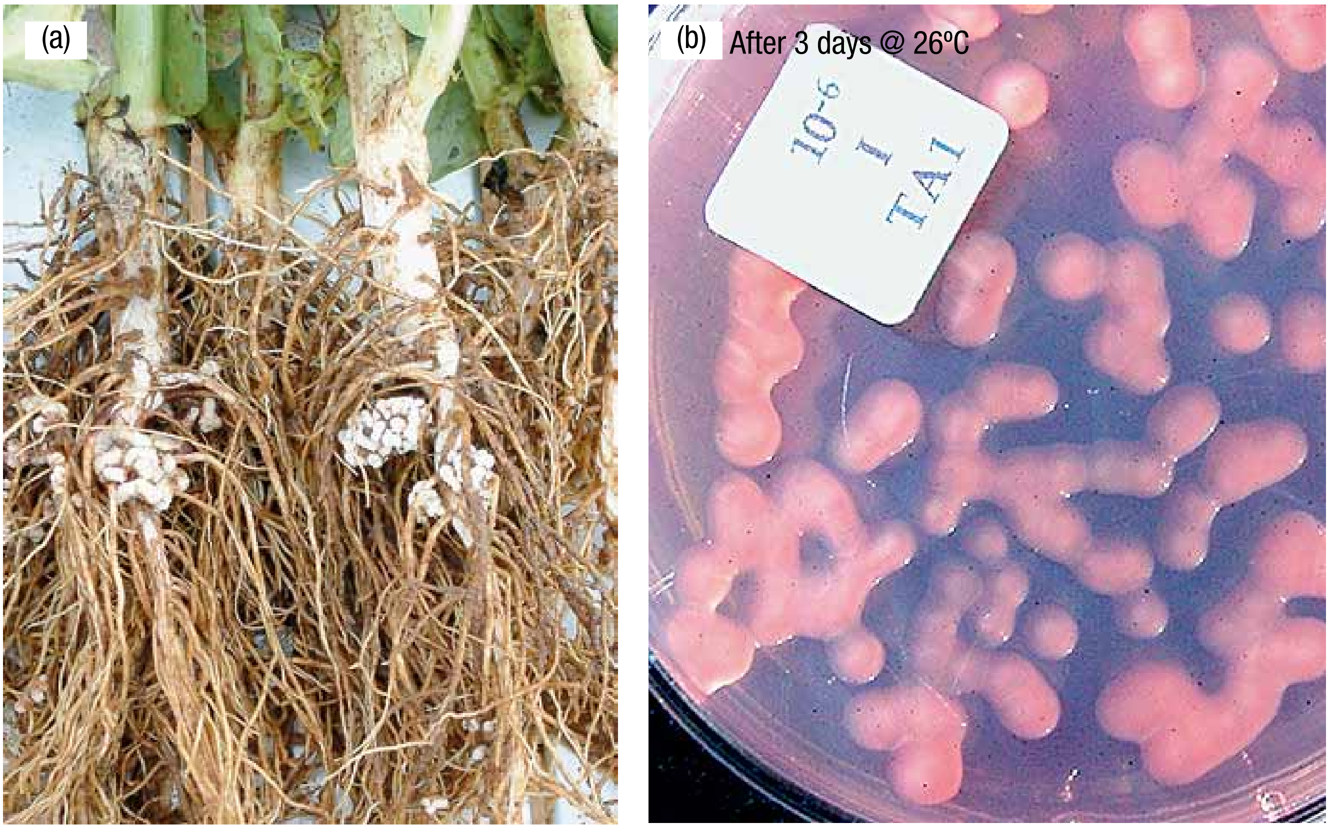


FIGURE 3.5 (a) Root nodules on faba beans. The rhizobia live within the nodules in which they fix atmospheric N_2. (b) Rhizobia grown on nutrient-rich agar media in a Petri plate



3.2 Rhizobia and legume inoculation

Legumes must be nodulated by effective, compatible rhizobia to fix N. This arrangement suits both parties. The rhizobia are provided with carbon (energy) and a protective habitat in the rhizosphere and nodules of the legume, and the legume gains the N that is fixed by the rhizobia. In agriculture, highly effective rhizobia are introduced into legume-growing soils via inoculation.

3.2.1 Rhizobia

Rhizobia are medium-sized, rod-shaped bacterial cells. They are called microorganisms because of their very small size – a chain of 500 rhizobial cells placed end to end is about 1 mm long. They are mobile, possessing appendages called flagella. Although usually found in soil, rhizobia are characterised by their ability to nodulate a legume. There are exceptions, however, and variants and mutants of rhizobia may have lost the ability to nodulate, but in all other respects are genetically identical to the nodulating parent.

Rhizobia can be observed in the soil and attached to legume roots using microscopy (Figure 3.5a). When observed in scientific study and in the process of inoculant manufacture, rhizobia are cultured in nutrient-rich media in fermenters and other vessels and on Petri plates (Figure 3.5b). Rhizobia can grow in a wide range of temperatures. They can be frozen and will survive temperatures of 35°C although prefer temperatures of 25°C to 30°C. They require oxygen to survive and multiply.

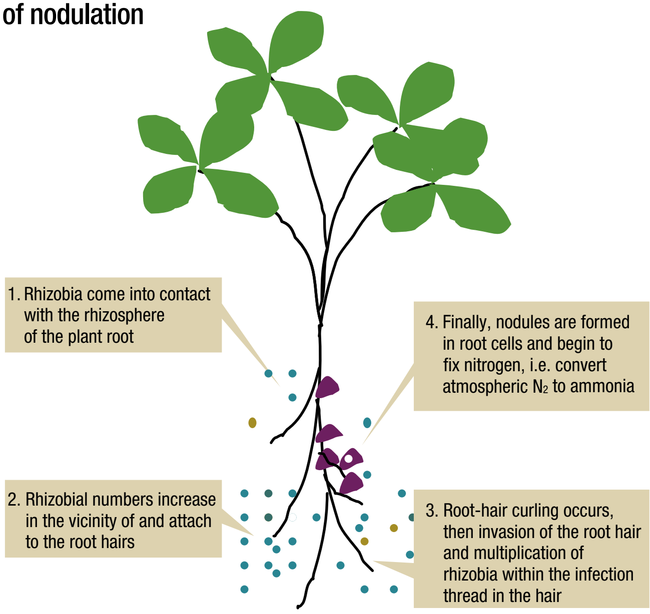
Rhizobia are part of the soil biology when not living in the vicinity of the legume's rhizosphere or inside the root nodules. They have to compete for nutrients with the rest of the soil microorganisms and contend with predators, toxicities and stresses. The populations of rhizobia in soils vary enormously, primarily influenced by the presence of the host legume, and soil and environmental factors, such as soil pH, soil texture (clay content), temperature, moisture and salinity (Howieson and Ballard 2004).

Soil pH has one of the strongest influences on rhizobial numbers. Slattery *et al.* (2004) reported dramatic effects of soil pH on the incidence of rhizobia that nodulate vetch, lentils, peas, faba beans, chickpeas and lupins at a range of sites in northern Victoria. The incidence of all rhizobia, except for the lupin rhizobia, increased with increasing soil pH. Clover rhizobia are far more tolerant of acid soils than the medic rhizobia, which is consistent with the acid tolerance of the clover themselves.

3.2.2 Legume nodulation

When rhizobia in the soil make contact with the roots of the natural host legume, a complex set of reactions occur between the plant and the rhizobia. First, rhizobial numbers increase in the vicinity (rhizosphere) of the

FIGURE 3.6 **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 and attach to the root hairs

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

legume roots, then attach to the root hairs (Figure 3.6). Thus population densities of rhizobia are much greater in the legume rhizospheres than in the bulk soil, 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.

The whole process is facilitated by a set of chemical signals that are exchanged between the legume and rhizobia. The plant produces flavonoids that trigger the rhizobia to produce nod-factors that in turn induce the root-hair deformation, cortical cell division etc. in the plant. The flavonoids are phenolic compounds, while the nod factors are modified lipo-chito-oligosaccharides (Broughton *et al.* 2003).

Nodules are sheltered habitats for the rhizobia. There is no competition for nutrients and space from other microorganisms and they are free of predators. 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-derived enzymes in the nodule. The amino compounds (and ureide compounds in certain tropical species) are exported from the nodule via the xylem stream to be utilised for plant growth. Young, active nodules may contain more than 500 million bacteroids, each of which is contributing to the N nutrition of the plant (Bergersen 1982).

In the field, nodules usually start to function within 3 to 4 weeks of seed germination, but can be delayed by unfavourable conditions of growth and by elevated soil nitrate. At the end of the life of the nodule the rhizobia are released back into the soil.

3.2.3 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. It is of special interest to us in Australia…".

Guthrie showed remarkable foresight because now, more than 100 years later, legumes growing on 25 million hectares of land in Australia fix more than $4 billion worth of N annually. Essentially, all of that N can be attributed to current and past inoculation (Brockwell 2004).

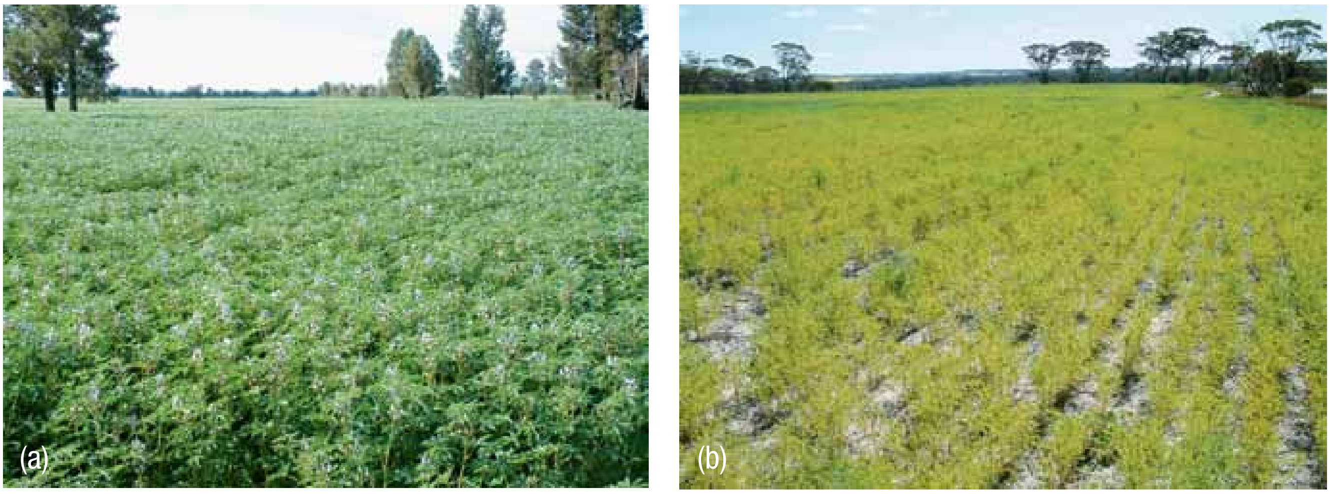
Early attempts at inoculation were rudimentary, such as moving soil from fields growing well-nodulated legumes to legume-free fields (Fred *et al.* 1932). Inoculation of legume seeds using pure cultures of rhizobia was made possible by the groundbreaking work of Hellriegel in Germany and Beyerinck in the Netherlands in the 1880s (Perret *et al.* 2000). Within a couple of years, cultures of rhizobia were available in the marketplaces of Europe for farmers to inoculate a variety of legumes (Guthrie 1896). By the 1940s, the production and distribution of legume inoculants had become established industries in many countries, including Australia.

Benefits of inoculation can be dramatic. With reasonable seasonal conditions, inoculated legumes are well-grown and green, signifying functioning N_2-fixing nodules (Figure 3.7a). In contrast, a crop of the same species (in this case narrow-leafed lupins) that had not been inoculated would likely be poorly grown and yellow because of N deficiency (Figure 3.7b).

Farmers often make a considered decision about whether to inoculate and will sometimes decide that it is not warranted. This tends to be at odds with the state departments of agriculture and other advisory organisations that recommend that all sown legumes be inoculated. The rationale for this conservative approach to inoculation is that unnecessary inoculation is preferable to the loss of economic yield that would certainly result from inadequate nodulation and crop N deficiency (see Figure 3.7b). The cost of inoculation is $5 to $10/ha, while the cost of nodulation failure can be as high as $500/ha.

It is readily acknowledged, however, that inoculation is beneficial in some situations but not in others. In soils that have low numbers of rhizobia or do not contain any rhizobia at all, the benefits of inoculation are dramatic

FIGURE 3.7 Lupin crops growing in different parts of the grainbelt in 2003, (a) Inoculated lupin crop and (b) uninoculated



(Figure 3.8). Typical yield increases are 50 to 150%, equivalent to 0.7 to 2.0 t/ha. In soils that already boast high populations of rhizobia, there may be little or no effect of inoculation of 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 pre-inoculated seed (Gemell *et al.* 2005) (see Chapter 3.2.6.). More likely the problem is associated with application of the inoculant, rather than inoculant quality itself. Application problems include:

- toxic chemicals on the seed causing death of the rhizobia;
- delay in sowing, resulting in the death of the rhizobia inoculated onto seed;
- low volumes of water – that is, less than 50 litres/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.

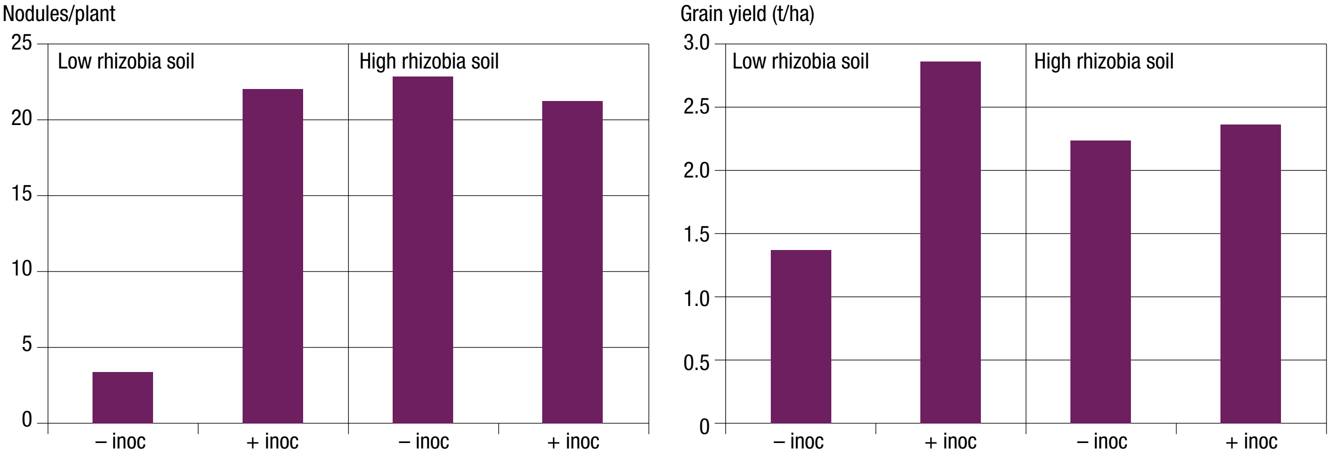
Farmers should always follow the label instructions. Seed should be sown as soon as possible after inoculation, i.e. within 4 hours. If sowing is delayed for more than a day, the farmer should consider re-inoculating the seed. The inoculant should never be mixed with chemicals toxic to the rhizobia. If in doubt about the chemical, contact the inoculant manufacturer. If possible, inoculated legumes should be sown into cool-warm, moist soil, rather than hot, dry soil.

3.2.4 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. The search for new inoculant strains is an ongoing process, driven by the need to provide rhizobia for new legume cultivars and species, to extend legume cultivation into new and/or hostile environments and to optimise productivity of currently grown species.

Strain improvement is conducted at a number of laboratories in Australia, primarily at Murdoch University in Perth and the South Australian Research and Development Institute (SARDI) in Adelaide. Although each centre has its own particular set of protocols, there is a common

FIGURE 3.8 Effects of inoculation on nodulation and yield of faba beans in low and high rhizobia soils. Data are aggregated from 18 experiments conducted during 1997 to 2003 in WA, Victoria and NSW



approach, as described by Howieson *et al.* (2000). It involves a step-wise program that starts with many hundreds of strains evaluated on the particular legume(s) grown in pots in a glasshouse and moves on to multi-locational field trials of elite material across the country.

In Australia, 156 different rhizobial strains have been used in commercial inoculants since 1953 (Bullard *et al.* 2005). In 1953, 17 strains were used for just 25 legume species. By 2008, in response to the greatly expanded range of legumes, Australian farmers had access to 41 different inoculant types, each with its own particular strain of rhizobia. Many of the strains used in inoculants originated outside Australia and some strains – for example, CB1809 for soybeans, TA1 for white and red clover and WU425 for lupins – have been used for many years (Table 3.6). For the most part, however, there has been a steady turnover of inoculant strains over time.

TABLE 3.6 Rhizobial strains used in the major inoculants in Australia

Inoculant group	No. strains used since 1953	Current strain	Introduced	Isolated from
Lucerne	10	RRI128	2000	Victoria, Australia
Annual medic	10	WSM1115	2002	Greece
White clover	9	TA1	1956	Tasmania, Australia
Subclover	7	WSM409	2000	Sardinia
Faba beans	3	WSM1455	2002	Greece
Lupins	4	WU425	1970	Western Australia
Chickpeas	2	CC1192	1977	Israel
Soybeans	5	CB1809	1966	USA

SOURCE: Bullard *et al.* 2005

TABLE 3.7 Rhizobial inoculants available for use in Australia

Manufacturer	Brand	Formulation	Application
Becker Underwood	Nodulaid™	Peat	Slurry on seed; slurry/liquid in furrow
	Nodulaid™	Liquid	On seed; in furrow
	Nodulator™	Clay granule	In furrow
	BioStacked®	Peat (rhizobia) plus liquid (*Bacillus subtilis*)	Slurry on seed; slurry/liquid in furrow
New-Edge Microbials	EasyRhiz™	Freeze-dried	Liquid on seed; liquid in furrow
	Nodule N™	Peat	Slurry on seed; slurry/liquid in furrow
Novozymes Biologicals Australia	N-Prove®	Peat	Slurry on seed; slurry/liquid in furrow
		Peat granule	In furrow
	TagTeam®	Peat (rhizobia)plus (*Penicillium bilaii*)	Slurry on seed; slurry/liquid in furrow
	TagTeam®	Peat granule (rhizobia) plus (*Penicillium bilaii*)	In furrow
ALOSCA Technologies	ALOSCA®	Clay granule	In furrow
Brushmaster	Inoculeze™	Peat	'Tea extract' on seed via an applicator

3.2.5 Inoculant brands and formulations

Until recently, the commonly used method of inoculation was to apply a peat-based inoculant, produced and marketed by just one or two manufacturers, as slurry to the seed just before sowing. Now, a more diverse range of inoculant products with different modes of application are available from a larger number of manufacturers (Table 3.7). Note that each of the manufacturers produces a set range of inoculant groups. For example, inoculants for lupins, faba beans and chickpeas are produced by all 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.

All inoculants, irrespective of manufacturer or brand, contain the same strain of rhizobia for each of the legume groups (for example, strain CC1192 is used by all manufacturers for chickpeas, and so on). All current inoculant strains were selected on the basis of exhaustive laboratory, glasshouse and field research conducted over a number of years. Fresh cultures of the strains are supplied annually to the manufacturers by the NSW DPI's Australian Inoculants Research Group (AIRG). In the future, it is possible that the manufacturers will use different strains from each other. Some of the strains may originate from their overseas operations (in the case of Becker Underwood and Novozymes).

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. Commonly, inoculant is applied directly on to the seed as it is augered into the seed bin on the sowing rig. 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 good levels of nodulation. However, if the seed dressings are particularly toxic or sowings are delayed for a number of days, numbers of live rhizobia on the seed can fall to levels that are insufficient for optimum nodulation.

Peat inoculants can also be suspended in water and applied directly to the soil 'in furrow' at rates of 50 to 100 litres per hectare (also termed liquid inoculation, spray inoculation and liquid injection 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 4 to 10 kg/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 bulk of the granules with the high rates of application (4 to 10 kg/ha versus 0.25 kg/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 farmers during the past five years. 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. More recently Becker Underwood and Novozymes began to trial and market granular products based on attapulgite clay and peat, 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 add water, 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. 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 or spray inoculation) have also been used widely in the US for a number of years (Smith 1992). In Australia, they are mainly used for soybeans. Normal application rates are 2 to 4 millilitres per kilogram of seed, with the inoculant applied to the seed as a batch or continuously via an applicator as the seed is augered into the seed box. Less commonly, liquid inoculants are diluted with water and applied directly into the seeding row.

Which inoculant to use?

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 needed to be balanced against the cost of setting up a machine to handle the large volumes of water. Results for the clay granular inoculants were variable, with the peat granules promising. At the end of the day, however, farmers will make decisions about which inoculant to use and the method of application based on their own experience, product availability and perceived advantages or disadvantages.

3.2.6 Inoculant quality – the role of AIRG

Independent quality testing of inoculants has been a feature of the industry in Australia for the past 55 years (Bullard *et al.* 2005). During the 1940s and early 1950s, legume sowings increased substantially, particularly for improved pastures, prompting private sector involvement in the manufacture and sale of inoculants in 1953. Widespread nodulation failures of sown legumes quickly followed, prompting Professor Jim Vincent at the University of Sydney to assert that poor quality inoculants caused the failures and associated economic losses and would eventually discredit the practice of rhizobial inoculation (Vincent 1954).

Vincent made a number of recommendations to address the situation including the formation of an independent testing body, U-DALS (University – Department of Agriculture Laboratory Service) in 1957. The U-DALS unit, a joint venture of the University of Sydney, NSW Agriculture and the inoculant manufacturers, operated out of the University of Sydney until 1971. It was then relocated to the NSW Agriculture (DPI) laboratories at Rydalmere, Sydney, and subsequently to laboratories at Gosford. Since 1971, the quality testing service has had a number of name changes and been managed solely by NSW Agriculture (DPI). Its current name is the Australian Inoculants Research Group (AIRG). Throughout the 55-year history of the independent quality testing of commercially produced inoculants and R&D support of the manufacturers, many problems have been solved that otherwise would have caused nodulation failures of sown legumes and substantial economic losses.

Currently, the AIRG 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 (QC) 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 with 95% pass rate. Failed batches were withdrawn from sale. AIRG also tested 280 inoculants at the point-of-sale with 95% pass rate. Another 4% just failed the standard (Herridge 2009).

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 tests pre-inoculated seed, mainly lucerne and subterranean clover, sourced from retailers across the country. Results from surveys conducted from 1999 to

FIGURE 3.9 **N cycling through a grain legume to the following cereal crop. Gaseous losses of N are not shown, nor are potential leaching losses. All of the flows of N are facilitated by the action of the soil biota**

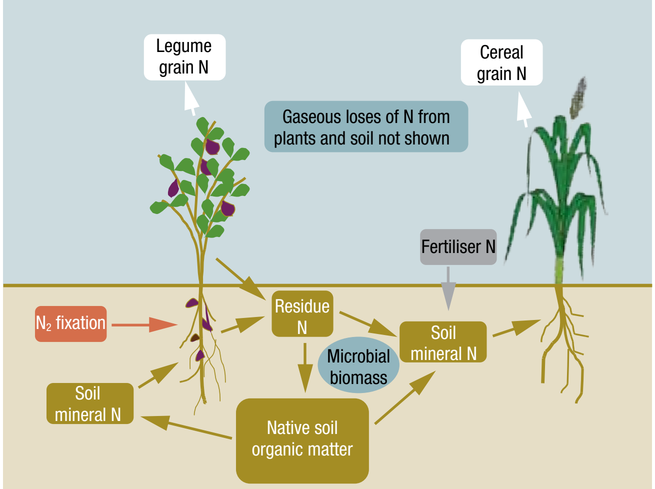


TABLE 3.8 Summary of a decade of rotation experiments in the northern grainbelt showing the benefits of chickpeas on yield and grain protein levels of the following wheat crop

Sites/rotations	Nil fertiliser N		+ fertiliser N (75-150 kg/ha)	
	Yield (t/ha)	% protein	Yield (t/ha)	% protein
New South Wales				
Chickpeas	1.9			
Wheat after wheat	2.1	11.2	2.7	13.2
Wheat after chickpeas	2.8	12.2	2.9	13.8
Queensland				
Chickpeas	1.5			
Wheat after wheat	2.2	10.3	2.8	13.8
Wheat after chickpeas	2.8	11.7	3.1	13.8

SOURCE: Lucy *et al.* 2005

2003 highlighted large differences between pasture legume species, with 73% of lucerne seed samples exceeding the standard of 1000 rhizobia per seed, compared with a 32% pass rate for subterranean clover and just a 3 to 4% pass rate 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.

3.3 Rotational benefits of legumes

As stated at the beginning of this chapter, N_2 fixation provides ‘free’ N to the legume, thereby eliminating the need for inputs of fertiliser N. That is only the first part of the story. The legume also produces N-rich residues that decompose in the soil after the crop is harvested. The residues release mineral N during decomposition to be taken up by the following crop or crops. Thus, legumes have a role in supplying N to the cropping system.

A substantial body of research has now been published from experiments that examined the N-supplying capacity and rotational benefits of N_2-fixing pulse crops and legume pasture leys in Australia’s wheat production systems. These include the:

- Warra experiments in south-eastern Queensland (Dalal *et al.* 1995);
- no-till farming systems experiments in north-eastern NSW (Felton *et al.* 1998);
- pasture and pulse rotations, Tamworth (Holford *et al.* 1998);
- SATWAGL experiments, Wagga Wagga (Heenan and Chan 1992); and
- Junee Reefs pasture ley experiments, central-west NSW (Angus *et al.* 2006).

In the following sections the legume benefits are examined.

3.3.1 Crop legumes

Crop legumes are usually grown in rotation with cereals and the benefits to the system are measured in terms of increased soil total and plant-available (nitrate) N and grain N and yield of the subsequent cereal crop, all relative to a cereal–cereal sequence. A great deal of research has now demonstrated that cereals grown after crop legumes commonly yield 0.5 to 1.5 tonnes of grain per hectare more than cereals grown after cereals without fertiliser N. To generate equivalent yields in the cereal–cereal sequence, research has also shown that 40 to 100 kg fertiliser N/ha needs to be applied.

Figure 3.9 shows the flow of N through the grain legume to the following cereal crop. Gaseous losses of mineral N are not shown, nor are potential leaching losses. The N available to the cereal is a combination of the N mineralised as part of the decomposition of legume residues and soil humus and from applied fertiliser N. A fourth source of N is the mineral N not used by the legume during its growth, but spared. The residue N that is not released as mineral N remains in the soil as organic matter.

Results from more than a decade (60 sites x years) of chickpea–wheat rotation experiments in the northern grainbelt were summarised recently (Lucy *et al.* 2005) (Table 3.8). Major observations were:

- wheat following chickpeas outyielded wheat after wheat by an average of 0.7 t/ha in the NSW trials and by 0.6 t/ha in the Queensland trials; grain proteins were also increased;
- where water was not limiting, the yield benefit was greater than 1.5 t/ha; and
- the major factor in the increased wheat yields was soil nitrate – in NSW there was, on average, an additional 35 kg plant-available nitrate-N/ha in the 1.2 m profile after chickpeas than in the continuous wheat.

The rotational benefits of crop legumes have also been demonstrated in other parts of the grainbelt. For example, Evans *et al.* (1991) reported experiments involving narrow-leafed lupins, peas, wheat and barley across 15 sites in southern NSW and Victoria. They concluded:

- wheat following lupins outyielded wheat after wheat by an average of 0.9 t/ha, a 44% increase; wheat after peas was 0.7 t/ha (32%) more than wheat after wheat;
- grain yield increases were variable, with a number greater than 200%; and
- the major factor in the increased wheat yields again appeared to be the increased levels of plant-available N (nitrate-N + ammonium-N); levels were increased by 54% following lupins and 61% following peas.

Legumes as disease breaks

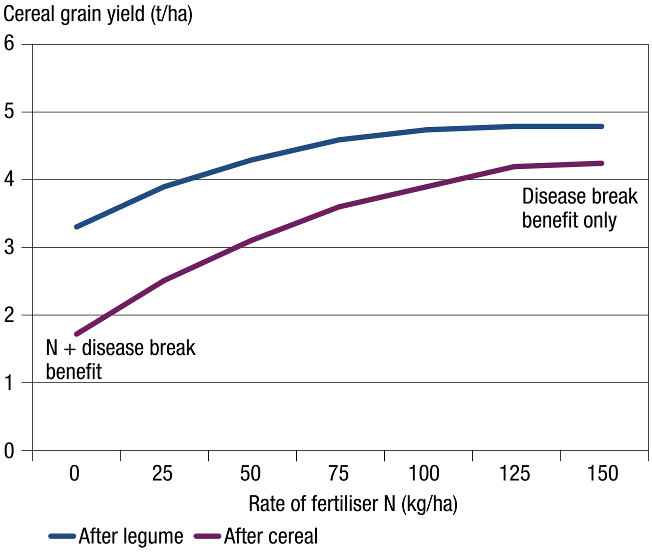
The increased levels of plant-available N are only part of the story. Some of the cereal yield increases can be attributed to the break effect of the legumes on soil- and stubble-borne diseases. Major cereal diseases in the northern grains region are shown in Table 3.9 (Wildermuth *et al.* (1997). All but the root lesion nematode are caused by fungi. Soil-borne cereal pathogens reduce the health of the roots, subcrown internodes and crowns of plants, resulting in a diminished ability of the plant to transport water and nutrients from the roots to the rest of the plant. The fungal pathogens grow into the plants and may kill the roots or crown, invade the sap channels and grow upwards into the tillers. Nematodes eat their way into the roots, then live there, eating and multiplying inside the roots.

With fungi, spores or other survival propagules are present in infested crop residues. The next crop's seedling roots make contact with the residues as they grow, stimulating the fungi to germinate and infect the new plants in response to the release of sugars from root tips. Nematodes survive as dried forms and eggs in crop residues and then become actively mobile when soil becomes moist. The crop legumes are generally effective disease breaks and are usually more effective than pasture leys because of the potential for grasses in the ley to provide alternative hosts for disease.

The diseases cause yield loss of cereals, with estimates of losses varying with site, season, species and cultivar. Wildermuth *et al.* (1997) suggested wheat yield losses of 10 to 20% from crown rot in the northern grainbelt. Other diseases – for example, common root rot, yellow leaf spot and root-lesion nematode – will add to that figure, with root-lesion nematode alone estimated to cost northern grains region farmers about $50 million annually.

Individual paddock studies of cereal disease have shown wide variations in yield loss, ranging from zero to more than 60% (Wildermuth *et al.* 1997; Felton *et al.* 1998; Kirkegaard *et al.* 2004). Data from the Warra and northern NSW farming systems experiments indicated a rotation benefit of chickpeas that was not related to nitrogen of about 17%. Thus, a reasonable figure for the average disease-break effect of legumes in the northern grainbelt is 0.5 t/ha, equivalent to about 20% of average yield.

FIGURE 3.10 Cereal yields following either a cereal or grain legume at increasing rates of fertiliser N. In this scenario the yield differences are made up of a disease-break effect (0.5 t/ha) and an N-effect, the latter ranging from zero at the highest rate of fertiliser N to 1.1 t/ha at the nil fertiliser N



SOURCE: Data aggregated from Doyle *et al.* (1988), Doyle and Leckie (1992) and Marcellos *et al.* (1993)

TABLE 3.9 Major cereal diseases of the northern grains region and effectiveness of legumes as break crops

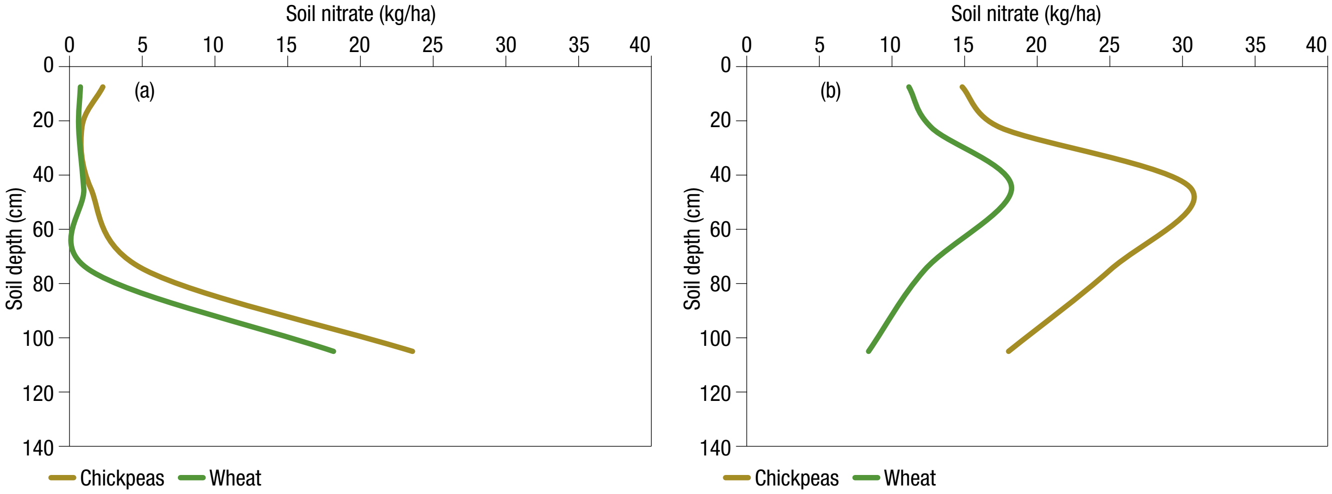
Cereal disease	Causal agent	Crop legumes (chickpeas, faba beans, mungbeans, soybeans) as disease breaks
Crown rot	*Fusarium pseudograminearum*	Effective
Common root rot	*Bipolaris sorokiniana*	Effective
Yellow leaf spot	*Pyrenophora tritici-repentis*	Effective
Take-all	*Gaeumannomyces graminis*	Effective
Fusarium head blight	*Fusarium graminearum*	Effective
Root lesion nematode	*Pratylenchus thornei,* *Pratylenchus neglectus*	Not particularly effective – all four crop legumes susceptible to *P. thornei*

SOURCE: Primarily Moore *et al.* 2005

The combined N and disease-break effects of legumes is shown in a hypothetical set of data that describes wheat yields following either wheat or a legume, all grown in a relatively low nitrate soil (Figure 3.10). The wheat is fertilised with different rates of N to determine the fertiliser N equivalence, that is, how much additional fertiliser N is required for wheat after wheat compared with wheat after the legume.

At zero fertiliser N, the increased wheat yield after the legume is a combination of the N and disease-break effects. As the rate of fertiliser N is increased, the N benefit of the legume diminishes and the disease-break effect remains constant. At the high rates of fertiliser N, the rotational benefit of the legume may be entirely due to the disease-break effect. In this hypothetical scenario, the fertiliser N equivalence of the legume benefit is about 60 kg N/ha.

FIGURE 3.11 **Chickpeas increase soil nitrate levels: (a) soil nitrate profiles near the end of either wheat or chickpea growth; (b) the same plots at sowing after the summer fallow, 6 months later**



SOURCE: Mean values of 6 tillage x N fertiliser treatments; unpublished data from 1989-90 of W Felton, H Marcellos, DF Herridge and GD Schwenke

TABLE 3.10 **Explaining the N and yield benefits of a chickpea–wheat rotation compared with unfertilised or N-fertilised wheat–wheat. Values are the means of no-till and cultivated treatments at two sites in northern NSW**

	Chickpea – wheat 0N	Wheat 0N – wheat 0N	Wheat 100N – wheat 0N
Year 1 (chickpeas or wheat)	Chickpeas	Wheat (0N)	Wheat (100N)
Sowing soil nitrate (kg N/ha, 1.2 m depth)	67	67	67
Fertiliser N applied (kg N/ha)	0	0	100
Grain yield (t/ha)	2.3	2.3	3.2
Total crop N (kg/ha)	205	55	115
Crop N fixed (kg/ha)	135	0	0
Residue N (kg/ha)	133	20	55
Residue C:N	25:1	50:1	44:1
Est. mineralisation or immobilisation (kg N/ha)	+16	–22	–21
Year 2 (wheat only)	Wheat (0N)	Wheat (0N)	Wheat (0N)
Sowing soil nitrate (kg N/ha, 1.2 m depth)	102	53	74
Grain yield (t/ha)	2.8	1.7	1.8
Grain N (kg/ha)	55	30	33

SOURCE: Herridge *et al.* 1995; unpublished data of W Felton, H Marcellos, DF Herridge and GD Schwenke

A closer look at the N benefit of legumes – importance of crop residues

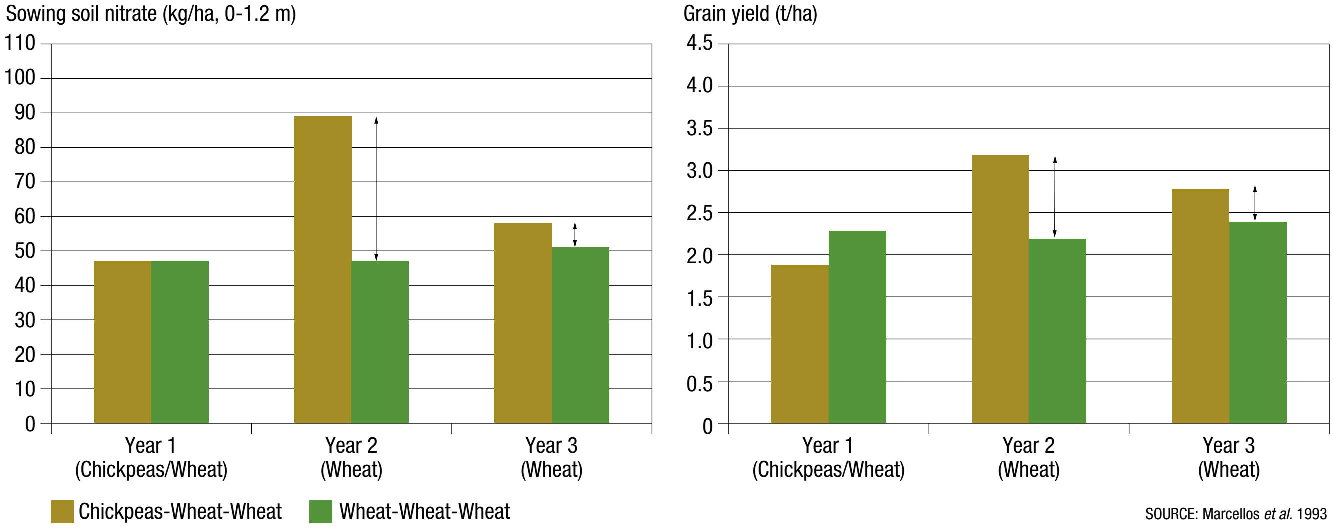
The N benefit of legumes is related to increased nitrate supply in the root-zone soil after the legume is harvested and usually after a fallow period (Figure 3.11). Typical increases are 30 to 60 kg N/ha (Evans *et al.* 1989; Heenan and Chan 1992; Dalal *et al.* 1998; Marcellos *et al.* 1998). The increases have been attributed to both the release of N from the N-rich legume residues and nitrate sparing by the legume (Evans *et al.* 1991; Herridge *et al.* 1995).

Greater detail of the amounts and concentrations of N in the crops and grain as they grow and are harvested and in the residues left behind are shown in Table 3.10. Data were aggregated from two chickpea–wheat rotation experiments from the NSW DPI farming systems program at North Star in northern NSW.

In the first year of the sequence, chickpeas, unfertilised wheat (wheat 0N) and N-fertilised wheat (wheat 100N) were grown in a soil with a moderate level of nitrate at sowing. The chickpeas fixed 135 kg N/ha. The chickpeas produced far more residue N than both wheats, with the residues also richer in N (C:N ratios of 25:1 versus C:N ratios of 44:1 and 50:1 for the wheats). The low C:N ratio of the chickpea residues means that mineral (ammonium and nitrate) N was released into the soil as they decomposed, in contrast to the wheat residues that immobilised mineral N as they decomposed. Thus, the chickpea residues released an estimated 16 kg mineral N/ha into the soil during the six to seven month summer fallow, versus 21 to 22 kg N/ha immobilised by the wheat residues during the same period.

At the end of the summer fallow at the time of sowing the following crop, nitrate levels in the soil following chickpeas

FIGURE 3.12 Rotational benefits of chickpeas for soil nitrate and grain yield of subsequent cereal crops are strongest in the season after chickpea harvest. Effects in the second season after chickpeas are small and inconsistent



SOURCE: Marcellos *et al.* 1993

TABLE 3.11 Simple gross margin (GM) analysis of the N and yield benefits of a chickpea–wheat rotation compared with unfertilised or N-fertilised wheat-wheat sequences. Yields taken from Table 3.10

	Chickpea – wheat 0N	Wheat 0N – wheat 0N	Wheat 100N – wheat 0N
Year 1 (chickpeas or wheat)	Chickpeas	Wheat (0N)	Wheat (100N)
Grain yield (t/ha)	2.3	2.3	3.2
Grain ($)[1]	920	575	800
Cost of production ($)[2]	465	270	400
Gross margin ($)	455	305	400
Year 2 (wheat only)	Wheat (0N)	Wheat (0N)	Wheat (0N)
Grain yield (t/ha)	2.8	1.7	1.8
Grain ($)	700	425	450
Cost of production ($)	270	270	270
Gross margin ($)	430	155	180
2-year gross margin ($)	885	460	580

1 Chickpea @ $400/t; wheat @$250/t 2 NSW DPI figures

SOURCE: Unpublished data of W. Felton, H. Marcellos, D. Herridge and G. Schwenke

were much higher than the following wheat crops. As a result, grain yields and grain N were higher after chickpeas. Clearly, the amount and the concentration of N in the crop residues largely determine how much nitrate N will be in a soil at the time of sowing the next crop.

The effect of crop legumes on soil organic fertility is less certain. Short- and long-term rotation experiments in northern NSW (Holford 1990; Holford *et al.* 1998) and south-eastern Queensland (Strong *et al.* 1986; Dalal *et al.* 1995; Hossain *et al.* 1996a) showed no significant benefits of crop legumes for soil organic N. This is not surprising. In all of these studies, the legume was in a 1:1 rotation sequence with unfertilised wheat. Thus, even though the legume may have contributed to soil organic N, the contribution would have been offset by the depletion of organic N in the cereal phase. In a more realistic scenario at the long-term no-till sites in northern NSW – in which the rotation consisted of either chickpeas or faba beans and N-fertilised wheat or barley – GD Schwenke and colleagues reported marginally positive effects of the legumes on soil organic matter (GD Schwenke, unpublished).

Economics of crop legume-cereal rotations

Gross margin analysis of the three crop sequences in Table 3.10 indicates that the chickpea–wheat rotations are far more profitable (Table 3.11). There was not a lot of difference between the gross margins of chickpeas and the N-fertilised wheat in Year 1, but in Year 2, wheat after chickpeas had gross margins more than double those of the wheat–wheat sequences. The least profitable sequence was the unfertilised wheat. Overall, the chickpea–wheat rotation had a gross margin that was 50 to 90% greater than the wheat–wheat sequences.

FIGURE 3.13 N cycling through a grazed pasture legume to the following cereal crop. Gaseous losses of N are not shown, nor are potential leaching losses. All of the flows of N are facilitated by the action of the soil biota

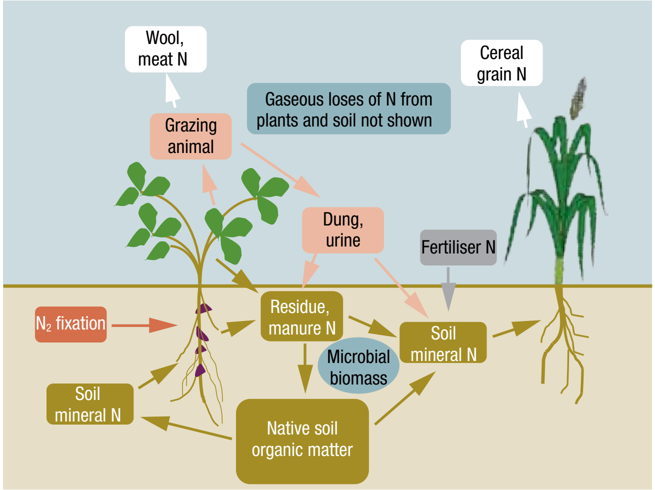
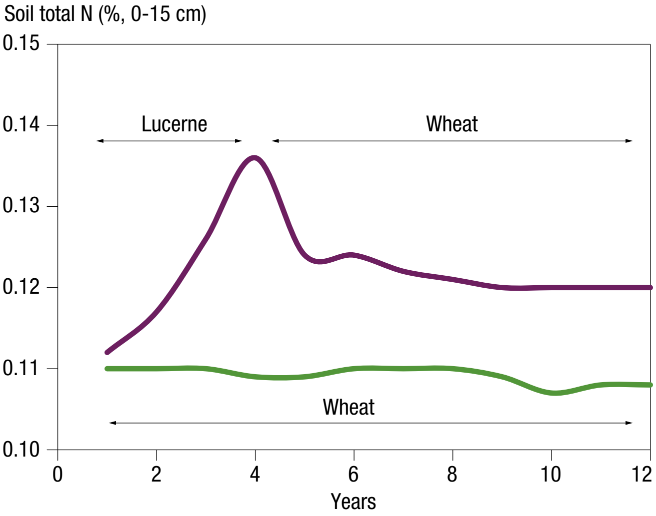


FIGURE 3.14 Build-up of soil organic N under a well-managed, intensively grazed lucerne pasture on a black earth at Tamworth and the subsequent rundown during the following nine years of wheat cropping



Soil N levels under the wheat monoculture are also shown. A 0.01% increment in soil N to 15 cm depth is equivalent to 180 kg N/ha (assumes bulk density of 1.2).

SOURCE: Redrawn from Holford,1981

How long does the benefit last?

The rotational benefits of crop legumes on wheat yields tend to last for one season only, with only small and inconsistent benefits in the second season. Marcellos *et al.* (1993) published results from six sites in northern NSW showing an average yield benefit of chickpeas of 1.0 t/ha (46%) for the first residual wheat crop (Figure 3.12). For the majority of the sites, there were no beneficial effects of the chickpeas on yields of a second residual wheat crop. Anecdotal evidence from northern NSW suggests that benefits from faba beans may be more long term, lasting into a second season.

3.3.2. Pasture legumes

With grazing systems, the major benefit of pasture legumes is greater productivity of the pasture flowing through to enhanced animal production. Benefits for soil N and structure also result in increased productivity of subsequent cereal crops grown on the same land. In fact, much of the agriculture in Australia's southern and western grainbelts was built around sequences of pasture leys and cereals (Fillery 2001; Peoples and Baldock 2001). As agricultural land used for cropping continues to lose organic matter and structural integrity, the role of pasture leys in restoring organic fertility and productivity may need to be expanded.

Figure 3.13 shows the flow of N through the pasture legume to the following cereal crop, either directly through the legume residues or via the grazing animal. The animal dung is treated in much the same way as plant residues. The animal urine is quickly converted to ammonia/ammonium via urea hydrolysis (see Chapter 1). Gaseous losses of mineral N are not shown, nor are potential leaching losses. The largest difference between the flow of N in the pasture-to-cereal scenario and that of the grain legume to cereal is that much more of the pasture legume N is recycled within the system, rather than exported as grain. Also, there tends to be a greater accumulation of soil organic N in the pasture system.

The benefit of legume-based pasture leys on soil organic N is clearly illustrated in the work of Ian Holford and colleagues at Tamworth, northern NSW (Holford 1981) in which they showed that well-managed, intensively grazed lucerne added about 110 kg N/ha/year on a red-earth soil and 140 kg N/ha/year on a black-earth soil. The higher soil N levels were maintained at the black-earth site during more than nine years of wheat cropping (Figure 3.14).

With most soils, the extra organic N has positive effects on soil structure. The data of Reeves (1991) in Figure 3.15 shows clearly effects of pasture leys and subsequent cropping on aggregate stability of a red earth at Rutherglen in the Victorian grainbelt.

Effects of organic N on structure varies with the type of clay and the clay content of the soil (Russell 1987). With vertosols (black earths high in clay content), there is little relationship between soil organic matter and structure. On the other hand, with soils of less than 30% clay and with high proportions of sand and silt, loss of organic matter can have serious negative effects on structure.

Effects of the legume leys on soil nitrate levels following termination of the pasture and on subsequent wheat production are also well illustrated by the Tamworth experiments (Table 3.12) (Holford and Crocker 1997; Holford *et al.* 1998). The table shows that the grazed pasture leys, particularly the lucerne ley, produced substantial amounts of shoot biomass and N during three years of growth. Following the pasture phase, soil nitrate

TABLE 3.12 Summary of data from pasture ley experiments at NSW DPI Tamworth during 1988–93. Data are averages for two soil types (self-mulching black earth (vertosol) and hard-setting red clay)

Previous pasture ley	Years duration	Shoot biomass dry matter	Shoot biomass N (kg/ha)	Nitrate-N (kg/ha, 1.2m, sowing 1991)	Wheat grain yield (t/ha, av. 3 years)	Wheat grain protein (%, av. 3 years)
Lucerne	3	24.7	854	180	2.9	12.7
Clover	3	12.7	425	106	2.8	10.4
Annual medic	3	10.8	290	77	2.2	9.5
Wheat	1	3.3	37	12	1.1	9.6

TABLE 3.13 Savings in fertiliser N from the 3-year legume pasture leys. Data from long-term rotation experiments on black and red soils at NSW DPI Tamworth 1988–93

Previous pasture ley	Wheat crop 1	Wheat crop 2	Wheat crop 3	Average 3 wheat crops
Lucerne	45*	120	65	80–100
Clover	>100	60	45	70
Annual medic	70	30	25	45

* Reduced because of the soil drying effect of the lucerne ley

TABLE 3.14 Rotational benefits of 1-year pasture leys compared with continuous wheat at Warra in southern Queensland

Previous crop/ pasture ley	Sowing soil nitrate (kg N/ha)	Sowing soil water (mm)	Wheat yield (t/ha)	Grain protein (%)
Lucerne	122	118	2.1	13.1
Annual medic	136	142	2.6	12.9
Wheat	48	145	2.0	9.7

SOURCE: Weston *et al.* 2002

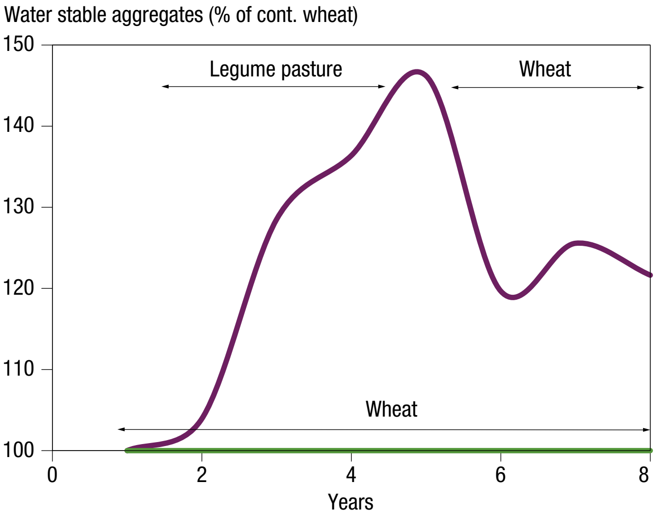
levels varied substantially, with levels strongly related to the productivity of the pasture. By comparison, nitrate levels were just 12 kg/ha in the adjacent continuous wheat plots.

Wheat grain yields and proteins for the three seasons following the pasture leys reflected the substantial inputs of legume N into the soil and elevated soil nitrate levels. The savings of N fertiliser inputs are shown in Table 3.13. Beneficial effects of the leys generally declined with succeeding wheat crops, but were still substantial for the third crop, particularly for lucerne.

Single-year pasture leys are also excellent for increasing soil nitrate levels and enhancing wheat production. Published data from the Warra experiments in southern Queensland were aggregated to demonstrate the benefits of one-year lucerne and annual medic leys (Table 3.14). The data show clear benefits of the leys, with increases in soil nitrates of 74 to 88 kg N/ha.

Effects of the leys on subsequent wheat yields were marginal, particularly for lucerne, because of the soil drying. The real impact of the extra nitrate was to greatly increase grain proteins.

FIGURE 3.15 Positive effects of pasture leys on aggregate stability of a red earth at Rutherglen, Victoria. Once wheat cropping commenced, aggregate stability declined



SOURCE: Redrawn from Reeves, 1991

CHAPTER 4: FERTILISER N

Nitrogen is the most widely used fertiliser in agriculture. It has been said that the industrial production of nitrogenous fertilisers using the Haber–Bosch process as a base reaction was one of the most important single technologies in the history of mankind, with a substantial proportion – perhaps as high as half – of the world's population alive today because of it (Smil 2001). It is a big call and is probably true. Fertiliser N can be used in the basic ammonia form or further processed into a variety of liquid and solid formulations – urea, ammonium sulfate, the ammonium phosphates etc. Globally, 90 to 100 million tonnes of mineral forms of fertiliser N are produced and used each year in agriculture (Jensen and Hauggaard-Nielson 2003). Nitrogen is also applied to soils in the form of organic fertilisers – waste products from animal production and other human activities.

Nitrogenous fertilisers are now widely used in grain cropping in Australia, as well as in the northern grains region. The practice is well supported by research in northern NSW and southern Queensland during the past 50 years that provided valuable data on fertiliser N responses for wheat and other grain crops for different seasons and soil conditions, see for example Strong (1981, 1982, 1986, 1995), Strong *et al.* (1986, 1992, 1996), Doyle and Shapland (1991), Doyle and Leckie (1992), Holford *et al.* (1992), Birch *et al.* (1997), Lester *et al.* (2008, 2010). Most of this research focused on the mineral forms of fertiliser N. Nitrogen fertilisation as a farming practice is also well supported by information and data sources of a more general nature, Angus and Fischer (1991), Angus (1995, 2001), Peoples *et al.* (1995b), Strong and Holford (1997), Asman *et al.* (1998), Goulding *et al.* (1998), Glendinning (1990, 1999), Jenkinson (2001), Freney (2002) and Minami (2002).

4.1 Fertiliser N use in Australia

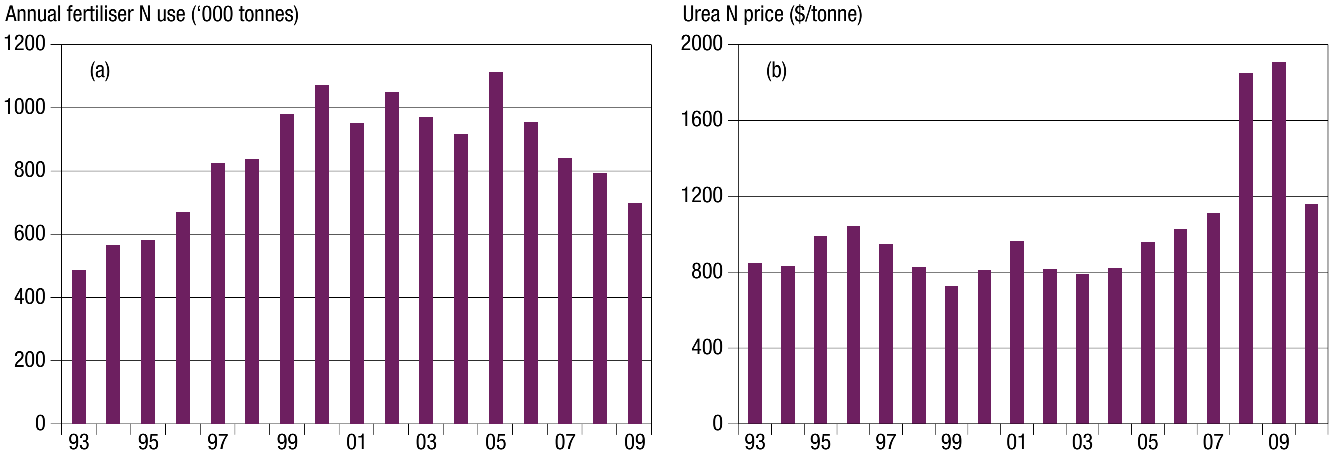
Use of fertiliser N in grain cropping in Australia increased dramatically during the 1980s and 1990s (Figure 4.1; Angus 2001). Prior to that, much of the N for grain cropping was sourced from the run-down of native soil organic matter and the mineralisation of pasture legume residues. Angus (2001) suggested the major reasons for the increased fertiliser-N usage were twofold: the adoption of effective, cereal-disease-breaking rotations based

TABLE 4.1 The most commonly used forms of nitrogenous fertilisers in grain cropping in Australia

Form	%N[1]	Price[2]		Additional elements[3]
		$/tonne fertiliser	$/kg N	
Mineral fertilisers				
Anhydrous ammonia	82	–	–	none
Ammonium sulfate	20	495	2.47	S
Urea	46	650	1.40	none
Ammonium nitrate	34	'Dangerous goods'		none
Urea-ammonium nitrate (UAN) liquid	32	–	–	none
Di-ammonium phosphate (DAP)	18	880	4.90	P
Mono-ammonium phosphate (MAP)	10			P
Organic fertilisers				
Manures, composts, biosolids	1–5			P, K, S, Zn, C

1 Dry weight basis 2 Average prices for the 5-year period 2005–09 3 S – sulfur, P – phosphorus, K – potassium, Zn – zinc , C – carbon

FIGURE 4.1 (a) Consumption and (b) bulk retail price of nitrogenous fertilisers in Australia between 1993 and 2010



SOURCE: ABARES 2010

on broadleaf crops such as canola and lupins and the increased premiums paid for high-protein wheats.

4.2 Forms of fertiliser N

Nitrogenous fertilisers are available in mineral and organic forms (Table 4.1). The form that a farmer might use will largely depend on price, convenience of application and perceived advantages. Fertiliser prices vary from year to year (e.g. Figure 4.1b) and the unit cost of N also varies substantially amongst the different forms. With the more expensive forms, e.g. DAP, other elements are also involved (phosphorus in the case of DAP).

4.2.1. Mineral fertilisers

All mineral forms of fertiliser N are based on ammonia (NH_3), which was first manufactured on an industrial scale in 1913 in Germany. The technology used in the process was developed by Fritz Haber, with Carl Bosch responsible for scaling up the table-top prototype for commercial production. The process essentially combines the hydrogen (H_2) from methane or natural gas (CH_4) with N_2 from the atmosphere under very high temperatures and pressures to produce ammonia. In some countries, coal is used instead of methane as the source of H_2:

$$N_2 + 3H_2 = 2NH_3$$

(in the presence of heat, pressure and a catalyst)

Ammonia is a gas at normal temperatures and pressure. In the manufacture of fertiliser, it is stored and handled as a liquid under refrigeration or in pressure vessels (Glendinning 1990). Ammonia is used either directly as a fertiliser itself or as a base to manufacture other forms of nitrogenous fertilisers. Following are short descriptions of the different forms of nitrogenous fertilisers used in grains cropping. Additional details can be found in Glendinning (1999).

Anhydrous ammonia

Anhydrous ammonia is used in high-input cropping – for example, irrigated grains, cotton – and is stored and transported as a liquid. It is a gas at normal temperatures and pressure, therefore some ammonia can be lost from the soil during and after application. It is the most concentrated of the nitrogenous fertilisers at 82% N.

Ammonium sulfate

Ammonia is combined with sulfuric acid (H_2SO_4) to form ammonium sulfate ($(NH_4)_2SO_4$). The fertiliser contains 20% N and is considered an excellent fertiliser for S-deficient as well as N-deficient soils.

Urea

Urea ($CO(NH_2)_2$) is the most widely used nitrogenous fertiliser in grains cropping, accounting for at least half of the N applied. It is manufactured by combining the carbon dioxide (CO_2) produced during ammonia manufacture with ammonia under high temperatures and pressure. Once applied, it is quickly transformed in the soil by the action of the enzyme urease to produce ammonia/ammonium and carbon dioxide (see details in Chapter 1). The ammonia/ammonium is then converted to nitrate via the process of nitrification. Urea is the cheapest form of N, is relatively concentrated (46% by weight) but does not contain any other crop nutrients. It, like most of the other fertiliser N forms, can damage very young seedlings if applied at high rates and placed too close to, or banded with, the seed.

Ammonium nitrate (Nitram)

Ammonium nitrate (NH_4NO_3) is manufactured by combining ammonia with nitric acid. It ceased to be used as a fertiliser after being classified as "Dangerous Goods". Variations of ammonium nitrate, such as calcium ammonium nitrate (CAN) (80% ammonium nitrate + 20% calcium carbonate ($CaCO_3$)) are available instead. CAN is 20% N.

Urea-ammonium nitrate (UAN)

UAN is a concentrated (43% N w/v or 32% w/w) solution of urea and ammonium nitrate. It is designed to be applied to the soil as an alternative to solid fertiliser where it is more convenient to use a liquid form. It is also used as a foliar-applied fertiliser.

DAP, MAP

These are in a group termed compound fertilisers, combining other plant nutrients with N, e.g. P, K. MAP and DAP are planting formulations, designed to deliver both P and N to the seedling. They are manufactured from ammonia and phosphoric acid.

4.2.2 Organic fertilisers (recycled organics)

Farmers fertilise with organic sources of N because of the desire to use organic inputs rather than mineral/chemical inputs and because of perceived economic and soil health advantages. Organic fertilisers (also termed recycled organics) – animal manures and plant-derived composts and mulches – have dual roles. They supply nutrients, particularly N, P and K to the soil, and crops. Organic fertilisers also supply organic matter, thereby increasing soil organic matter levels leading to improved soil biological activity and soil structure (aggregate stability, porosity, bulk density, water-holding capacity, erodibility). Manures/composts may also suppress plant diseases. Composted organics are processed organics, i.e. drier and more decomposed, with about 30% loss of dry matter, C and N (as ammonia).

In recent years and with greater community emphasis on recycling and environmental management, the sources of organic fertilisers have increased (Table 4.2)

Table 4.3 provides details of concentrations of major elements in organic fertilisers. The major plant nutrients in the organic fertiliser – N, P and K – can be valued using the cost of those elements in mineral fertilisers. For N, a reasonable current cost is $1.30/kg, for P it is $4.17/kg and for K it is $1.63/kg. Using these $ values and average

TABLE 4.2 Different sources and annual volumes of organic fertilisers in Australia

	Annual production (million tonnes)
Biosolids	1.60
Feedlot manures	1.30
Poultry litter	1.10
Layer chicken manure	0.47
Piggery solids	0.32
Grape mark	0.15
Mushroom compost	0.15
Cotton gin trash	0.12
Total	**5.21**

SOURCE: GRDC Recycled Organic Fertiliser Fact Sheet 2010

TABLE 4.3 Properties of different organic fertilisers

Organic source	% water	% C	% N[1]	% P[1]	% K[1]
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
Piggery solids	49	65	1.6	0.7	1.0
De-watered biosolids	82	26–36	3.7	3.4	0.3
Composted plant material	26	24	1.0	0.2	0.5

[1] Dry weight basis.

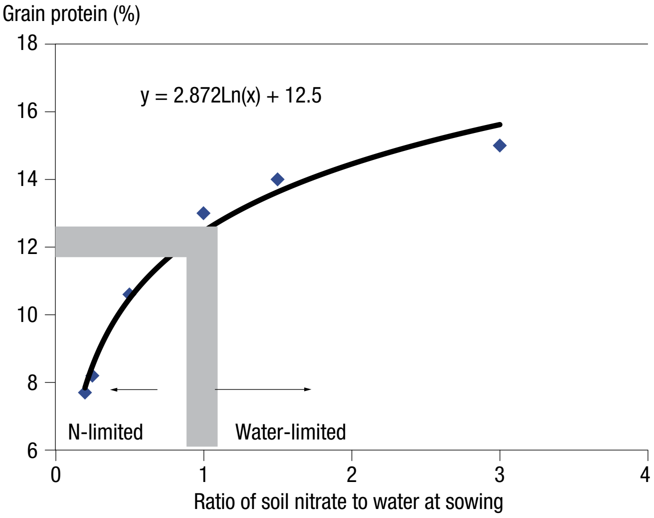
SOURCE: GRDC Recycled Organic Fertiliser Fact Sheet 2010

TABLE 4.4 Effects of %N of the organic fertiliser on N availability

%N of organic fertiliser	% N released in Year 1	% N released in Year 2	Amount (t) to deliver 100 kg nitrate-N in Year 1
1.0	22	13	37
1.5	31	13	25
2.0	41	12	17
2.5	50	12	11
3.0	60	12	7.5
3.5	70	11	5.0
4.0	80	11	3.4
4.5	89	10	2.3

SOURCE: Mathers and Goss 1979

FIGURE 4.2 Showing the relationship between the relative amounts of soil nitrate and water in the root zone (0 to 1.2 m depth) at sowing and grain protein levels in the harvested grain. Grain protein of 12% delineates soils that are either nitrate-limited or water-limited at sowing



SOURCE: Redrawn from Dalal *et al.*,1997

nutrient concentrations from Table 4.3, the nutrient value of an organic fertiliser equates to $55 per cubic metre. Costs of using organic fertilisers vary from site to site and include the costs associated with transport, handling, storage and spreading. Availability of the nutrients, particularly N, in the organic fertilisers is a key issue with their use. As the nutrients are part of the organic matter of the fertiliser, they need to 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 for N availability – the key factor was the N concentration of the organic fertiliser (Table 4.4).

In the case of P, availability is much more immediate, with 75 to 85% available in the first six months.

Therefore, to deliver 100 kg plant-available mineral N/ha would require about 14 t/ha feedlot manure, 4 t/ha dewatered biosolids and 2 to 10 t/ha fresh poultry litter. The manures would at the same time deliver 90 kg available P/ha (feedlot manure), 120 kg P/ha (dewatered biosolids) and 35 to 80 kg P/ha (chicken manure). It has been suggested that manures be used as a source of P or K, rather than N, because of the availability issue and for N to be supplemented with mineral fertiliser N.

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

- incorporated into the top 10 cm of soil to enhance mineralisation, reduce ammonia volatilisation and position immobile nutrients (e.g. P) where they will be used;
- applied several months before sowing;
- aged and screened for uniformity;
- used at rates of 10 t/ha every four to five years; and
- with long-term use, ongoing soil testing should be done to monitor the build up of nutrients and other chemicals.

4.3 When to apply fertiliser N

At a point in time before sowing a particular paddock, farmers need to make decisions about rates of fertiliser N. In the case of cereal cropping, the key issue is meeting the N requirements for target yield and protein outcomes; with oilseeds it will be meeting target yields and oil content. Researchers in the northern grainbelt have advocated different approaches to these questions.

One approach used grain protein as an indicator of soil N supply and its adequacy in providing for the N demands of future cereal cropping (Holford *et al.* 1992; Doyle and Leckie 1992; Strong *et al.* 1996). Strong (1981) had clearly shown that grain proteins were a good predictor of relative yields in wheat. At 10% protein, crops were producing only about 70% of potential yield. At 12%, it was 95%. Above 13% protein, yields would not be expected to further increase with additional N inputs and increased grain protein levels would not affect quality and price premiums. Data from the NSW DPI farming systems experiments in northern NSW showed very similar trends (Table 4.5).

TABLE 4.5 Using wheat grain proteins to determine relative yield

Wheat grain protein (%)	% maximum yield	
	Strong *et al.* (1981)	Unpublished data Windridge[1]
9	52	45
10	72	62
11	86	77
12	95	88
13	100	97

[1] Data from Windridge (W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished). See Chapter 6.3.

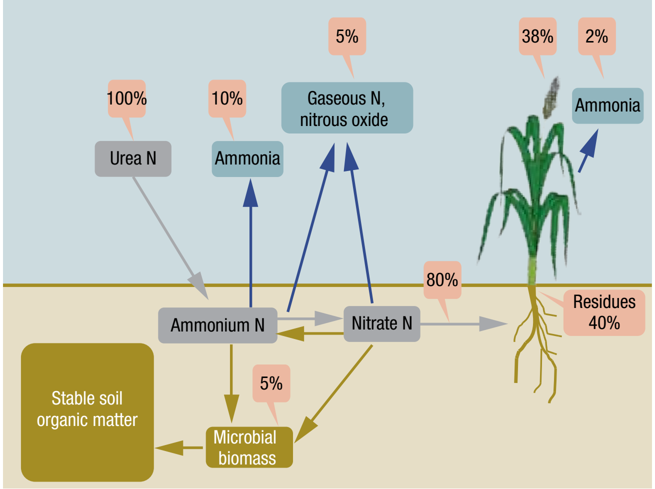
The generalised recommendation coming from this work was to identify the critical protein level (CPL) – above which wheat gave little or no response to fertiliser N – to be about 12%. For grain protein levels less than 12%, N supply was limiting yields to some degree and crops were generally responsive to additional fertiliser N. This information is retrospective, rather than predictive. It told the farmer that the harvested wheat crop was either sufficient in N or lacked N with the appropriate yield consequences. It did not provide the farmer with the means to estimate the amount of fertiliser N required for targeted crop yields and/or proteins for a given paddock in the coming season.

Such estimations were provided with N budgeting, a second approach. With N budgeting, soil N supply – either measured in soil testing prior to sowing or estimated using modelling or paddock history – was compared with predicted crop N demand and the shortfall made up with fertiliser N (Myers 1987; Marcellos and Felton 1994; Lawrence *et al.* 1995; Martin *et al.* 1996; Edwards and Herridge 1998). The budgeting was done initially by the farmer using knowledge on N supply and demand learned in associated workshops. Nitrogen budgeting for cereal production appears to have been highly successful, both in terms of participation, with an estimated 400 Queensland grain growers taking part during 1995 and 1996, and impact (Lawrence *et al.* 1997). Nitrogen budgeting is the basis of 'NBudget', the N management tool presented in the following chapter.

It should be emphasised that the classical N fertiliser experiments consisting of rates x sites x seasons (Holford *et al.* 1992; Doyle and Leckie 1992; Strong *et al.* 1996) highlighted the need for N fertilisation of cereals in the northern grainbelt and of rates that might be appropriate. These experiments also provided insights into N cycling in these systems, as well as data from which useful, empirical relationships could be derived. Such relationships feature throughout this manual, particularly in this chapter, Chapter 6 and the Appendices.

It is worth noting another empirical relationship that has been used to make decisions about fertiliser N inputs. Dalal *et al.* (1997b) suggested that the need for fertiliser N is essentially determined by the balance between soil N supply and crop N demand. The latter is largely determined by water supply (water stored in root-zone soil at sowing plus in-crop rainfall).

FIGURE 4.3 The application and cycling of fertiliser N (in mineral form) in a typical scenario in the northern grains region (a 3 t/ha wheat crop of 11.5% grain protein)



The authors showed grain protein of wheat and barley were highly correlated with the relative amounts of soil nitrate (kg/ha) and water (mm) to 1.2 m depth at sowing and that grain protein was a useful indicator of the N supply:N demand balance. They suggested that the index could be used by farmers to target premium grades of wheat and barley – ratios were close to 1:1 for prime hard wheat (13% protein) and 1:2 for malting barley (10.5% protein). Thomas *et al.* (2007a), in a study of wheat and barley production in southern Queensland, successfully applied this methodology to target grain protein levels (Figure 4.2).

Although the balance of soil nitrate and water at sowing may indicate the need for fertiliser N input, it does not provide information on the rate needed. A person using this approach would have to calculate the actual amount of fertiliser N required by comparing N supply and projected N demand, i.e. N budgeting.

4.4 Making the most of fertiliser N – N use efficiency

A number of efficiency values need to be known for understanding the fate of applied fertiliser N in systems and to calculate the amount of fertiliser N required to produce a targeted grain yield and protein. They are the efficiency with which fertiliser N is incorporated into soil nitrate and then into grain N. The efficiency of soil nitrate into grain N can be further split into efficiency of uptake of soil nitrate and efficiency of partitioning of plant N into grain N.

The efficiency with which that fertiliser N is utilised by the growing crop varies with season, management and soil nitrate status. The challenges for farmers are to know when fertiliser N is needed, how much to apply and how to manage for maximum efficiency.

4.4.1 Converting fertiliser N to grain N (FUE)

Figure 4.3 provides a guide to the fate of 100 kg of fertiliser N (as urea) applied to a moderately fertile soil in the northern grainbelt. All 100 units of the urea N are hydrolysed to ammonia and ammonium to be lost either through ammonia volatilisation (10%) and emissions of nitrogen gas and nitric and nitrous oxides associated with nitrification and denitrification (5%). About 5% is immobilised by soil microbes. Leaching losses are assumed to be zero. The remaining nitrate (80% of applied fertiliser N; see also Pilbeam 1996) is available to be taken up by the growing crop. Some 38% of the applied N is incorporated into the harvested grain (3 t/ha wheat crop at 11.5% protein) and 2% is lost through ammonia volatilisation from the maturing crop. The remaining 40% returns to the soil as shoot and root residues.

The following grain harvest, about 45% of the applied fertiliser N remains in the soil in an organic form, either as fresh residues, soil organic matter or microbial biomass. Note that plant and grain N derived from the mineralisation of native organic matter and existing residues are not included in this flow diagram.

The efficiency with which the fertiliser N is turned into grain protein varies substantially. It varies with season (i.e. total and pattern of rainfall), the background level of nitrate in the soil and level of disease. For crops that are diseased and for crops growing in a season with a dry finish, fertiliser N efficiency may be reduced because of lower uptake of N during grain filling, resulting in low N harvest indices. Doyle and Leckie (1992) showed that the recovery of fertiliser N in grain was halved when the season ended with a dry finish.

Efficiencies with which fertiliser N is converted into grain N and grain mass for wheat and sorghum are shown in Table 4.6. The values were derived from the lines of best fit using data from both published and unpublished experiments in the northern grainbelt (see Appendix 1).

The values in the table are consistent with those published by Lester *et al.* (2010) for barley, wheat and sorghum at two sites in southern Queensland and northern NSW, by Doyle and Leckie (1992) and Doyle and Holford (1993) for experiments in northern NSW and in the review of research across the region by Strong and Holford (1997).

What are the effects of variations in seasonal conditions and management on the numbers in the N-flow diagram? Some scenarios are shown in Table 4.7. High efficiency of fertiliser-N use (40 to 50% of fertiliser N converted to grain N) is usually associated with high-yielding crops (greater than 3 t/ha) that are grown in fertiliser-N responsive, low-nitrate soils (less than 50 kg N/ha to 1m depth) in seasons with normal to good finishes. In these situations, losses of N from volatilisation and immobilisation of N may be low and N harvest index high.

On the other hand, low recovery of fertiliser N in the harvested grain (20%) is usually associated with either low-yielding crops (less than 2 t/ha) or non-responsive, high-nitrate soils (greater than 100 kg N/ha to 1 m depth) or both (Table 4.7). In these situations, N losses can be greater and the N harvest index reduced. Importantly, not all of the nitrate-N derived from the fertiliser may be used, but left in the soil. Waterlogging will tend to increase gaseous losses of the fertiliser N through denitrification and high residue loads may increase immobilisation.

In the dry finish/diseased crop scenario, as much as 40% of the fertiliser N remains in the soil unused (Table 4.7). In fact, in a drought year, less than 10% of the fertiliser N may end up in the grain, with substantial amounts remaining as nitrate in the soil. Of practical

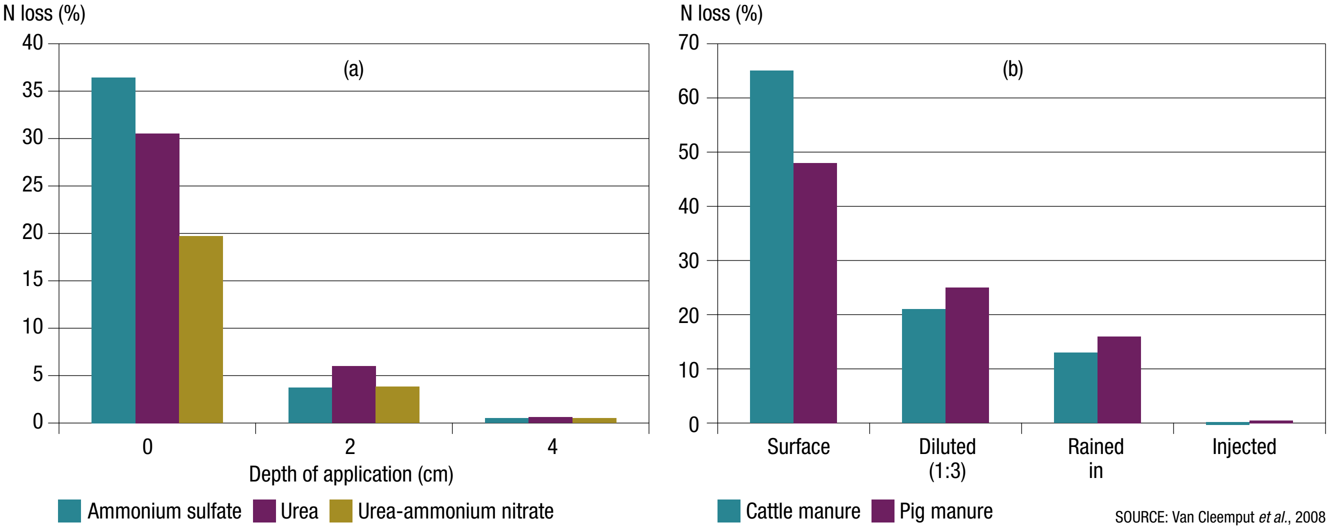
TABLE 4.6 Effects of grain proteins on the efficiencies with which fertiliser N is converted into grain N and grain yield for wheat and sorghum in the northern grains region. (Values from lines of best fit of graphs in Appendix 1.)

Grain protein (%)	Wheat		Sorghum	
	kg grain N/ kg fertiliser N	kg grain/ kg fertiliser N	kg grain N/ kg fertiliser N	kg grain/ kg fertiliser N
6	–	–	0.50	34
7	–	–	0.42	28
8	0.47	27	0.33	22
9	0.42	23	0.25	15
10	0.36	18	0.17	9
11	0.31	14	0.08	3
12	0.25	10	–	–
13	0.20	6	–	–
14	0.14	2	–	–

TABLE 4.7 N budgets for wheat, showing effects of growing conditions on the various components of the N cycle and eventually on the efficiency with which fertiliser N is incorporated into grain

Scenario	Grain protein (%)	N losses (volatilisation, denitrification) (kg/ha)	N immobilised (kg/ha)	N unused (kg/ha)	N harvest index (%) (grain:above-ground)	% efficiency of fertiliser N to grain N (%)
N demand:N supply – Normal finish						
Responsive	<11.5	15	5	0	85	45
Neutral	12.0	20	15	0	70	30
Non-responsive	>12.5	20	15	20	60	20
N demand:N supply – Dry finish, diseased crop						
Responsive	<11.5	20	5	20	70	27
Neutral	12.0	25	15	20	60	18
Non-responsive	>12.5	25	15	40	50	8
High losses/immobilisation – Normal finish						
Waterlogging	12.0	40	15	0	70	20
Residues	12.0	20	35	0	70	20

FIGURE 4.4 Placement of (a) mineral and (b) organic fertiliser N at depth in the soil reduces losses



SOURCE: Van Cleemput *et al.*, 2008

interest is whether that N will be lost or will remain available for the following crop. The short answer is that it should remain available for the following crop. Angus and Fischer (1991) reported that an average of 53% of fertiliser N applied in 1982 (drought year) was recovered in the 1983 crop grain and stubble, compared with an average of 54% for the N applied in 1983. The average amount of the 1982 fertiliser recovered in the 1982 crops was just 6%. Strong *et al.* (1986) reported similarly high recoveries of fertiliser N in the year after application.

It is good economics to optimise the efficiency with which fertiliser N is used. Efficiencies can be lower because fertiliser N is lost from the system or immobilised before being converted to nitrate. Practices that minimise N losses and immobilisation are banding and point placement of the fertiliser in the soil, timing N application in order that supply is reasonably well matched to demand (may include split applications) and separating the fertiliser N from high C:N ratio stubble or residues (Strong 1995; Angus 1995; Peoples *et al.* 1995b).

On the other hand, practices associated with low efficiencies are surface applications of fertiliser N leading to high gaseous losses (ammonia volatilisation and denitrification), poor timing of application leading to gaseous losses and immobilisation, and contact with stubble and residues (immobilisation). Denitrification and leaching losses are also increased by heavy, prolonged rainfall following application (Strong *et al.* 1992).

4.4.2 Placement of fertiliser N and effects on FUE

Nitrogenous fertilisers, whether they are in mineral or organic forms, are prone to losses if placed on top of the soil. They become progressively more protected as they are applied deeper in the soil (Figure 4.4). Cox and Strong (2008) recommend that:

- fertiliser N be banded between the seed rows using coulters/discs or narrow point tynes to minimise disturbance;
- placement should be at least 3 cm from the seed using every second inter-row space, rather than in the seed row, unless applying at very low rates. Cox and Strong (2008) provide a table of safe rates of mineral N fertilisers that can be applied with the seed; and
- placement should be not too deep, also to minimise disturbance.

The major mechanism of N loss of surface-applied fertilisers is through volatilisation of ammonia. As mentioned above, fertilisers such as urea are processed after application to the soil to form ammonia/ammonium and carbon dioxide. At soil pHs above neutral (pH 7.0), progressively more of the ammonia/ammonium is in the gaseous ammonia form and subject to loss to the atmosphere. The extent of losses appears to be much the same for urea and ammonium sulphate (Terman 1979). With both forms of fertiliser, the N will be in the ammonium/ammonia form at some stage and available for volatilisation, provided conditions are right.

Schwenke and McMullen (2009) listed some of the conditions that favour volatilisation of ammonia. They are:

- surface application of urea and ammonium forms of fertiliser N;
- warm to hot temperatures;
- alkaline, calcareous soils, with losses increasing with increasing pH;
- soils low in clay content and high in buffering capacity;
- wind;
- drying soils;
- lack of crop canopy, i.e. open air above the soil; and
- residues on the soil surface.

Ammonia volatilisation is just one way that N use efficiency can be reduced. Placement of the fertiliser can also affect N immobilisation. In a study in the US by Tomar and Soper (1981), N use efficiency was greatest when the fertiliser was banded into the soil and the residues were left on the surface (Figure 4.5). In other words, the two were separated.

FIGURE 4.5 **Effects of placement of fertiliser N and residue management on efficiency with which the N is used by the growing crop. Values are the percentages of fertiliser N remaining in the soil after grain harvest**

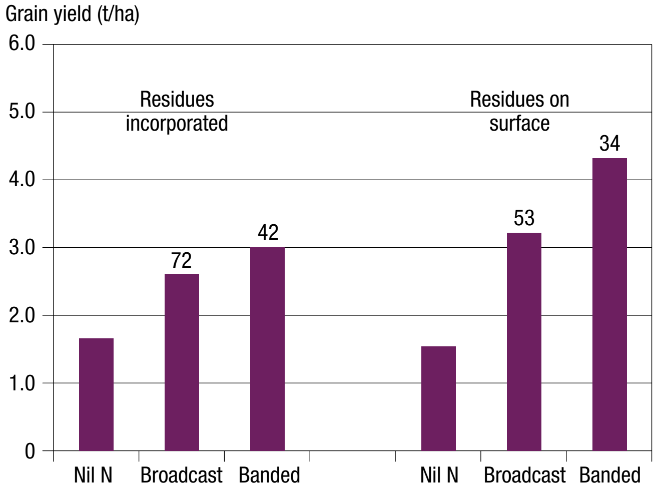
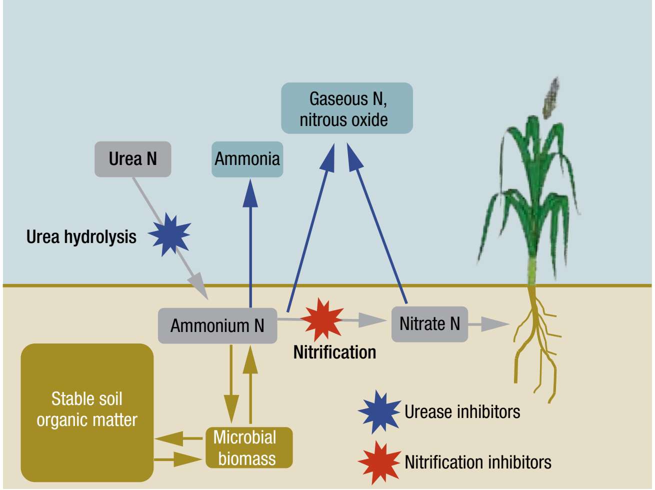


FIGURE 4.6 **Urease inhibitors block the urea hydrolysis in which urea is converted to ammonia/ammonium. Nitrification inhibitors block the action of the nitrifying bacteria that convert ammonium to nitrate**



4.4.3 Timing of fertiliser N application and effects on FUE

In northern grains cropping, most fertiliser N is applied during the pre-crop fallow or at planting, rather than in-crop. Doyle and Shapland (1991) and Strong *et al.* (1992) recommended applying fertiliser N at or close to planting, but not early in fallow, and drilled into the soil. Cox and Strong (2008) concluded from the many northern grainbelt studies that the timing of application is generally of less importance than the amount applied, i.e. there should be sufficient to optimise crop profitability. Cox and Strong (2008) listed the advantages and disadvantages of pre-plant (fallow), planting and in-crop applications of fertiliser N (Table 4.8).

McMullen (G McMullen, personal communication) examined in-crop and split applications of fertiliser N in northern NSW over a three-year period. He concluded that in-crop and split applications were advantageous in favourable rainfall scenarios with early sown, long-season crops grown in low-nitrate soils.

4.4.4 N-efficient formulations

Nitrification inhibitors, urease inhibitors and slow-release forms of fertiliser N have been used in North America and Europe for a number of years to improve fertiliser-N use efficiency and are starting to gain attention here in Australia (Glendinning 1999; Chen *et al.* 2008; Laycock 2009):

- Urease inhibitors temporarily block urea hydrolysis, the conversion of fertiliser urea to ammonia/ammonium, water and carbon dioxide (Figure 4.6). The blockage is to allow time for the urea to be washed into the soil with rainfall/irrigation, thereby protecting the ammonia from volatilisation. A product example is Green Urea™.

TABLE 4.8 **Advantages and disadvantages of pre-crop fallow, planting and in-crop fertiliser N applications**

Advantages	Disadvantages
Pre-plant (fallow)	
N can move down into the root zone Convenient Only option with planting gear Can take advantage of lower fertiliser price	Can cause soil moisture loss Requires earlier decision on N Up-front cost of fertiliser Increased risk of waterlogging-induced losses
At planting	
Cost of fertiliser linked to cropping certainty Can make more informed decision on N rates Convenient, particularly for wide-row summer cropping Soil moisture losses minimised Less risk of waterlogging-induced losses	Greater workload at planting Requires appropriate planting gear Risk of N being quarantined in the topsoil, rather than in the root zone
In-crop	
Flexibility of overall rate increased Can result in higher yields More often results in higher grain proteins	Should be applied during first half of crop growth Requires appropriate equipment May need rain soon after application, particularly if soil-surface applied or foliar With foliar applications, rates need to be low to avoid crop damage

SOURCE: adapted from Cox and Strong 2008)

- Nitrification inhibitors block the conversion of ammonium to nitrate for up to three months by acting directly on the ammonia oxidising bacteria (*Nitrosomonas* spp.) that facilitate the first part of the conversion (Figure 4.6). Nitrifying inhibitors remain effective longer in cool-cold climates, rather than in the subtropics or tropics. Nitrification inhibitors target losses of N via denitrification and leaching. Examples of products are N-Serve® (Nitrapyrin), Terrazole® and Entec® (DMPP).
- Slow-release N formulations are for the most part standard N fertilisers coated with a product to render them more insoluble. As with the urease inhibitors, the idea is to buy time for the urea or other forms of fertiliser to be washed into the soil. Examples of slow-release formulations are wax-coated urea, polymer-coated urea and plastic-coated urea.

Trials in the northern grainbelt using these products have had mixed results (G McMullen, personal communication). A potential benefit of products such as Entec® is the reduction of emissions of nitrous oxide, the very potent greenhouse gas. Suter (2011a, b) reported reductions in nitrous oxide emissions of 73% (field) and 19 to 98% (laboratory) when Entec® was added to urea fertiliser. There was a very strong effect of temperature, with the lower reductions associated with higher temperatures.

CHAPTER 5: ‘NBUDGET’ – AN EXCEL-BASED CALCULATOR FOR MANAGING N IN THE NORTHERN GRAINS REGION

Farmers need to make decisions about N inputs and for mainly economic reasons they need to get it right. ‘NBudget’ is a simple-to-use web-based calculator designed to help farmers and their advisers in Australia’s northern grains region estimate soil nitrate and water levels at sowing and fertiliser N requirements for cereals and oilseeds. It is located on the NSW DPI-hosted web site CropMate™. There are 22 stations (locations) in the program, from Roma and St George in southern Queensland to Dubbo in the central-west of NSW (Figure 5.1). There are two versions of ‘NBudget’, one for winter cropping and one for summer cropping.

‘NBudget’ uses the established N budgeting approach in which estimates of N demand and N supply are compared in order to calculate fertiliser N requirements (for example, Myers 1987; Marcellos and Felton 1994). ‘NBudget’ is a practical model based on observations and empirical relationships. Good use is made of rules of thumb, a strategy used successfully in engineering for millennia (Passioura 1996). In the conclusion of his paper, Passioura (1996) warns that for models to be useful they need to:

- be as simple as possible;
- require little input data;
- be based on robust empirical relationships; and
- have their use restricted to the conditions under which the empirical relationships were founded.

The aim in developing ‘NBudget’ was to satisfy all of the above. According to the definitions of Myers (1987), ‘NBudget’ is a static, empirical model. It is essentially a structured set of linked mathematical equations and values that lead the user to estimates of the amounts of fertiliser N needed to grow a cereal or oilseed crop in a particular paddock in the coming season. Other end-point calculations include the amount of N fixed by the crop legumes, chickpeas, faba beans, mungbeans and soybeans.

A major difference between ‘NBudget’ and other calculators/tools for N management is that soil testing for either nitrate, organic carbon or water is not required. Rather, ‘NBudget’ contains rule-of-thumb values for soil nitrate based on paddock nutrient fertility status and recent paddock history and linked equations for calculating soil nitrate following crop growth and post-crop fallow. A soil test at the appropriate time, i.e. just before sowing, could give an accurate estimate, but as already discussed, a large percentage of cropping paddocks are not deep-cored for nitrate prior to sowing so test results are not available. Also, nitrate levels are variable across a paddock, resulting in unreliable test values unless the number of cores taken from each paddock is relatively high, i.e. between 8 and 10.

Other key calculations in ‘NBudget’ determine soil water at sowing based on fallow rainfall or depth of wet soil, biomass and grain yields of the different crops based on water use efficiencies, N_2 fixation of the legumes based on crop biomass and soil nitrate effects, production of crop residues and the net release or immobilisation of nitrate-N from those residues as they decompose in the soil.

Input data to develop ‘NBudget’ were sourced from published and unpublished experiments conducted principally by the farming systems and plant (N) nutrition programs of the NSW and Queensland agricultural agencies during the past 30 years. Input data required to run ‘NBudget’ includes: location and description of the

FIGURE 5.1 The CropMate home page (left) and the top of the ‘NBudget’ page in the Preseason planning section of CropMate (right)

paddock as either very low, low-medium, medium or high fertility; tillage practice; yield and protein level (for cereals) of the previous crop; fertiliser N applied to previous crop; simple assessment of crown rot risk for the winter cereals; and fallow rainfall or depth of wet soil.

5.1 Working through 'NBudget'

The winter cropping version of 'NBudget' includes bread wheat, durum, barley, canola, chickpeas and faba beans. The summer cropping version contains sorghum, sunflowers, mungbeans and soybeans. Formats for both versions are essentially the same as is the logic. The 22 stations in 'NBudget' each have unique rainfall data, sourced from the Australian Bureau of Meteorology (BoM) and the Queensland Climate Change Centre of Excellence.

There are seven steps to work through to estimate yields and fertiliser N requirements for the cereal and oilseed crops and yields and N_2 fixation inputs for the crop legumes:

1. Site details

The user goes to the CropMate home page and first selects the State (NSW, Queensland, Victoria or SA), followed by the station (nearest town) (Figure 5.1). There are a total of 96 stations in CropMate across the four states, but only the 22 stations (17 in NSW and 5 in Queensland) in the northern grainbelt have access to 'NBudget'. The 'Enter' button is then pressed, which takes the user to the 'Preseason planning' section. This section contains three decision tools – 'Nbudget', 'CropChooser' and 'Frost and heat risk analyser', as well as weather and climate information. The user clicks on 'NBudget' in the left menu, which opens the page (Figure 5.1).

The default is the winter cropping version of 'NBudget'. If the summer crop version is required instead, the user clicks on the Summer Cropping NBudget button to open it. The farm and paddock names are then inserted (Figure 5,2). Also selected from drop-down lists are the fertility status of the paddock (high, medium, low-medium or very low, according to the short description of each – see Chapter 6.1) and soil type (clay soil, red-brown earth, sandy loam). Tillage practice is selected using the buttons.

The next choice is whether to use a measured soil test value for post-fallow (sowing) soil nitrate or a value calculated by 'NBudget' based on paddock history. In most cases it is the latter, because only a small minority of paddocks are soil tested.

2. What was in the paddock two seasons ago?

The user selects from the drop-down list the crop grown in the paddock the season before last (Figure 5.2). A rule-of-thumb estimate of soil nitrate at the start of last season, aggregated from published and unpublished data, is then shown (see Chapter 6.1).

3. Last season

The user selects from a drop-down list the crop that was last grown in the paddock and inserts the yield, protein (in the case of the cereal crops) and amount of fertiliser N applied.

4. Current summer fallow

Soil nitrate

'NBudget' provides an estimate of post-fallow soil nitrate, i.e. soil nitrate at the time that the farmer or adviser is making a decision about fertiliser N inputs for the coming cropping season (procedure for this determination shown as Appendices 10 and 11).

Soil water

The other key value is post-fallow (sowing) soil water, determined using either fallow rainfall records (see Chapter 6.2), depth of wet soil (push probe) or by other means, e.g. HowWet? Both soil water and soil nitrate values are for soil depths of 1.2 metres (Figure 5.2).

5. Crown rot assessment for bread wheat, durum wheat and barley for current season (only in the winter cropping version)

The expected level of crown rot is selected from the drop-down list. The yield loss for the three cereals is then calculated using default data from the NSW DPI Grain Pathology research program, Tamworth (S Simpfendorfer, personal communication).

6. Targeting grain yields and proteins

The user inserts the target grain proteins for bread wheat, durum and barley (winter crop version) and sorghum (summer crop version). The default protein values are 11.5% for bread wheat, 13% for durum, 10% for barley and 9.5% for sorghum (see Woodruff 1992; Cox and Strong 2008; Appendix 6). Grain proteins for canola, chickpeas, faba beans (winter crop version) and sunflowers, soybeans and mungbeans (summer crop version) are at set values that don't require changing (Figure 5.2).

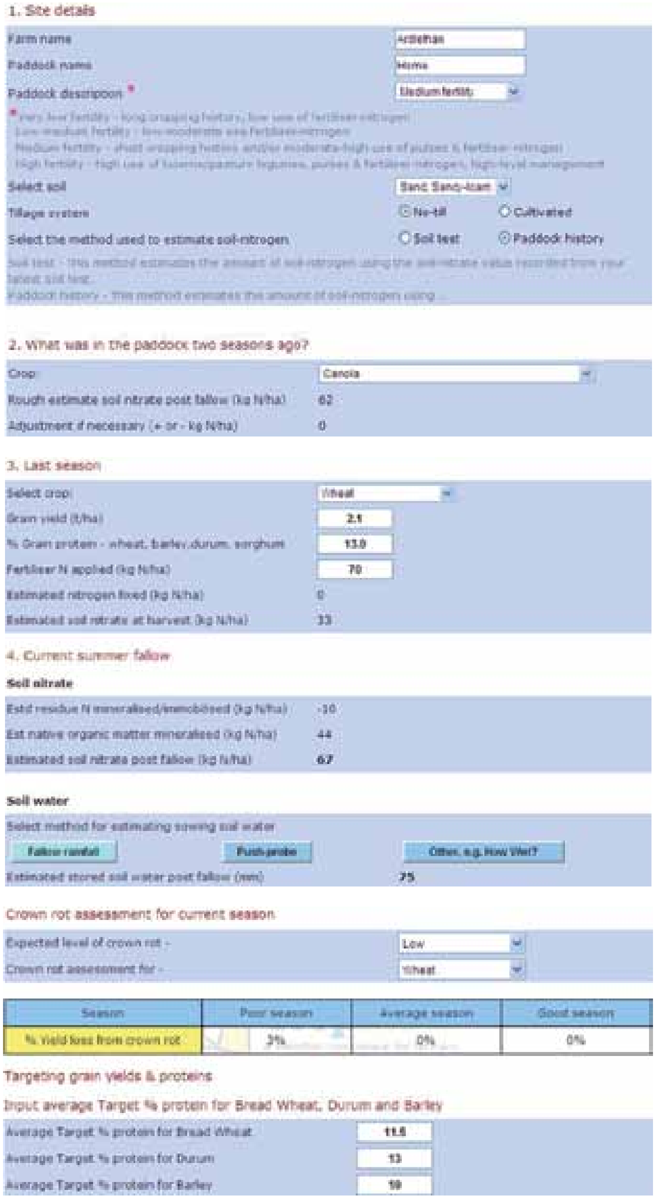
7. Estimating fertiliser N requirements

Grain yields are calculated automatically for poor (30 percentile), average (50 percentile) and good (70 percentile) seasons using historic rainfall data and default water use efficiency (WUE) values (Chapter 6.3). Grain proteins are adjusted for the poor and good seasons. The fertiliser N requirements for the cereal and oilseed crops (Chapter 6.4) and the amounts of N fixed by the crop legumes (Chapter 6.7) are then calculated together with residual (post-fallow) nitrate levels (Figure 5.3).

5.2 Using 'NBudget'

An example of how 'NBudget' would be used by a farmer or adviser is now presented. The scenario involves winter cropping at Dubbo, NSW and it is within a month of sowing, i.e. late April, early May. The calculator could

FIGURE 5.2 Working through 'NBudget' for winter cropping at Dubbo, NSW. The steps involve site details, estimating soil nitrate and water at sowing using paddock history and fallow rainfall, details of expected crown rot levels and target grain proteins.



1. Site details

Farm name	Ardlethan	
Paddock name	[illegible]	
Paddock description *	Medium fertility	
Select soil	Sand: Sandy-loam	
Tillage system	● No-till	○ Cultivated
Select the method used to estimate soil-nitrogen	○ Soil test	● Paddock history

2. What was in the paddock two seasons ago?

Crop	Canola
Rough estimate soil nitrate post fallow (kg N/ha)	62
Adjustment if necessary (+ or - kg N/ha)	0

3. Last season

Select crop	Wheat
Grain yield (t/ha)	2.1
% Grain protein - wheat, barley, durum, sorghum	13.0
Fertiliser N applied (kg N/ha)	70
Estimated nitrogen fixed (kg N/ha)	0
Estimated soil nitrate at harvest (kg N/ha)	33

4. Current summer fallow

Soil nitrate

Estd residue N mineralised/immobilised (kg N/ha)	-10
Est native organic matter mineralised (kg N/ha)	44
Estimated soil nitrate post fallow (kg N/ha)	67

Soil water

Select method for estimating sowing soil water

Estimated stored soil water post fallow (mm)	75

Crown rot assessment for current season

Expected level of crown rot -	Low
Crown rot assessment for -	Wheat

Season	Poor season	Average season	Good season
% Yield loss from crown rot	3%	0%	0%

Targeting grain yields & proteins

Input average Target % protein for Bread Wheat, Durum and Barley

Average Target % protein for Bread Wheat	11.5
Average Target % protein for Durum	13
Average Target % protein for Barley	10

have been used earlier in the pre-crop fallow. Figures 5.1 to 5.3 are from the Dubbo winter cropping scenario.

5.2.1 Winter cropping

The State (NSW) and Station (Dubbo) are selected on the home page of CropMate. 'NBudget' is activated from the 'Preseason planning' section of CropMate. Farm and paddock names are typed in. The paddock is characterised as a medium fertility, i.e. moderate use of pulses and fertiliser N. Soil type is a sandy-loam. No-till describes the management.

'Two seasons ago' – the crop in the paddock two seasons ago was N-fertilised canola (selected from the drop-down list). The estimate of post-fallow soil nitrate, i.e. at the start of last season, is 62 kg N/ha. The value would have been about 20% higher had the paddock been cultivated.

'Last season' – wheat yielding 2.1 t/ha, 13.0% grain protein and fertilised with 70 kg N/ha.

'Current summer fallow' – 'NBudget' estimates sowing soil nitrate at 67 kg N/ha. Soil water at sowing is estimated at 75 mm from the inserted fallow rainfall of 243 mm.

'Crown rot assessment' – the paddock characterised as low crown rot risk because canola, an effective break crop for crown rot, was grown two season ago.

'Target grain proteins' – They were the default values of 11.5% (bread wheat), 13% (durum) and 10% (barley).

'Grain yields and fertiliser N requirements' – In the example, 'NBudget' predicted bread wheat yields of 2.3, 3.0 and 3.5 t/ha for poor (30 percentile), average (50 percentile) and good seasons (70 percentile) requiring 72 kg fertiliser N/ha (Figure 5.3). The predicted grain proteins varied from 10.8% (good season) to 12.5% (poor season). Predicted durum yields were much the same, with fertiliser N requirements 50% higher at 110 kg N/ha. Barley, on the other hand, was predicted to yield about 30% higher but require substantially less fertiliser N (31 kg N/ha). Canola's predicted yields were 1.2 to 1.8 t/ha, requiring about 80 kg fertiliser N/ha. The program predicted that chickpeas and faba beans would yield as much as 2.3 and 2.8 t/ha, respectively, and fix as much as 117 and 147 kg N/ha, respectively, in the good season scenario.

Post-fallow nitrate levels, i.e. soil nitrates in 12 months time, are also predicted for each of the six crops and for each of the three seasonal scenarios for those crops. Values ranged from just 4 kg N/ha following good season (high-yielding) barley to more than 80 to 90 kg N/ha following faba beans and the low-yielding (water-stressed) canola and durum crops.

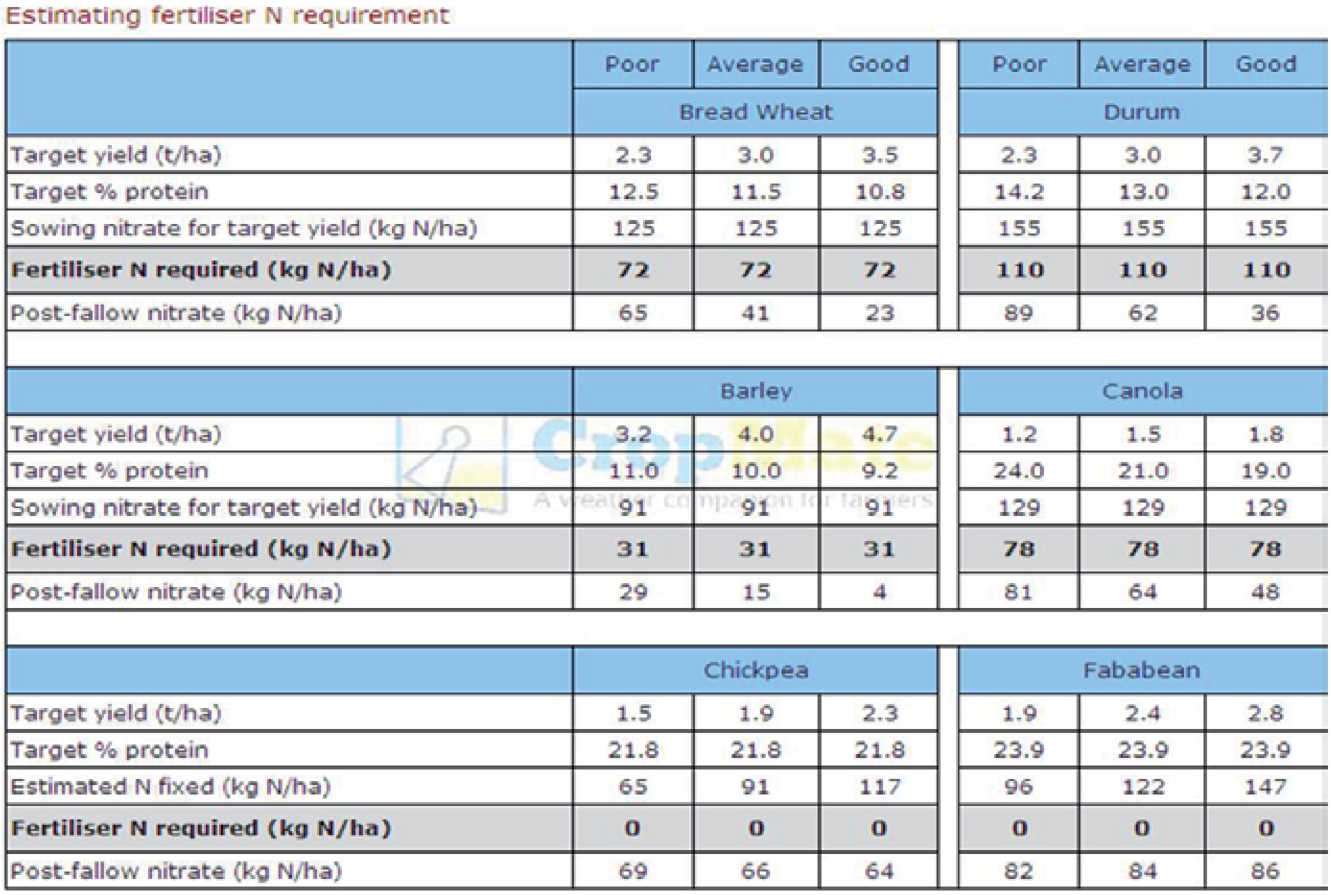
5.2.2 Summer cropping

The sequence of steps for the summer cropping version of 'NBudget' are essentially the same as those for the winter crops. The State and Station are selected on the front page of CropMate. 'NBudget' is then activated from the 'Preseason planning' section of CropMate. Once in 'NBudget', the 'Summer Cropping NBudget' button is pressed to activate the summer version of the program. Farm and paddock names are typed in, and the steps for estimating soil nitrate, soil water, grain yields of sorghum, sunflowers, mungbeans and soybeans, fertiliser N requirements of the sorghum and sunflowers, and N fixed by mungbeans and soybeans are as detailed above.

5.2.3. Asking 'what-if' questions

'NBudget' can be used to ask simple what-if questions. For example, what happens when a chickpea crop north-east of Moree in northern NSW grows well and produces high biomass but yields poorly or, in extreme

FIGURE 5.3 **Output of predicted grain yields, proteins and fertiliser N requirements for the six winter crops. The pulses, chickpeas and faba beans do not require fertiliser N; instead the estimated amounts of N fixed are shown.**



Estimating fertiliser N requirement

	Poor	Average	Good	Poor	Average	Good
	Bread Wheat			Durum		
Target yield (t/ha)	2.3	3.0	3.5	2.3	3.0	3.7
Target % protein	12.5	11.5	10.8	14.2	13.0	12.0
Sowing nitrate for target yield (kg N/ha)	125	125	125	155	155	155
Fertiliser N required (kg N/ha)	**72**	**72**	**72**	**110**	**110**	**110**
Post-fallow nitrate (kg N/ha)	65	41	23	89	62	36
	Barley			Canola		
Target yield (t/ha)	3.2	4.0	4.7	1.2	1.5	1.8
Target % protein	11.0	10.0	9.2	24.0	21.0	19.0
Sowing nitrate for target yield (kg N/ha)	91	91	91	129	129	129
Fertiliser N required (kg N/ha)	**31**	**31**	**31**	**78**	**78**	**78**
Post-fallow nitrate (kg N/ha)	29	15	4	81	64	48
	Chickpea			Fababean		
Target yield (t/ha)	1.5	1.9	2.3	1.9	2.4	2.8
Target % protein	21.8	21.8	21.8	23.9	23.9	23.9
Estimated N fixed (kg N/ha)	65	91	117	96	122	147
Fertiliser N required (kg N/ha)	**0**	**0**	**0**	**0**	**0**	**0**
Post-fallow nitrate (kg N/ha)	69	66	64	82	84	86

circumstances, yields nothing? This was exactly what happened during 2010.

Measured chickpea data from two of the NSW DPI long-term farming systems sites near North Star, already featured in Tables 3.10 and 3.11, is shown in Table 5.1. The predicted values in Table 5.1 were generated using 'NBudget'. The input data needed to run the 'NBudget' calculations were station (Croppa Creek), tillage (both no-till and cultivated were simulated), soil type (clay), soil fertility level (one site classified as low-medium and the second site as medium), sowing soil nitrate (67 kg N/ha) and chickpea grain yield (2.3 t/ha). The predicted values closely approximated the measured values for all parameters.

For the crop harvested for grain, the predicted post-fallow soil nitrate was 105 kg N/ha, almost identical to what was measured. For the scenario of the chickpea grain not being harvested, the post-fallow soil nitrate was predicted to be 40 kg N/ha higher at 146 kg N/ha. About 60% of the additional 70 kg residue-N/ha was predicted to end up as soil nitrate at the end of the summer fallow.

TABLE 5.1 **Measured and predicted values for post-fallow soil nitrate levels (kg N//ha, 1.2 m depth) for a paddock that grew a 2.3 t/ha chickpea crop that was either harvested normally or not harvested because of weather damage. (See also Tables 3.10 and 3.11)**

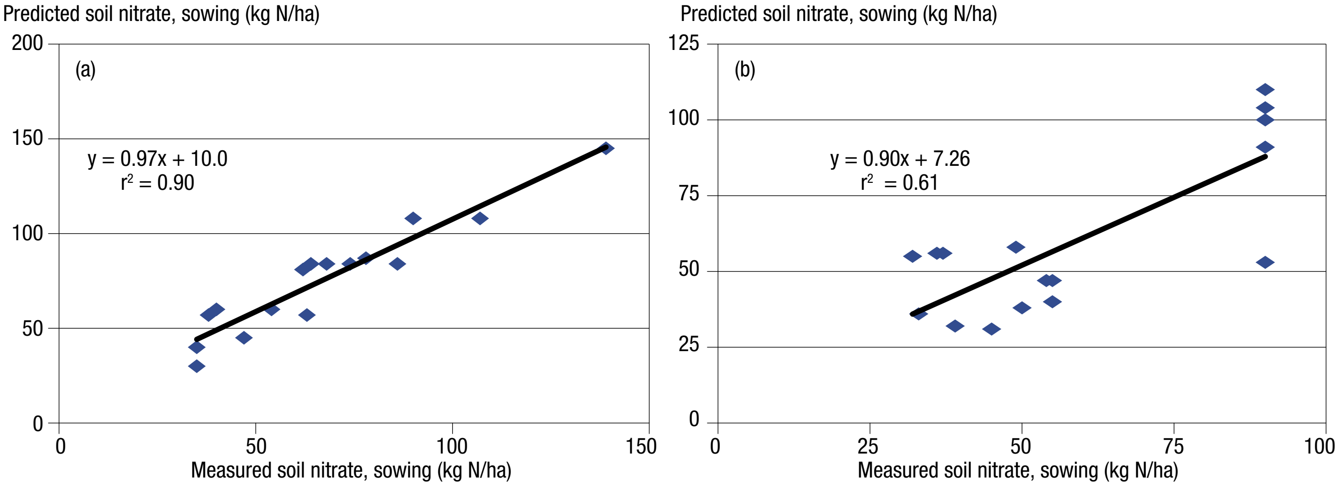
	Measured	Predicted	
Shoot biomass (t/ha)	5.9	5.7	
Total crop N (kg/ha)	205	212	
Crop N fixed (kg/ha)	133	121	
Grain yield (t/ha)	2.3	2.3	0
Shoot+root residue-N (kg N/ha)	133	130	200
Estimated C:N ratio of residues		25:1	25:1
Estimated N mineralised or immobilised		+16	+57
Post-fallow soil nitrate (kg N/ha)	**102**	**105**	**146**

SOURCE: Herridge *et al.* 1995; unpublished data of W Felton, H Marcellos, DF Herridge and GD Schwenke

5.3 Validating 'NBudget'

Two sets of data from southern Queensland – from the long-term site at Warra (Dalal *et al.* 1998) and the Western Downs site at Nindigully (Thomas *et al.* 2007a) – were used to test the ability of 'NBudget' to predict soil nitrate levels at sowing. For Nindigully, data were for no-tilled wheat, grown with four different fertiliser N regimes. Data for the Warra site were from the cultivated continuous wheat (0N) and chickpea–wheat rotations grown without inputs of fertiliser N.

FIGURE 5.4 **Measured and 'NBudget'-predicted values for soil nitrate at sowing for two experimental sites in southern Queensland at (a) Warra and (b) Nindigully**



SOURCE: For measured data (a) Dalal *et al.* 1998; (b) Thomas *et al.* 2007a

Predicted sowing soil nitrate values were very similar to the measured values at the Warra site (Figure 5.4a). At Nindigully, one predicted value was quite different to the measured value – with the remainder reasonably similar (Figure 5.4b). With each, the line of best fit was close to the 1:1 line. These two validation exercises are encouraging and indicate accuracy in the logic and functions in 'NBudget'.

5.4 A final word on 'NBudget'

The prime motivation in developing 'NBudget' was to enhance the accuracy and capabilities of the simple paper-based tools developed in the 1990s for N budgeting in northern grainbelt cropping. Deficiencies in those tools were addressed, such as accounting for the effects of legumes on cereal diseases and soil nitrate levels and modifying the efficiency with which soil nitrate is converted into cereal grain protein as the relative supplies of water and N vary. Functions for estimating inputs of N fixed by legume crops were included.

Considerable effort went into structuring the calculator in a logical way and making it simple to use. An experienced user can run through a paddock scenario in less than a minute, provided the basic input information is on hand. Considerable effort also went into making sure that the functions and values in the tool were accurate and robust. In the next chapter, some of the science that underpins 'NBudget' is presented.

Finally, the value of 'NBudget' will largely be determined by the level of use by farmers and advisers as they make decisions about fertiliser N inputs and general N management. The risk is that farmers may be more comfortable with fixed fertiliser N rates or their own rules-of-thumb, rather than introducing more fine-tuning and precision into the process (Henzell and Daniels 1995; Turpin *et al.* 1998).

CHAPTER 6: THE SCIENCE BEHIND ‘NBUDGET’

The broad principles that underpin ‘NBudget’ were taken from the national and international scientific literature. As much as possible, specific values and functions for the N pools and processes – for example, N mineralisation rates, water-use and N-use efficiencies for wheat, barley, sorghum and so on – were derived from northern grains region data.

6.1 Estimating soil nitrate at sowing

Farmers need to know how much plant-available (nitrate) N they have in their cropping soil in order to determine fertiliser N inputs. In most cases, the information is required at or near the end of the fallow just prior to planting (Figure 6.1). The actual amount will be the sum of:

- N mineralisation of humus (stable soil organic matter);
- N mineralisation of fresh crop residues; and
- unused (spared) soil nitrate from the previous crop or land use.

If the paddock had been used for grazing animals, then there would be a fourth source of nitrate:

- N mineralisation of dung and urine.

Some of the N will be lost on the way through the cycle as gaseous N, associated with ammonia volatilisation, nitrification and denitrification. Some may be lost through leaching, although this would be uncommon in well-managed paddocks containing clay soils that are typical in the region.

6.1.1 Rule-of-thumb estimates of sowing soil nitrate

The calculations in ‘NBudget’ start with a rule-of-thumb estimate of soil nitrate at the time of sowing the previous season’s crop (Step 2 in Figure 5.2). This is instead of a soil test for nitrate. A look-up table containing a matrix of values, aggregated from published and unpublished data (Appendix 4), provides the estimate. The same approach was used to generate the rule-of-thumb soil nitrate values as was used for the in-crop and fallow mineralisation values in section 6.1.2 (Tables 6.1 and 6.2). A set of experimental data from the farming systems sites in northern NSW provided the core values which were then modified for paddock fertility and soil texture effects (more detail in section 6.1.2.). Part of that core data are presented as Figure 6.2. The graph shows clearly the effects of tillage and immediate paddock history on sowing soil nitrate levels.

Clearly, there is quite a bit of variation in the measured soil nitrate values for each of the scenarios in Figure 6.2. Only one value is used in ‘NBudget’, the average value. However, in the following step in ‘NBudget’ (Step 3), specific crop data for the particular paddock is inserted (yield, protein and fertiliser N input) and an adjustment will automatically be made at this stage to counter a low estimate of soil nitrate in Step 2.

FIGURE 6.1 **The cycling of N from one crop to the next. The figure shows that the pool of nitrate available for this season’s crop is the sum of N mineralised from previous crop residues, from humus (soil organic matter) and unused nitrate from the previous crop. If the paddock had been used for grazing animals, there would be a fourth source i.e. dung and urine**

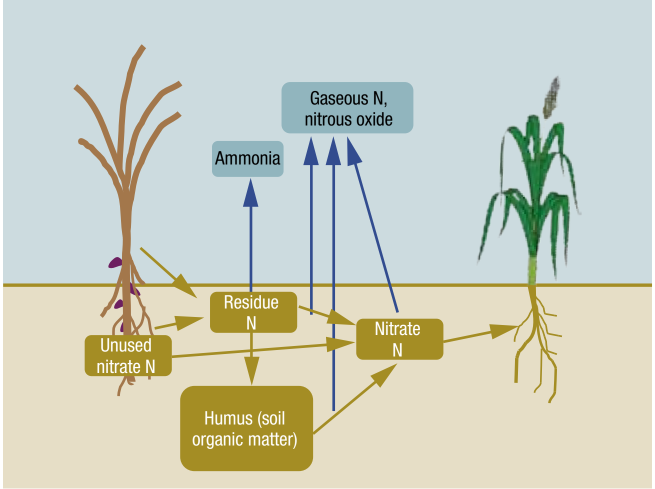
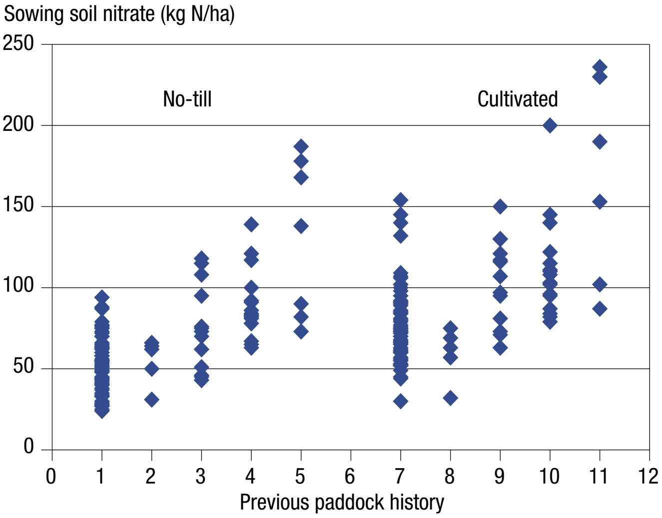


FIGURE 6.2 **Data from the NSW DPI long-term farming systems trials in northern NSW showing effects of tillage and paddock history on soil nitrate levels at sowing**



Codes for previous paddock history: 1–5 no till and 7–11 cultivated
1 & 7 = cereal with 0–40 kg fertiliser N/ha; 2 & 8 = cereal with 50–100 kg fertiliser N/ha;
3 & 9 = cereal with >100 kg fertiliser N/ha; 4 & 10 = pulse; 5 & 11 = no crop/long fallow

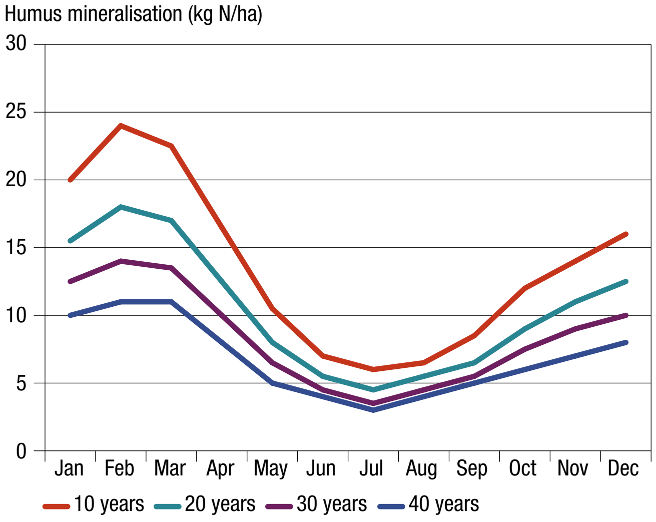
SOURCE: Unpublished data of W Felton, H Marcellos, DF Herridge and GD Schwenke

6.1.2 Mineralisation of humus

‘NBudget’ contains a matrix of values for the mineralisation of soil humus for the different soil types, paddock fertilities (reflecting management and histories) and tillage practice. The values feature in the calculations of soil nitrate in Step 3. The starting points were APSIM simulations of potential rates of N mineralisation (J Turpin, personal communication) for the stations of Moree, Narrabri, Gunnedah, Walgett, Coonamble and Dubbo, average organic C levels for those districts (e.g. Figure 2.3) and the relative rates of N accretion for cultivated and no-tillage fallows (Appendix 2). Figure 6.3 shows the simulated potential monthly N mineralisation rates for Moree, Gunnedah and Narrabri.

The rates declined with increasing years of cropping in accordance with declining soil organic matter levels (refer to Figure 2.2). Values shown in Figure 6.3 are for a cultivated soil. These rates were potential rates, which were then adjusted for effects of low soil water and tillage practice. Potential rates were multiplied by 0.75 to account for moisture deficits (see also Cox and Strong 2008). Data from southern Queensland indicated N mineralisation in no-till fallows to be either the same as in cultivated fallows or marginally less, i.e. 5 to 25% reduction (Strong *et al.* 1996; Thomas *et al.* 2005, 2007a, b). In the northern NSW farming systems experiments, N mineralisation in the no-till fallows were reduced by an average 27% (Appendix 2). For 'NBudget', no-till fallows are calculated to mineralise N at 80% of the rate for cultivated fallows.

FIGURE 6.3 Monthly rates of potential N mineralisation for soils at Moree, Gunnedah and Narrabri, NSW, showing effects of years of cropping. Values were subsequently modified for moisture stress and tillage effects. Values generated using APSIM



SOURCE: J Turpin, personal communication

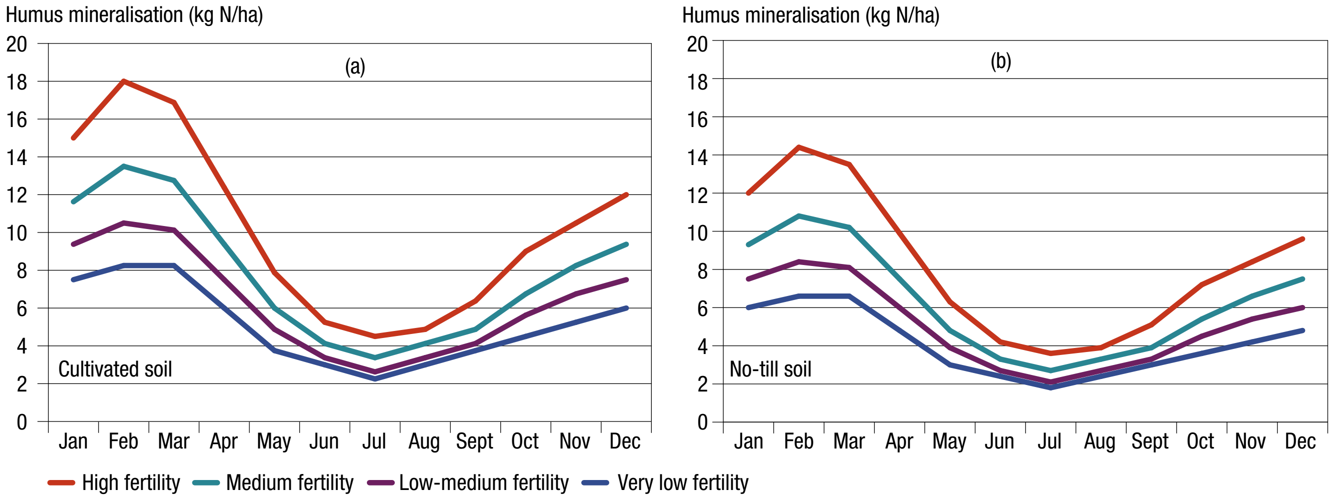
Using data on soil organic carbon as a guide, e.g. Figure 2.3, the APSIM-generated values for 10, 20, 30 and 40 years of cropping were equated to paddocks with high, medium and low-medium and very low fertility status.

This relativity was used in developing monthly rates of N mineralisation (Figure 6.4). Note that these values are for the mineralisation of native soil organic matter, i.e. humus. They have not been adjusted for the residues of the previous crop (see section 6.1.3).

The process to cover a broader group of 22 stations, from Dubbo, NSW, in the south to Roma, Queensland, in the north was as follows for the original Excel-based 'NBudget' calculator. The rationale was that typical soil organic matter levels varied across the region, with the highest levels found in the higher-rainfall zones to the east and the lowest levels in the drier western areas (Dalal and Chan 2001; see also Figure 2.3). Thus, the stations were grouped into three groups, based on rainfall data (Appendices 12 and 13), published and unpublished soil organic matter data and, to a lesser extent, soil type.

In the revised web-based 'NBudget', the major factors determining N mineralisation rates are soil type and paddock fertility, the latter reflecting length of cropping and management, rather than rainfall. A clay soil is defined as one with more than 35% clay; a red-brown earth with 20 to 35% clay and a sand, sandy-loam with less than 20% clay. The reason for the change was the poor predictive capacity of the original 'NBudget' in the

FIGURE 6.4 Monthly rates of N mineralisation of humus in (a) cultivated and (b) no-till soils of varying levels of fertility for the mid-range stations, Moree, Gunnedah, Narrabri (NSW) and Goondiwindi and Roma (Queensland). See boxed text overleaf for descriptions of the fertility status of the soils.



Basic assumptions

The APSIM simulations monthly rates of mineralisation of soil organic matter in cultivated soils were multiplied by 0.75 to account for moisture limitations. Rates of mineralisation of N for no-till soils were assumed to be 80% of the rates for cultivated soils (Appendix 2).

Paddock descriptions

High fertility – high use of lucerne/legume pasture leys, pulses and fertiliser N; high-level management
Medium fertility – short cropping history and/or moderate-high use of pulses and fertiliser N
Low-medium fertility – long cropping history, low-moderate use of fertiliser N
Very low fertility – long cropping history, low inputs of fertiliser N

High N fertility – equivalent to 10 years' cropping in APSIM simulations
Med N fertility – equivalent to 20 years' cropping in APSIM simulations
Low-medium N – fertility equivalent to 30 years' cropping in APSIM simulations
Very low N – fertility equivalent to 40 years' cropping in APSIM simulations

Paddock descriptions and soil organic C (%) levels

Quirindi, Croppa Creek, Dalby, Warialda, Inverell, Tamworth – 1.8 (High), 1.3 (Med), 1.0 (Low-medium), 0.8 (Very low)
Gunnedah, Moree, Narrabri, Goondiwindi, Roma – 1.3 (High), 1.0 (Med), 0.8 (Low-medium), 0.7 (Very low)
Walgett, Dubbo, Coonamble, Coonabarabran, St George – 0.9 (High), 0.7 (Med), 0.55 (Low-medium), 0.4 (Very low)

drier, western parts of the grainbelt, i.e. Walgett and Coonamble areas.

The outcome of all of the above are the two look-up tables for fallow and in-crop rates of N mineralisation of humus, one for winter cropping and one for summer cropping (Tables 6.1 and 6.2).

With winter cropping, in-crop is the period June to October inclusive. The fallow is November to May inclusive. Long fallow, when moving from summer to winter cropping, is calculated as the 12 months of mineralisation. In the case of summer cropping, in-crop is November to February inclusive and the winter fallow is March to October inclusive. Long fallow, when moving from winter cropping to summer cropping, is November to October inclusive (12 months).

6.1.3 Mineralisation of fresh crop residues

'NBudget' deals with the mineralisation of fresh crop residues by assuming that 65 to 70% of the calculated residue carbon (C) is respired during the post-crop fallow, with the remaining 30 to 35% locked into stable soil organic matter with a C:N ratio of 11:1 (Ladd 1987). Depending on the C:N ratio of the fresh residues (Figure 6.5), mineral N will either be released during the fallow, as with low C:N residues, or immobilised in the case of high C:N ratio residues.

Residue decomposition is actually part of the breakdown of organic compounds in the soil by the soil microflora and fauna with the specific aim of obtaining energy, i.e. carbon (C), for respiration. Secondary to carbon utilisation is the release of nutrients, primarily mineral N, into the soil.

The rate at which the residues decompose depends

TABLE 6.1 Winter cropping in-crop and fallow N mineralisation values for the three soil types in 'NBudget', adjusted for tillage practice and paddock fertility

Soil fertility	No-till			Cultivated		
	Clay soil	Red-brown earth	Sand, sandy-loam	Clay soil	Red-brown earth	Sand, sandy-loam
In-crop N mineralisation (June – October)						
Very low	17	14	10	21	17	13
Low-medium	20	15	12	25	19	15
Medium	24	18	14	30	23	18
High	32	24	18	40	30	23
Fallow N mineralisation (November – May)						
Very low	47	36	28	59	45	35
Low-medium	59	46	35	74	57	44
Medium	74	56	44	92	70	55
High	96	74	58	120	93	72
Long fallow N mineralisation						
Very low	64	50	38	80	62	48
Low-medium	80	61	47	100	76	59
Medium	98	74	58	122	93	73
High	128	98	76	160	123	95

TABLE 6.2 Summer cropping in-crop and fallow N mineralisation values for the three soil types in 'NBudget', adjusted for tillage practice and paddock fertility

Soil fertility	No-till			Cultivated		
	Clay soil	Red-brown earth	Sand, sandy-loam	Clay soil	Red-brown earth	Sand, sandy-loam
In-crop N mineralisation (November – February)						
Very low	28	22	17	35	27	21
Low-medium	35	27	22	44	34	27
Medium	45	34	26	56	43	33
High	58	45	34	72	56	43
Winter fallow N mineralisation (March – October)						
Very low	36	28	22	45	35	27
Low-medium	43	34	26	54	42	33
Medium	54	41	32	67	51	40
High	70	54	42	87	67	53
Long fallow (summer-winter) N mineralisation (November – October)						
Very low	64	50	38	80	62	48
Low-medium	78	61	48	98	76	60
Medium	98	75	58	123	94	73
High	127	98	77	159	123	96

FIGURE 6.5 Carbon to nitrogen (C:N) ratios of wheat, chickpea and faba bean residues, animal manure, soil particulate organic matter (POM) and soil organic matter (SOM)

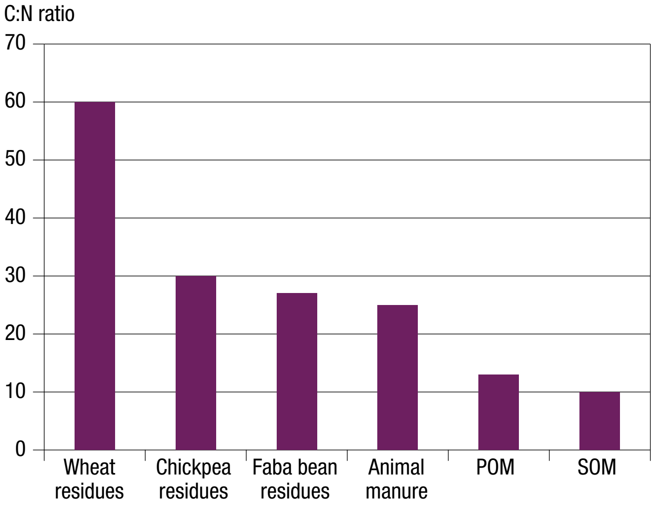


TABLE 6.3 Examples of the amounts of N released or immobilised during the mineralisation of residues during the summer fallow

Crop	Grain yield (t/ha)	Grain protein (%)	Residue N (kg/ha)	% residue C retained in soil	N immobilised or released from residues (kg/ha)
Wheat	3.0	11.5	57	30	-21
Barley	4.0	10.0	46	30	-33
Chickpeas	1.9	21.8	110	35	+13
Faba beans	2.4	23.9	90	35	+16
Canola	1.5	26.0	90	35	+16

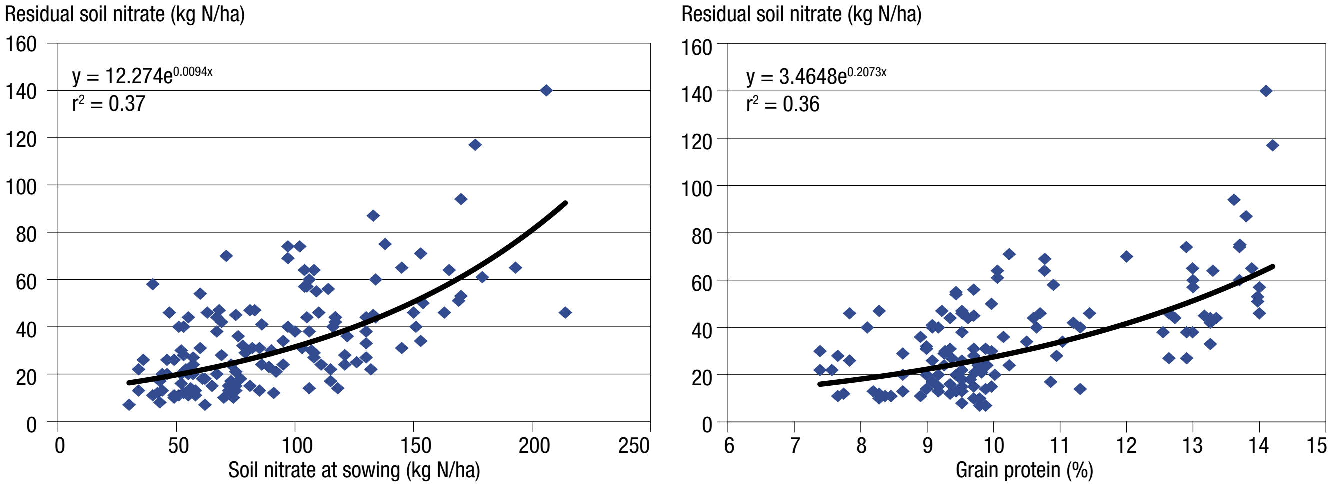
on temperature and moisture conditions (generally the higher the better), on their carbon to nitrogen (C:N) ratio and on other residue quality aspects such as lignin and polyphenol contents. The C:N ratio also determines whether mineral N is released from the residues or immobilised. Generally, residues of crops such as wheat with C:N ratios of greater than 30 will immobilise soil mineral N while residues with C:N ratios of less than 30 will release mineral N into the soil.

Examples of the amounts of mineral N either released or immobilised from residues of winter crops are shown in Table 6.3. The grain yields and proteins are considered to be typical of well-grown crops in the northern grains region. 'NBudget' calculated the cereal residues to immobilise 21 to 33 kg N/ha during the summer fallow, versus the net release of 13 to 16 kg N/ha for the pulses and canola. The set of linked equations that are used in the estimations of immobilisation/release of N can be found in Appendices 10 and 11.

The other factor affecting the rate of residue decomposition is the soil-residue contact. Thus, residue incorporation with tillage in soil may lead to an increased rate of breakdown. This may be more of an issue for the cereal residues than for legume residues. Schomberg *et al.* (1994) showed four- to five-fold differences in breakdown rates between surface and incorporated residues of wheat and sorghum, but only marginal differences for lucerne. However, the assumption is made with 'NBudget' that the dynamics of residue breakdown is unaffected by tillage system.

There are two ways in which the amount of residue N left in the soil after grain harvest is calculated in 'NBudget'. The first way is by combining grain yields and proteins with N harvest index (NHI) (Appendix 8) and

FIGURE 6.6 Not all of the nitrate in the top 1.2m of soil will be used by growing crops. The graphs show for wheat cropping how residual soil nitrate increases with increased soil nitrates at sowing and with increased grain proteins



SOURCE: Unpublished data of W Felton, H Marcellos, DF Herridge and GD Schwenke

below-ground N values (see Chapter 3.1.1) to calculate residue N (Appendices 10 and 11). The second way takes advantage of the strong relationship, consistent across different crops, between grain protein levels and the %N concentration of the crop residues (Appendix 3). The values computed in 'NBudget' using each of the methods are combined to calculate an average value, which is then used in the calculation of N either immobilised or released to the soil during the post-crop fallow (Appendices 10 and 11). Also in Appendix 3 is a table comparing residue N estimates for the northern grainbelt winter crops using both methods.

6.1.4 Unused (spared) soil nitrate

For consistency, the root zone is considered to be the top 1.2 m soil (see Chapter 2.5). The annual crops readily utilise nitrate N in the top 0.9 m but not always with the same efficiency in the next 30 cm layer, i.e. 0.9 to 1.2 m depth. Thus, nitrate is not used for crop growth and can remain in the soil at these depths in the absence of water leaching through the profile (Figure 2.8).

The efficiency with which crops use soil nitrate from throughout the root zone also varies (nitrogen use efficiency – NUE; see Chapter 6.4). As sowing soil nitrate levels increase, the crop finds it progressively more difficult to access enough water (either already stored in the soil or through in-crop rainfall) to make use of it (Figure 6.6). Thus, more and more soil nitrate is left unused by the growing crop. The graphs above show clearly the increase in residual soil nitrate as sowing soil nitrate levels increase. The relationship between grain proteins and residual soil nitrate is similar.

It was difficult to fully account for the unused (spared)

TABLE 6.4 N dynamics of a chickpea–wheat rotation compared with unfertilised or N-fertilised wheat-only sequences. Estimated values were derived from 'NBudget' (in bold). Measured values are the means of no-till and cultivated treatments at two sites in northern NSW

	Chickpea – wheat 0N	Wheat 0N – wheat 0N	Wheat 100N – wheat 0N
Year 1 (wheat or chickpeas)			
Sowing soil nitrate (kg N/ha, 1.2 m depth)	67	67	67
Fertiliser N applied (kg N/ha)	0	0	100
Grain yield (t/ha)	2.3	2.3	3.2
Total crop N (kg /ha)	205	55	115
Estimated residue N (kg/ha)	**133**	**20**	**55**
Estimated residue C:N	**25:1**	**50:1**	**44:1**
Summer fallow			
Estimated min or immobil residues (kg N/ha)	**+16**	**–22**	**–21**
Estimated native SOM mineralisation (kg N/ha)	**75**	**75**	**75**
Estimated spared N (kg N/ha)	**14**	**11**	**45**
Year 2			
Estimated sowing soil nitrate (kg N/ha)	**105**	**64**	**98**
Measured Sowing soil nitrate (kg N/ha)	102	53	74

SOURCE: Herridge *et al.* 1995; unpublished data of W Felton, H Marcellos, DF Herridge and GD Schwenke

N in 'NBudget'. The simplest solution was to ensure that estimated soil nitrate at harvest in Step 3 (Last season) was at least 20 kg N/ha. If it was less than 20 kg N/ha, the deficit was calculated (value shown in Step 2 – Adjustment if necessary) and this amount added to other values to estimate post-fallow soil nitrate (Step 4).

6.1.5 Mineralisation of animal dung and urine

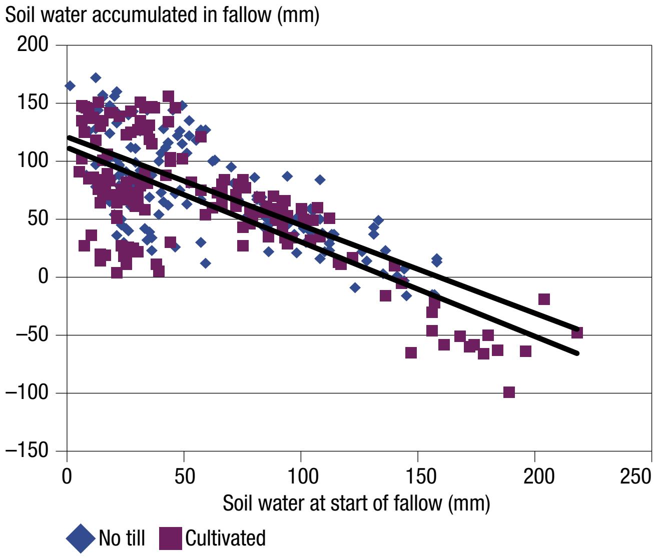
At this stage, there is no facility in 'NBudget' for including animal dung and urine as sources of N for crops. For information on the release of mineral N from organic fertilisers see Chapter 4.2.2.

6.1.6 Net mineralisation of nitrogen

Net mineralisation is a term to describe the net accumulation of nitrate N during a particular period of time. With winter cropping, most net mineralisation occurs during the summer fallow. With summer cropping, it occurs in-crop. Net mineralisation is the sum of the mineral N released from previous crop residues and humus minus the N immobilised or lost as gaseous emissions and leaching.

Net mineralisation for the summer fallow in the northern grainbelt is calculated as the difference between soil nitrate at sowing in May–June and harvest of the previous crop. In Table 6.4, the same data set from the NSW DPI farming systems experiments that featured in Tables 3.10, 3.11 and 5.1 is put through 'NBudget' to demonstrate the relative importance of the different sources of N in the accumulation of mineral N during the summer fallow. Estimated amounts of N released or immobilised from residues, released from the mineralisation of humus and spared are shown. With the fertilised and unfertilised wheat, N was immobilised as the residues decomposed. There was a calculated net release of 16 kg N/ha from the chickpea residues. The estimated amounts of post-fallow soil nitrate were very close to the measured values for chickpeas and the unfertilised wheat and slightly more for the fertilised wheat.

FIGURE 6.7 Effects of stored water at the start of the summer fallow on the efficiency with which water accumulates in the soil during the fallow



Lines of best fit are described by:
$y = -0.76x + 121.0$, $r^2 = 0.49$ (no-till) and
$y = -0.81x + 111.8$, $r^2 = 0.56$ (cultivated)

SOURCE: Herridge *et al.* 1995; Felton *et al.* 1998; Marcellos *et al.* 1998; unpublished data of W Felton, H Marcellos, DF Herridge and GD Schwenke

6.2 Fallowing efficiency to store soil water

The amount of plant-available water (mm) in the soil at sowing is required in Step 4 in 'NBudget' for the estimation of crop yields for the coming season (Step 6). Plant-available soil water at sowing is added to projected in-crop rainfall (average monthly totals taken from the Bureau of Meteorology (BoM) website, see section 6.9, Appendices 12 and 13) to determine total water availability. Total water is then inserted into the equation describing water use efficiency (WUE) to predict crop yield (see next section).

There are three options in 'NBudget' for estimating soil water at sowing. The first uses fallow rainfall and a fallow efficiency (see more details below). The second uses depth of wet soil (push probe) and a conversion factor to account for soil texture, i.e. to determine millimetres of plant-available water, multiply centimetres of wet soil by 1.8 for black clay, 1.5 for grey clay and 1.0 for a red-brown earth. The third option is to insert a value, determined from soil testing or from the use of other tools, such as HowWet?

Fallowing efficiency is variable. For example, analysis of 12 site x years of data from the NSW DPI winter cropping experiments at North Star in northern NSW indicated soil water at the start of the summer fallow (i.e. wetness of the soil) had a huge influence on the efficiency with which water was stored in the soil during the fallow (Figure 6.7). The no-till system was more efficient than the cultivated system.

These data confirm previous work of Freebairn and colleagues in south-eastern Queensland (see for example Freebairn and Wockner 1986). Freebairn *et al.* (1997) highlighted the dominant effects of the moisture condition of the soil on water infiltration and run-off. Compared to a dry soil, reductions in infiltration were 20% for a moderately dry soil, 50% for a wet soil and 70% for a very wet soil. They also showed the benefits of stubble cover and no-till to increase water infiltration and reduce run-off.

The large effect of soil water at the start of the fallow on fallowing efficiency, as well as other less important factors such as fallow temperatures and rainfall patterns, meant that there was substantial variation in measured efficiencies amongst the 12 site years of NSW DPI data (Appendix 5). The average summer fallow efficiencies, termed apparent fallow efficiencies, were 0.31 for no-till and 0.28 for cultivated fallows. These values were calculated as stored plant-available water (mm) to 1.2 m depth of soil at the end of the summer fallow divided by fallow rainfall and did not account for soil water at the start of the fallow.

Apparent fallow efficiency
= plant available soil water at end of fallow ÷ fallow rainfall

TABLE 6.5 Calculating soil water at sowing for no-tillage and cultivated fallows in the northern grainbelt using recorded fallow rainfall data (see Appendix 5)

Fallow rainfall (mm)	Stored soil water at end of fallow (sowing) (mm)	
	No tillage	Cultivated
100	31	28
200	62	56
300	93	84
400	124	112
500	155	140
600	186	168

TABLE 6.6 Efficiency with which additional (future) rainfall is stored in the soil for no-tillage and cultivated fallows in the northern grainbelt (see Appendix 5)

Fallow rainfall (mm)	Stored soil water at end of fallow (sowing) (mm)	
	No tillage	Cultivated
25	4	4
50	9	7
75	13	11
100	17	14
125	21	18
150	26	21

TABLE 6.7 Relative yields and water use efficiencies for the major winter and summer crops in the northern grainbelt

Winter crops	Relative yields	WUE^1	Summer crops	Relative yields	WUE*
Wheat	100	12.5	Sorghum	100	16.0
Durum	105	13.1	Sunflowers	35	5.6
Barley	133	16.6	Mungbeans	25	4.0
Canola	50	6.3	Soybeans	30	4.8
Chickpeas	64	8.0			
Faba beans	80	10.0			

1 WUE after subtracting the first 100mm to account for evaporation

Values were aggregated from published and unpublished data of the Queensland and NSW DPI farming systems programs, other published experiments in the region (e.g. Herridge and Holland 1992, Kirkegaard *et al.* (2004), Thomas *et al.* (1995, 2007a) and Wylie (2008), GD Schwenke, personal communication) and National Variety Trial (NVT) reports.

These values were very similar to the average values of 0.33 (no-till) and 0.31 (cultivated) of Thomas *et al.* (1995) for winter cropping at Billa Billa in southern Queensland. Average fallowing efficiencies for the winter fallows (summer cropping) in the Billa Billa trials were 0.27 for both no-till and cultivated soils.

Real fallow efficiencies (actual water stored in the soil profile during the fallow divided by fallow rainfall) were, on average, 0.17 (no-till) and 0.14 (cultivated) (Appendix 5).

Real fallow efficiency
= change in plant available soil water during fallow ÷ fallow rainfall

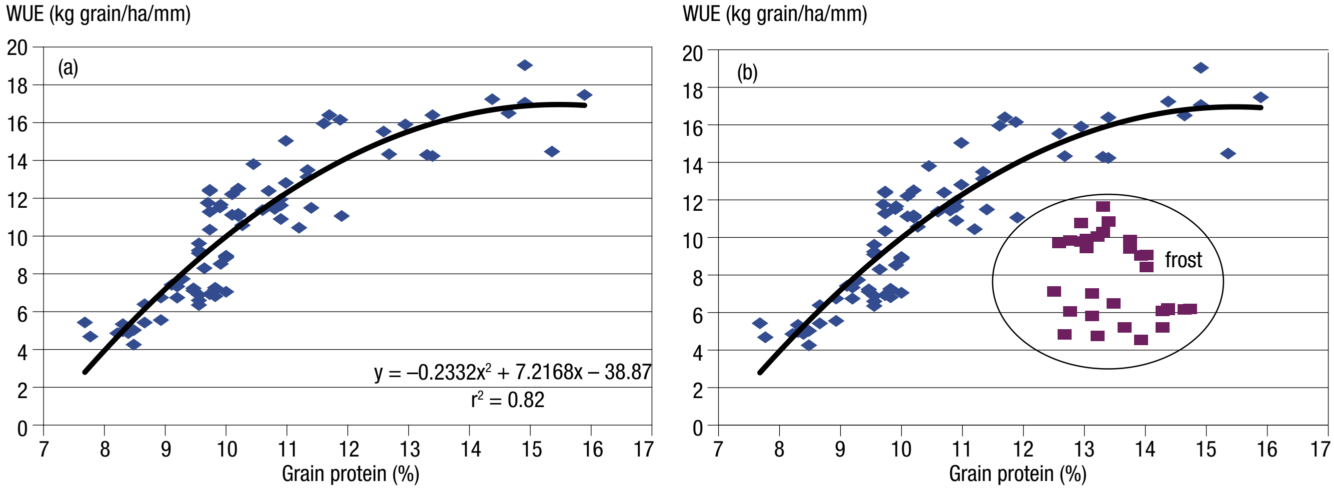
These values are also supported by data from southern Queensland. Thomas *et al.* (2007a) reported summer fallow efficiency values for farming systems trials at Nindigully in the Western Downs of south-west Queensland of 0.16 and 0.13.

Both the apparent and real fallow efficiency values are used in different ways in 'NBudget'. Apparent fallow efficiencies, i.e. 0.31 (no-till) and 0.28 (cultivated), are used to estimate stored soil water at the end of the fallow, i.e. at sowing. The only input is a total fallow rainfall value (Table 6.5). If an estimate of sowing soil water is required some time before the end of the fallow, fallow rainfall up to that point of time is used to estimate stored soil water. The real fallow efficiency values, i.e. 0.17 (no-till) and 0.14 (cultivated), are then applied to the BoM rainfall data for the rest of the fallow to estimate how much of that rainfall will be stored in the soil (Table 6.6). The sum of the two estimates is the predicted sowing soil water.

6.3 Converting soil water into grain

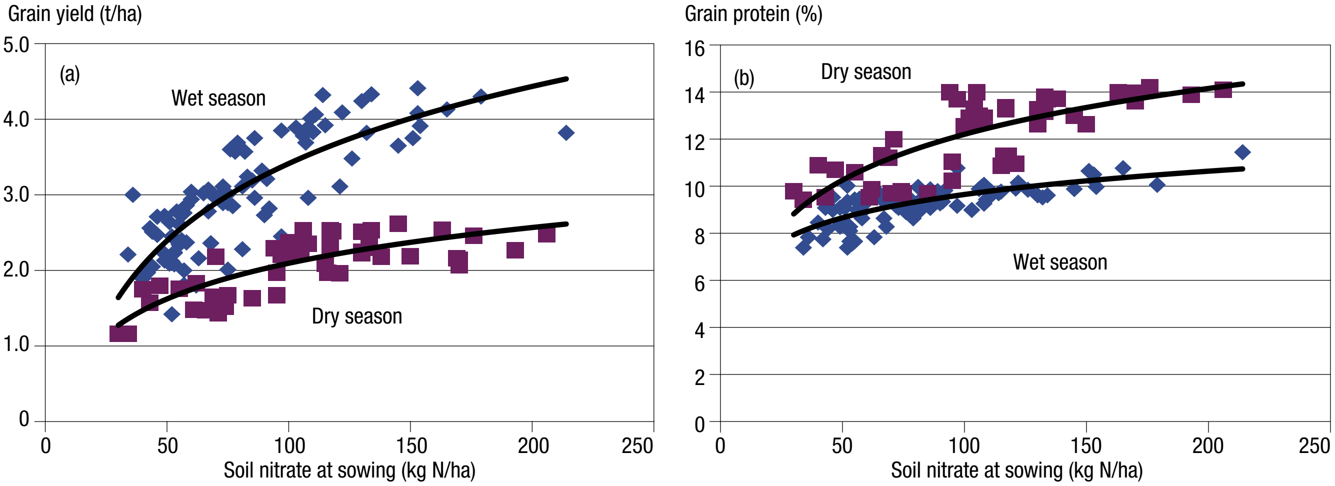
Much has been written about crop water use efficiency (WUE) since the groundbreaking work of French and

FIGURE 6.8 Data showing the (a) relationship between grain protein and WUE for wheat and (b) damaging effects of frost on WUE



SOURCE: Unpublished data from the NSW DPI long-term farming systems experiments in northern NSW of W Felton, H Marcellos, DF Herridge and GD Schwenke

FIGURE 6.9 **Levels of soil nitrate at sowing affect (a) grain yield and (b) proteins in wheat in the northern grainbelt. In the wetter seasons, yields increased with increasing nitrates while grain proteins remained relatively low. The reverse occurred in the drier seasons.**



SOURCE: Unpublished data from the NSW DPI farming systems trials in northern NSW, W Felton, H Marcellos, DF Herridge and GD Schwenke

Schultz (1984). They reported a maximum (potential) WUE value for wheat of 20 kg grain/ha/mm plant-available water after 110 mm was subtracted to account for evaporation. More recent reports (e.g. Hochman *et al.* 2009a) indicate that growers across a range of production regions and systems are achieving an average WUE of 15.2 kg wheat grain/ha/mm (with x intercept of 67 mm). As part of that study, scenario analysis using APSIM highlighted the importance of optimising plant density, sowing date and N supply for further improving WUE. Therefore:

Water use efficiency (kg/ha/mm)
= grain yield (kg/ha) ÷ (crop water supply – soil evaporation (mm))

Positive effects of increasing N supply (to increase grain proteins) on WUE of wheat were evident in the data from the NSW DPI farming systems experiments in northern NSW (Figure 6.8a). Even with optimised agronomy, other factors reduce WUE, such as disease and pest damage, extremes of temperature (high and low) and high vapour pressure deficits particularly during anthesis and post anthesis. The effect of frost on WUE is highlighted in Figure 6.8b.

The WUE value for bread wheat in ‘NBudget’ was aggregated from a number of published and unpublished data sources and set at 12.5 kg grain/ha/mm after subtracting 100 mm for evaporation (Table 6.7). Water use efficiencies for the other crops were calculated by multiplying the estimated wheat yields by constants – 1.10 for durum, 1.33 for barley, 0.50 for canola, 0.64 for chickpeas and 0.80 for faba beans – using data from published experiments in which all or some of these crops were grown. Data on relative yields were also sourced from the National Variety Trial (NVT) program. A similar approach was taken to calculate the values for the summer crops.

Note that the WUE values in Table 6.7 are for crops following a short fallow. Wheat, durum, barley and sorghum are also grown in the northern grainbelt after a long (i.e. 12- to 15-month) fallow as the cropping is changed from summer to winter and vice versa. In these cases, substantially more water will be stored deeper in the soil and may be used by the growing crop to produce grain with greatly improved efficiency (Kirkegaard *et al.* 2007). Hard evidence for this is elusive; however, it warrants further investigation.

6.4 Converting nitrate N into crop and grain N

For the cereal and oilseed crops in the northern grainbelt, soil nitrate levels strongly influence yields and proteins (or grain oil contents in the case of the oilseed crops). Just how soil nitrate can influence either grain yield or protein or both is shown using data from northern NSW (Figure 6.9). In the wet seasons with high in-crop rainfall, there was a strong relationship between soil nitrate at sowing and grain yield. Grain proteins at these sites remained relatively low, i.e. between about 8 and 11%.

With the second group of (dry season) sites, the reverse occurred. Grain yields responded only weakly to increased soil nitrate levels at sowing, but there was a

TABLE 6.8 Efficiencies of nitrate use for wheat in the northern grainbelt. Values calculated from the graphs in Appendix 6.

Grain protein (%)	NUE (kg grain N/kg sowing nitrate N)	Agronomic efficiency (kg grain/ kg nitrate N)	Kg nitrate N/tonne grain
9	0.66	41	24
10	0.58	33	31
11	0.51	27	39
12	0.44	22	48
13	0.39	18	59
14	0.34	14	73

FIGURE 6.10 **With increasing grain protein levels in wheat, relatively more soil nitrate N is unused by the crop and less finishes up in the grain**

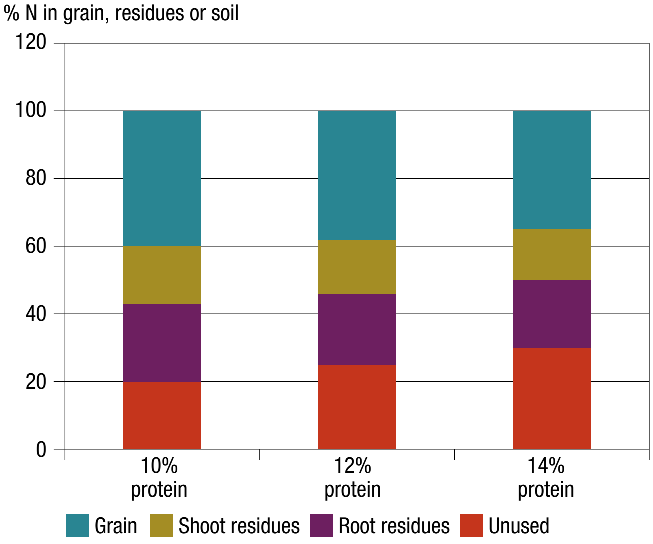


TABLE 6.9 Values for soil nitrate levels at sowing (kg N/ha to a depth of 1.2m) required to grow wheat crops for the designated yields and proteins. Values calculated from the graphs in Appendix 7.

Grain yield (t/ha)	Grain protein (% @ 12% moisture)					
	9	10	11	12	13	14
1	24	30	37	47	60	75
2	47	60	75	94	120	150
3	71	90	112	140	178	225
4	94	120	150	188	237	300
5	118	148	187	235	297	375
6	140	178	224	282	356	450

TABLE 6.10 Values for soil nitrate levels at sowing (kg N/ha to a depth of 1.2 m) required to grow barley crops for the designated yields and proteins. Values calculated from the graphs in Appendix 7 adjusted for 0% grain protein.

Grain yield (t/ha)	Grain protein (% @ 0% moisture)					
	8	9	10	11	12	13
1	15	19	23	28	35	43
2	31	38	46	57	70	86
3	46	56	69	85	105	130
4	61	75	93	114	140	172
5	77	94	116	142	175	215
6	92	113	140	170	210	260

TABLE 6.11 Values for soil nitrate levels at sowing (kg N/ha to a depth of 1.2 m) required to grow sorghum crops for the designated yields and proteins

Grain yield (t/ha)	Grain protein (% @ 13% moisture)					
	6	7	8	9	10	11
2	20	26	32	42	54	72
3	30	40	52	63	84	108
4	40	52	64	84	108	144
5	50	65	80	105	135	180
6	60	78	104	126	168	215
7	70	90	112	147	190	250

much stronger response in grain proteins, i.e. up to 14% at nitrate levels of 200 kg N/ha.

Clearly, at both groups of sites, soil nitrate is driving productivity, with the effects showing up in slightly different ways. Whether increasing soil nitrate leads to increasing yields or proteins will depend to a large extent on the availability of water. In-crop rainfall for the first group of yield-responsive sites was, on average, 304 mm versus just 178 mm for the non-responsive sites.

Nitrogen use efficiency (NUE) describes the conversion of soil nitrate-N into grain N. Knowing that, the amount of soil nitrate required to grow a crop with a certain yield and protein content can be predicted.

Nitrogen use efficiency is defined in a number of ways. The definition used here is somewhat consistent with that of Higgins and Pan (1993, quoting Moll *et al.* 1982) who defined it as grain production per unit available soil N. There is no accounting here for soil nitrate mineralised in-crop and therefore available for grain production or for the nitrate present at sowing that might be lost (and unavailable) during crop growth. Thus, NUE is calculated as unit of grain N per unit of sowing soil nitrate-N.

As the relative availability of soil nitrate to soil water increases and grain proteins increase, NUE decreases. The relationship between grain proteins and NUE for wheat is shown in Appendix 6. Also in Appendix 6 is a graph showing the relationship between grain proteins and agronomic efficiency, i.e. the efficiency with which soil nitrate is converted into grain biomass. Table 6.8 details values for NUE and agronomic efficiency for wheat, calculated using the functions in the figures in Appendix 7. The table clearly shows the declining efficiencies with increasing grain proteins.

Why does the NUE decline as sowing soil nitrate levels and grain proteins increase? To a large extent, it is to do with the efficiency with which soil nitrate is taken up by the crop (N-uptake efficiency). As sowing soil nitrate levels increase, the crop finds it progressively more difficult to access the water to make use of it. Thus, more and more soil nitrate is left unused by the growing crop, i.e. spared nitrate. This was discussed in more detail in section 6.1.4. A second and minor reason for the decline in NUE is the efficiency with which the crop partitions the N between the grain and other plant parts (physiological efficiency).

So, taking a 3 t/ha wheat crop, how much N (kg/ha) ends up in the grain, the shoot, the whole plant (including roots) and how much will generally be left in the profile after crop harvest can be calculated as follows:

- Grain N = Grain yield (t/ha) x %grain protein/5.7 x 10 (a value of 5.7 is used to convert grain %N to %grain protein);
- Shoot N = grain N/0.7 (the NHI for wheat is 0.7);

- Crop N = shoot N*1.4 (to convert shoot N into whole crop N, a multiplication factor of 1.4 is used (section 6.6.1)); and
- Residual N = $3.465*e^{0.207*\%\text{grain protein}}$ (see Figure 6.5).

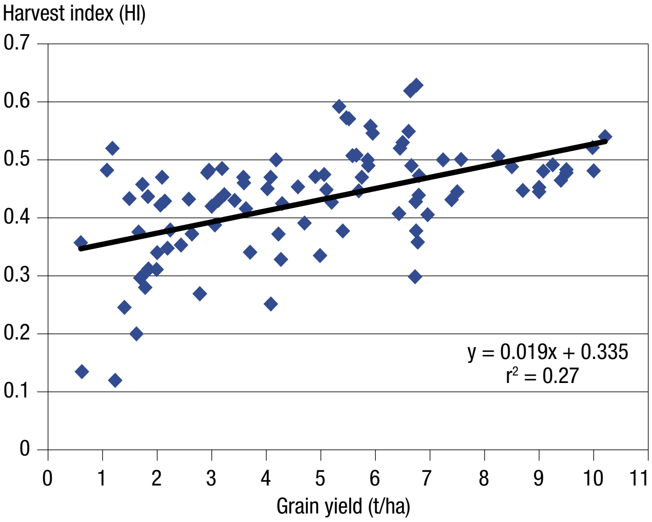
Values are shown in Figure 6.10. As grain proteins increase, progressively less of the N ends up in the grain (40% down to 35%) and progressively more is left unused in the soil (30% up to 40%).

What about the NUEs for the other major cereal crops, barley and sorghum? A comparison of wheat and barley data from the same experiments showed no difference in NUE between the two crops once the moisture content of the grain had been taken out as a factor. Note that grain proteins for wheat are commonly expressed at 12% moisture compared with 0% moisture for barley (receival standards). At the same grain protein levels, barley appears to be much more efficient at using soil N. Nitrogen use efficiencies for durum are assumed to be 7% higher than wheat, based on NVT data for 2007–09. The NUEs for sorghum were calculated to be slightly higher than for wheat.

Tables 6.9, 6.10 and 6.11 summarise amounts of soil nitrate at sowing that are required to grow the cereals crops, wheat, sorghum and barley, at certain yield and protein levels (see Appendix 7 for functions).

Additional nitrate will be released in-crop that is not accounted for. Remember also nitrate will usually be left unused by the crop at the high protein levels. For the practical management of N, these are irrelevant. What farmers need to know is how much soil nitrate is required at sowing for the particular crop they want to grow. If they know how much soil nitrate is already there, any shortfall can be made up with fertiliser N inputs.

FIGURE 6.11 Relationship between grain yield and harvest index (HI) for sorghum



SOURCE: Doughton and McKenzie 1984; Holland and Felton 1989; Herridge and Holland 1992; Kamoshita *et al.* 1998a, b, c; Armstrong *et al.* 2003; GD Schwenke, unpublished data

6.5 Converting grain %N into grain protein

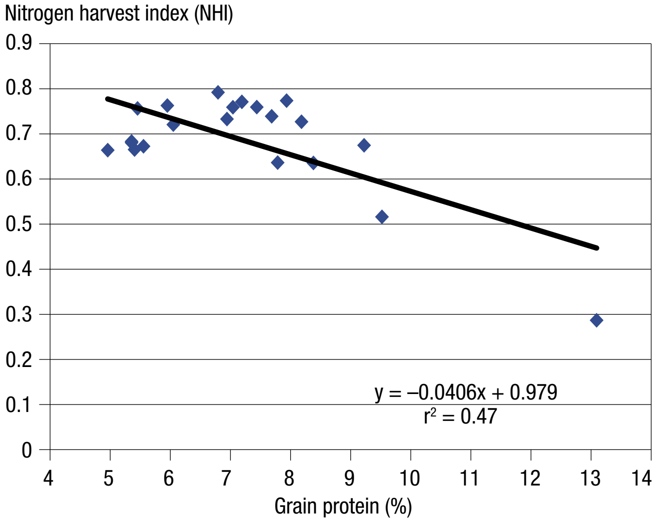
For the past 80 years, for all crops other than wheat, a factor of 6.25 has been used to convert grain %N to grain protein. This appears to be incorrect (see for example Mosse 1990). Tkachuk (1969) published N-to-protein conversion values for 18 cereal and oilseed materials (grains, flour etc.). The 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.

In the development of 'NBudget', grain proteins were determined from grain %N values and vice versa. Throughout, the standard conversion factors of 5.7 (wheat) and 6.25 (the remainder) were used. There appeared to be little choice on this because there needs to be consistency between the grain protein values in 'NBudget' and those in the farmer's world. It was assumed that grain-testing equipment and protocols were all

TABLE 6.12 Harvest indices for the major winter and summer crops of the northern grains region with estimates of shoot biomass, total crop biomass (shoot + roots) and total crop (shoot + roots) residues. All data are for average grain yields of the various crops. See Appendix 8 for HI values or functions describing HI.

Crop	Grain yield (t/ha)	HI	Shoot biomass (t/ha)	Total crop biomass (roots + shoots) (t/ha)	Residues (shoots + roots) (t/ha)
Winter crops					
Wheat	3.0	0.40	7.3	10.4	7.2
Durum	3.2	0.41	7.7	10.8	7.5
Barley	4.0	0.49	8.2	11.3	7.2
Chickpeas	1.9	0.39	4.9	9.7	7.5
Faba beans	2.4	0.40	5.9	8.3	5.8
Canola	1.5	0.28	5.4	7.5	5.8
Summer crops					
Sorghum	5.0	0.43	11.6	16.2	11.0
Sunflowers	1.7	0.44	3.9	5.4	3.6
Mungbeans	1.2	0.37	3.2	4.5	3.3
Soybeans	1.5	0.36	4.2	5.8	4.2

FIGURE 6.12 **Relationship between grain protein and nitrogen harvest index (NHI) for sorghum**



SOURCE: Doughton and McKenzie 1984; Herridge and Holland 1992; Kamoshita *et al.* 1998

calibrated using the standard conversion factors.

6.6 Partitioning of crop dry matter and N

6.6.1 Accounting for dry matter and N in roots and nodules

Total crop biomass and N are usually determined from measures of shoot material alone. Many consider that biomass, carbon (C) and N in the roots represent only small fractions (5 to 15%) of the total, and that estimates based on the shoots alone provide reasonable approximations of total crop biomass, C and N. This is not correct. A large number of studies have now been published showing that below-ground biomass, C and N associated with, or derived from, roots can represent 30 to 50% of total biomass, C and N for both legumes and cereals (see for example Buyanovsky and Wagner 1986; Russell and Fillery 1996; McNeill *et al.* 1997; Bolinder *et al.* 1997; Rochester *et al.* 1998; Unkovich and Pate 2000; Khan *et al.* 2002).

There is no single value for below-ground N, with variations in published estimates reflecting the influence of species, soil, climate, etc. (Unkovich *et al.* 2010). To account for below-ground biomass and N when calculating total crop N, residue N, crop N fixed etc., shoot N is multiplied by 2.0 for chickpeas (assumes 50% of plant N is below ground), 1.5 for soybeans (assumes 33% below-ground N) and 1.4 for the remainder of the grain legumes (assumes 30% below-ground N). To calculate total pasture/fodder legume N, shoot N is multiplied by 2.0 for lucerne, 1.7 for subterranean clover and 1.4 for the remainder. A factor of 1.4 is used for cereal crops. Although these are approximations, we believe that the errors associated with their use are far less than those incurred by ignoring below-ground N or by using values for physically recovered roots.

6.6.2 Harvest index - HI

Harvest index (HI) is defined as grain yield as a proportion of total above-ground biomass yield (Hay 1995). Harvest index will often increase with increasing yield. A good example is for sorghum (Figure 6.11).

Harvest index is used in 'NBudget' to calculate above-ground biomass from grain yield data (Appendices 10 and 11). Values and functions for calculating HI were derived from published and unpublished data, almost all of which was generated in the northern grainbelt (Appendix 8). Functions accounting for the effect of grain yield were used instead of set values if the relationships between grain yield and HI were statistically significant (see Appendices 8).

Table 6.12 shows biomass data for the winter and summer crops at typical yield levels. Shoot biomass was calculated as grain yield/HI. Then total crop (shoot + roots) biomass calculated as shoot biomass x 1.4 for all crops

TABLE 6.13 **Nitrogen harvest indices for the major winter and summer crops of the northern grains region with estimates of shoot N, total crop (shoot + roots) N and total crop (shoot + roots) residue N. Data are for average grain yields and proteins of the crops. See Appendix 8 for NHI values or functions describing NHI.**

Crop	Grain yield (t/ha)	Grain protein (%)	Grain N (kg/ha)	NHI	Shoot N (kg/ha)	Total crop (shoot + roots) N (kg/ha)	Residue (shoot + roots) N (kg/ha)
Winter crops							
Wheat	3.0	11.5	60	0.70	86	120	54
Durum	3.2	13.0	72	0.70	102	143	64
Barley	4.0	10.0	57	0.75	76	106	44
Chickpeas	1.9	21.8	59	0.67	88	176	108
Faba beans	2.4	23.9	82	0.64	128	180	88
Canola	1.5	24.0	51	0.55	93	130	73
Summer crops							
Sorghum	5.0	9.5	76	0.59	128	180	94
Sunflowers	1.7	16.0	44	0.65	69	96	47
Mungbeans	1.2	24.0	46	0.70	66	92	40
Soybeans	1.5	38.0	91	0.73	125	174	75

except chickpeas (x 2) and soybeans (x 1.5). Finally, total residue biomass (including roots) was calculated as the difference between the biomass of the whole crop (including roots) and harvested grain (at 0% moisture). There is an allowance for a loss of 5% of crop biomass.

6.6.3 Nitrogen harvest index (NHI)

Nitrogen harvest index (NHI) is defined as grain N as a proportion of total above-ground biomass N. Nitrogen harvest index, unlike HI, does not respond positively to increasing yield. Rather, it tends to decline with increasing grain protein levels. Figure 6.12 shows the negative relationship between grain proteins and NHI.

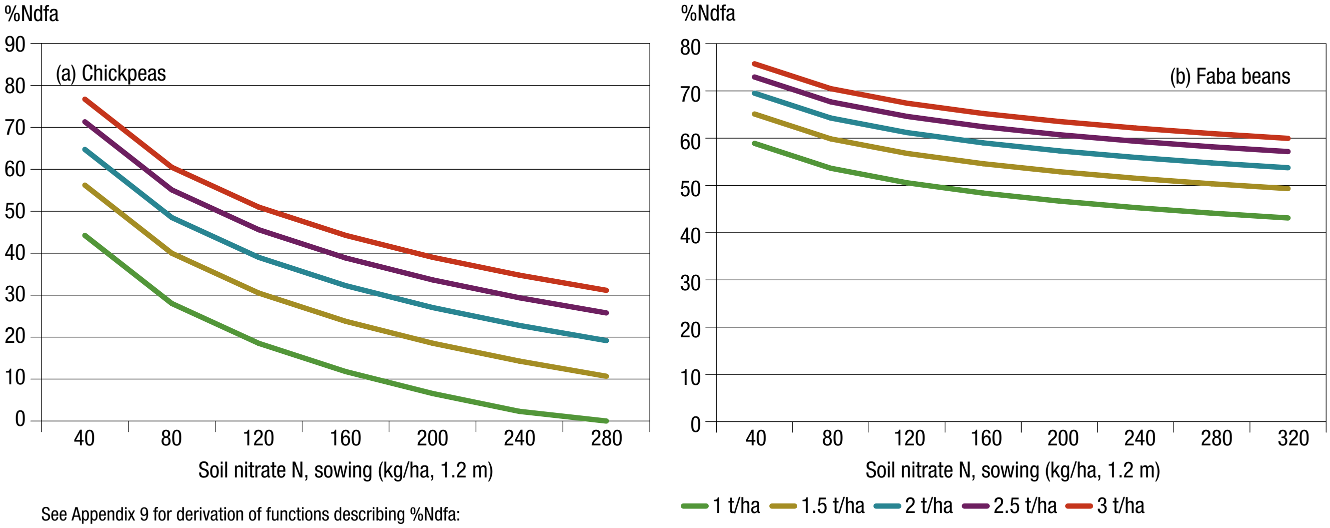
Nitrogen harvest index is used in 'NBudget' to calculate above-ground biomass N from grain proteins (Appendices 10 and 11). As with HI, values and functions for calculating NHI were derived from published and unpublished data, almost all of which were generated in the northern grainbelt (Appendix 8). Functions accounting for the effect of grain proteins were used instead of set values if the relationships between grain yield and HI were significant.

Table 6.13 shows N data for the winter and summer crops at typical yield levels. Shoot biomass N was calculated as grain N/NHI. Then total crop biomass (shoot + roots) N calculated as shoot biomass N x 1.4 for all crops except chickpeas (x 2) and soybeans (x 1.5). Finally, total residue biomass N (including roots) was calculated as the difference between the biomass N of the whole crop (including roots) and harvested grain (at 0% moisture). There is an allowance for a loss of 5% of crop biomass N.

6.7 Legume N_2 fixation

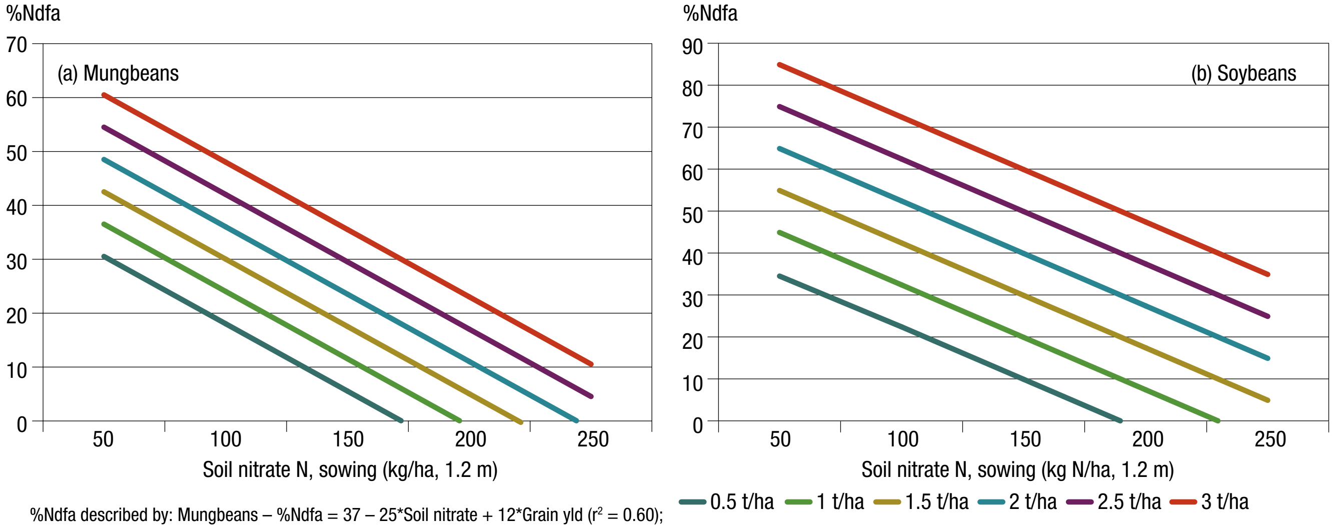
The amount of N that a legume crop or pasture fixes can vary enormously, between zero to more than 400 kg N/ha. The factors accounting for such variations

FIGURE 6.13 Values for %Ndfa for (a) chickpeas and (b) faba beans at different levels of sowing soil nitrate and grain yield



See Appendix 9 for derivation of functions describing %Ndfa:
Chickpeas – %Ndfa = 130.6 – 23.4*Ln Soil nitrate + 29.6*Ln Grain yld ($r^2 = 0.60$); Faba beans – %Ndfa = 86.9 – 7.6*Ln Soil nitrate + 15.3*Ln Grain yld ($r^2 = 0.50$)

FIGURE 6.14 Values for %Ndfa for (a) mungbeans and (b) soybeans at different levels of sowing soil nitrate and grain yield



%Ndfa described by: Mungbeans – %Ndfa = 37 – 25*Soil nitrate + 12*Grain yld ($r^2 = 0.60$);
Soybeans – %Ndfa = 37 – 25*Soil nitrate + 20*Ln Grain yld ($r^2 = 0.50$)

SOURCE: Data for developing functions Herridge *et al.* 1990; Herridge and Peoples 2002a,b; Herridge *et al.* 2005 are quite simple. Provided there are adequate numbers of highly effective rhizobia in the soil in which the legume is growing, N_2 fixation is essentially determined by the growth (biomass yield) of the legume and its utilisation of soil mineral N (Appendix 9). With higher-yielding crops or pastures, more N tends to be fixed. When the legume is grown in low N fertility soil, more N also tends to be fixed. The reverse is also true: less N will be fixed by low-yielding crops or pastures growing in high N fertility soils.

A key term in N_2 fixation studies is %Ndfa – the percentage of legume N derived from N_2 fixation. It is important because it is needed to calculate how much N is fixed. Therefore:

Legume N_2 fixation (kg/ha) = (total N yield (kg/ha) × %Ndfa)/100

Data for chickpeas and faba beans showing independently the effects of yield and soil nitrate on %Ndfa are presented in Appendix 9. The %Ndfa, grain yield and soil nitrate data were combined in multi-variate analysis to develop functions describing %Ndfa in terms of both yield and soil nitrate (Figure 6.13).

A smaller data set was similarly used for generating %Ndfa functions for the summer legumes – mungbeans and soybeans (Figure 6.14).

6.8 N budgeting – a set of linked functions

Steps 3 and 4 in 'NBudget' contain a set of linked functions that estimates biomass dry matter and N from grain yields and proteins, then subsequently breaks down the residues to release or immobilise soil nitrate. The principal outputs of this N budgeting are estimates of:

- legume N_2 fixation;
- crop uptake of soil nitrate;
- residual soil nitrate at crop harvest; and
- residual soil nitrate after the post-crop fallow.

The final output is shown as 'Estimated soil nitrate post-fallow' in Step 4 to be used in the N budgeting of the coming season's crop. The N budgeting functions are also used to estimate 'Post-fallow nitrate'.

Details of N budgeting are shown in Appendices 10 (winter crops) and 11 (summer crops).

6.9 Rainfall data

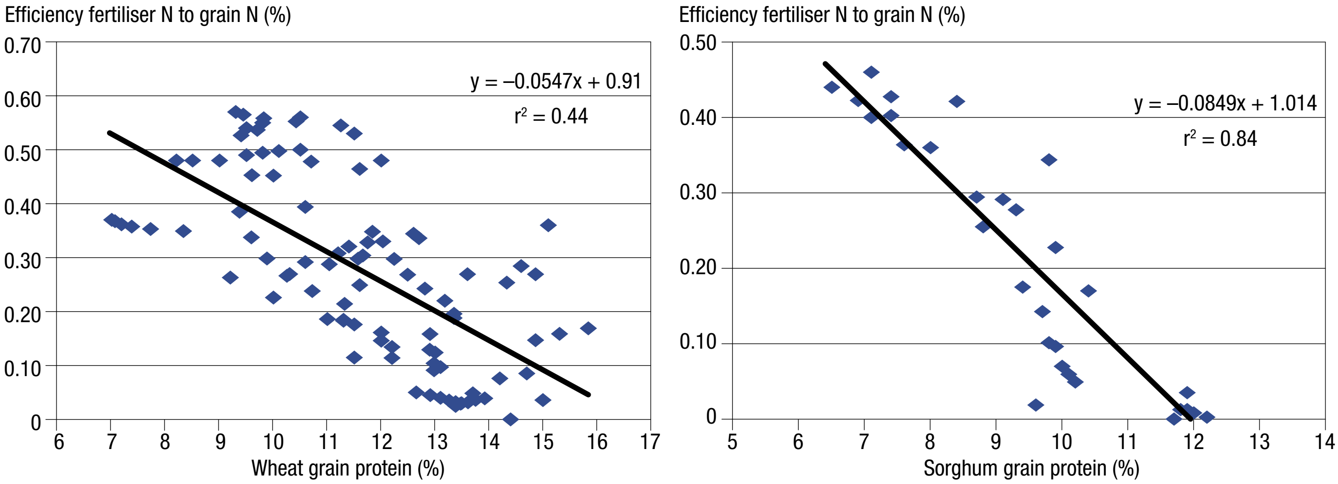
The rainfall data used in 'NBudget' was accessed from the Bureau of Meteorology website at http://www.bom.gov.au/climate/data/index.shtml (see tables of rainfall statistics for the different stations in Appendices 12 and 13).

APPENDICES

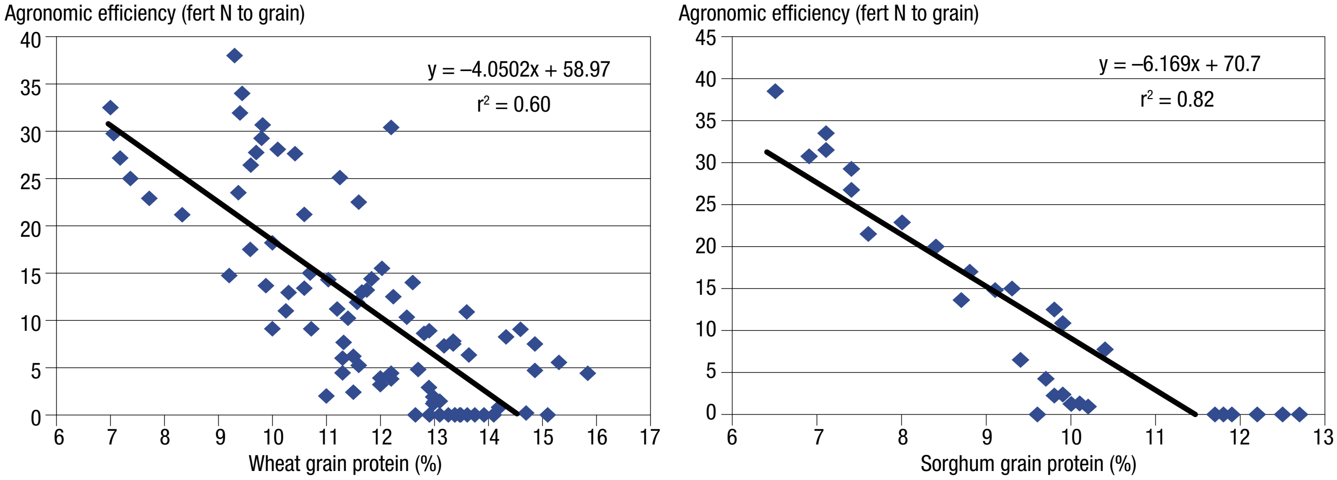
Appendix 1 Efficiencies with which fertiliser N is converted to (a) grain N and (b) grain dry matter of wheat and sorghum in the northern grains region

Data sources: Wheat – Doyle and Shapland 1991; Doyle and Leckie 1992; Strong and Holford 1997; Weston *et al.* 2002; Thomas *et al.* 2007a; unpublished data from the NSW DPI long-term farming systems experiments (W Felton, H Marcellos, DF Herridge, GD Schwenke); sorghum – Holford *et al.* 1997.

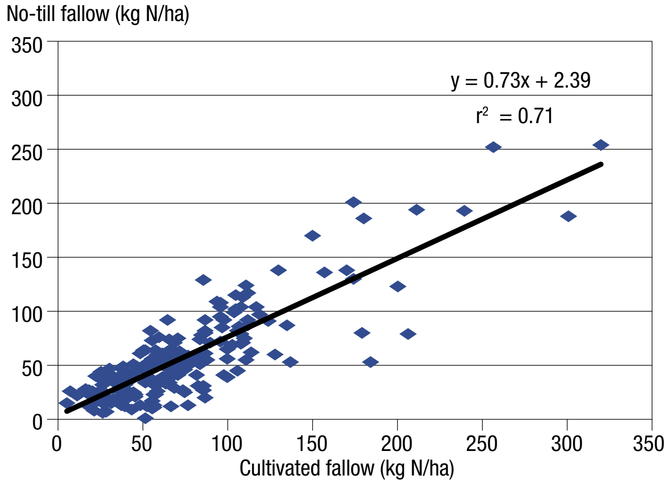
(a) Conversion of fertiliser N into grain N for wheat and sorghum in the northern grains region



(b) Conversion of fertiliser N into grain dry matter for wheat and sorghum in the northern grains region



Appendix 2 Effects of tillage practice on accumulation of nitrate-N during summer fallows



Data sourced from the NSW DPI long-term experiments in northern NSW during 1991–99 (n = 208; the higher values, i.e. greater than 100 to 120 kg N/ha would have also included fertiliser N inputs) (source: W Felton, H Marcellos, DF Herridge and GD Schwenke, unpublished data).

Appendix 3 Estimating residue N using the generic relationship between grain protein (%) and residue %

Figure showing the strong relationship between grain protein and %N in crop residues. Data are from many data sets from the northern grains region.

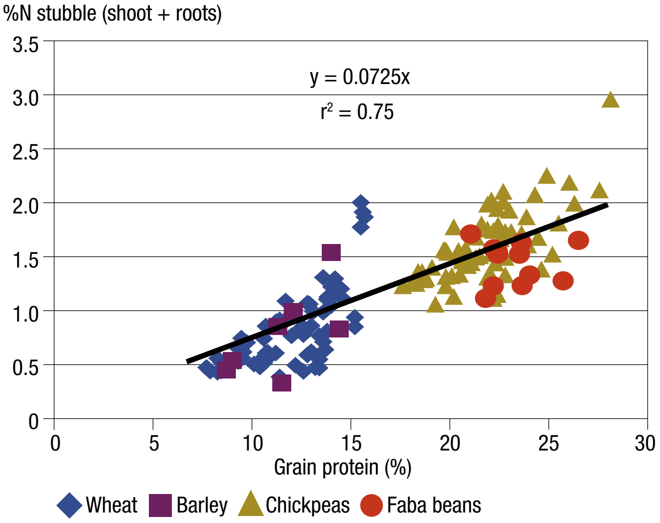


Table showing calculated values for residue N using NHI and the grain protein–% residue N relationship (graph left). More detail in Appendices 10 and 11.

Crop	Grain yield (t/ha)	Grain protein (%)	Calculated (root + shoot) residue N (kg/ha)	
			NHI	Grain protein
Wheat	3.0	11.5	54	60
Durum	3.2	13.0	64	71
Barley	4.0	10.0	44	47
Chickpeas	1.9	21.8	108	110
Faba beans	2.4	23.9	88	90
Canola	1.5	24.0	73	93

Appendix 4 Matrices of rule-of-thumb estimates of sowing soil nitrates for the summer and winter cropping versions of 'NBudget' according to soil type, cultivation practice, and paddock fertilities and histories

Winter cropping

Last winter	Soil fertility	No-till			Cultivated		
		Clay soil	Red-brown earth	Sand, sandy-loam	Clay soil	Red-brown earth	Sand, sandy-loam
Double crop	Very low	18	14	11	23	17	14
	Low-medium	22	16	13	27	20	16
	Medium	26	20	16	33	25	20
	High	34	26	21	43	32	26
Cereal 0–40N	Very low	47	35	29	59	44	36
	Low-medium	55	42	34	69	52	42
	Medium	68	51	41	85	64	51
	High	90	68	54	113	85	68
Cereal 50–100N	Very low	56	42	34	71	53	43
	Low-medium	66	50	40	83	62	50
	Medium	82	62	49	102	77	61
	High	109	82	66	136	102	82
Cereal 100N+	Very low	66	50	39	82	62	49
	Low-medium	78	58	46	97	73	58
	Medium	95	72	58	119	90	72
	High	127	95	76	159	119	95
Canola +N	Low	71	53	42	88	66	53
	Low-medium	83	62	50	104	78	62
	Medium	102	77	62	128	96	77
	High	136	102	82	170	128	102
Pulse crop	Very low	75	56	46	94	71	57
	Low-medium	89	66	54	111	83	67
	Medium	110	82	66	137	102	82
	High	145	109	87	181	136	109
No crop, long fallow	Very low	97	73	58	122	92	73
	Low-medium	114	86	69	143	108	86
	Medium	143	108	86	179	135	107
	High	186	142	112	233	177	140

Summer cropping

Paddock history	Soil fertility	No-till			Cultivated		
		Clay soil	Red-brown earth	Sand, sandy-loam	Clay soil	Red-brown earth	Sand, sandy-loam
Double crop	Low	18	14	11	23	17	14
	Low-medium	22	16	13	27	20	16
	Medium	26	20	16	33	25	20
	High	34	26	21	43	32	26
Winter cereal 0–40N, long fallow	Low	64	48	39	80	60	48
	Low-medium	75	57	46	94	71	57
	Medium	92	70	55	115	87	69
	High	122	92	73	152	115	91
Winter cereal 50–100N, long fallow	Low	73	55	44	92	69	55
	Low-medium	86	65	52	108	81	65
	Medium	106	80	63	132	100	79
	High	140	106	84	175	132	105
Winter cereal 100N+, long fallow	Low	83	63	50	104	78	62
	Low-medium	98	74	58	122	92	73
	Medium	119	90	72	149	113	90
	High	158	119	94	198	149	118
Canola +N, long fallow	Low	88	66	52	110	82	65
	Low-medium	103	78	62	129	97	77
	Medium	126	95	76	158	119	95
	High	167	126	100	209	158	125
Winter pulse crop, long fallow	Low	92	69	56	116	87	70
	Low-medium	109	82	66	136	102	82
	Medium	134	101	80	167	126	100
	High	176	133	106	220	166	132
Sorghum, short fallow	Low	33	24	20	41	31	25
	Low-medium	38	29	23	48	36	29
	Medium	45	34	27	56	42	34
	High	60	45	36	75	56	45
Sunflowers, short fallow	Low	51	38	31	64	48	38
	Low-medium	60	45	36	75	56	45
	Medium	72	54	43	90	68	54
	High	97	73	58	121	91	73
Mungbeans, short fallow	Low	77	58	46	96	72	58
	Low-medium	90	68	54	113	85	68
	Medium	110	82	66	137	103	82
	High	146	110	87	182	137	109
Soybeans, short fallow	Low	61	46	36	76	57	45
	Low-medium	71	54	42	89	67	53
	Medium	86	64	51	107	80	64
	High	114	86	69	143	107	86

Appendix 5 Efficiencies (real and apparent) of summer fallows for accumulating water in the soil in the northern grainbelt.

Summary of 12 site x years of data from the NSW DPI winter cropping experiments at North Star in northern NSW (source Herridge *et al.* 1995; Felton *et al.* 1998; Marcellos *et al.* 1998; W Felton, H Marcellos, DF Herridge and GD Schwenke unpublished)

Real fallow efficiencies in which plant-available soil water accumulated during the fallow is compared with fallow rainfall, i.e. (soil water (mm) at end of fallow – soil water (mm) at start of fallow)/fallow rainfall (mm)

Real fallow efficiency

			Accumulated soil water		Fallow efficiency (%)	
	Fallow	Fallow rain	No Till	Cultivated	No Till	Cultivated
Glenhoma	1990-91	400	55	47	14	12
	1991-92	366	70	73	19	20
	1993-94	304	38	-48	13	0
	1994-95	466	94	71	20	15
	1995-96	621	142	139	23	22
Windridge	1989-90	694	84	56	12	8
	1990-91	400	94	92	24	23
	1991-92	366	88	68	24	19
	1992-93	304	38	17	13	6
	1993-94	372	36	54	10	15
	1994-95	468	44	47	9	10
	1995-96	621	134	128	22	21
All site/years		**449**	**76**	**62**	**17**	**14**

Apparent fallow efficiencies in which plant-available soil water at sowing is compared with fallow rainfall, i.e. soil water (mm) at end of fallow/fallow rainfall (mm)

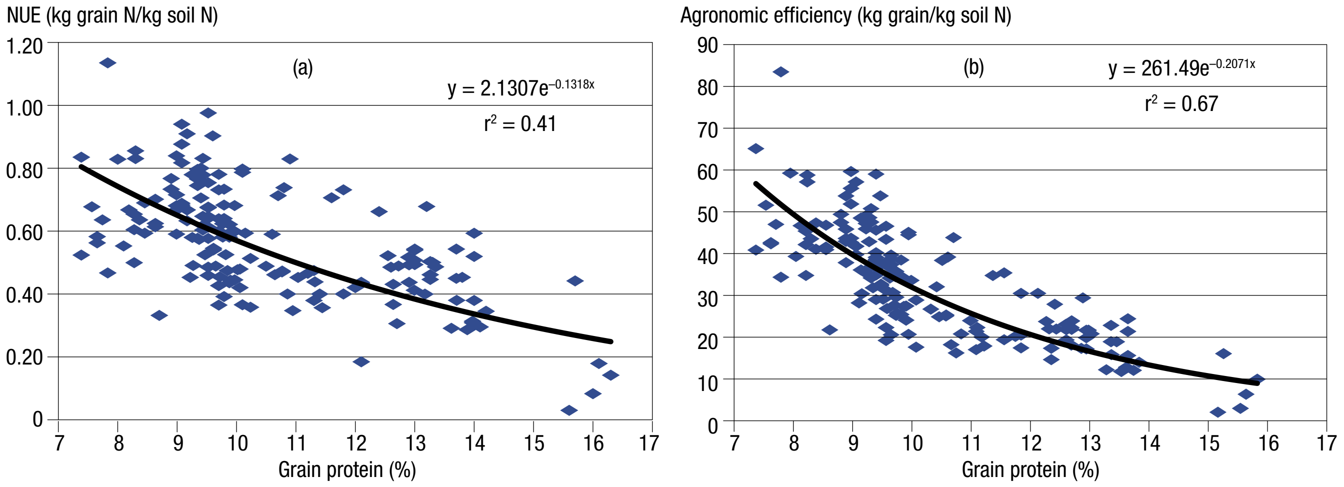
Apparent fallow efficiency

			Accumulated soil water		Fallow efficiency (%)	
	Fallow	Fallow rain	No Till	Cultivated	No Till	Cultivated
Glenhoma	1990-91	400	125	110	31	28
	1991-92	366	95	91	26	25
	1993-94	304	140	117	46	38
	1994-95	466	154	132	33	28
	1995-96	621	164	151	26	24
Windridge	1989-90	694	168	167	24	24
	1990-91	400	126	118	32	30
	1991-92	366	110	93	30	25
	1992-93	304	70	42	23	14
	1993-94	372	151	143	41	38
	1994-95	468	139	139	30	30
	1995-96	621	175	169	28	27
All site/years		**449**	**135**	**123**	**31**	**28**

Appendix 6 Relationships for wheat between (a) grain proteins and NUE, and (b) grain proteins and agronomic efficiency

NUE is defined as kg grain N per kg soil nitrate-N to a depth of 1.2 m at sowing; agronomic efficiency (AE) is defined as kg grain per kg soil nitrate-N.

Data are from Dalal *et al.* (1998, 2004), Weston *et al.* (2002) and unpublished from the NSW DPI long-term farming systems experiments in northern NSW (W Felton, H Marcellos, DF Herridge and GD Schwenke).



Appendix 7 Functions, values describing the relationships between soil nitrate at sowing and its conversion into grain N (protein) and biomass for winter and summer crops for the northern grains region

NUE is defined as kg grain N per kg soil nitrate-N to a depth of 1.2 m at sowing; agronomic efficiency (AE) is defined as kg grain per kg soil nitrate-N.

Crop	Functions[1] or values	References
Bread wheat	$NUE = 2.1307 * e^{-0.1318 * \text{grain protein}}$	Dalal *et al.* 1998, 2004
	$AE = 261.5 * e^{-0.2071 * \text{grain protein}}$	Weston *et al.* 2002
	$\text{Sowing nitrate-N} = 2.933 * e^{0.2313 * \text{grain protein}}$	W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data
Durum	$\text{Sowing nitrate-N} = 3.139 * e^{0.2162 * \text{grain protein}}$	Adapted from function for bread wheat, adjusted for 7% increases efficiency
Barley	$\text{Sowing nitrate-N} = 2.933 * e^{0.2065 * \text{grain protein}}$	Adapted from function for bread wheat, adjusted for grain moisture content
Canola	Sowing nitrate-N = 94 kg N (24% grain protein)	Calculated using crop N demand (Appendix 10)
Sorghum	$NUE = 1.5342 - 0.0946 * \text{grain protein}$	Thomas *et al.* 1995
	$\text{Sowing nitrate-N} = 1.3408 * e^{0.3103 * \text{grain protein}}$	Holford *et al.* 1997
		G McMullen, personal communication
Sunflowers	Sowing nitrate-N = 55 kg N (16% grain protein)	Calculated using crop N demand (Appendix 11)

[1] Functions all significant at $P<0.01$

Appendix 8 Functions, values describing harvest index (HI) and N harvest index (NHI) for winter and summer crops for the northern grains region

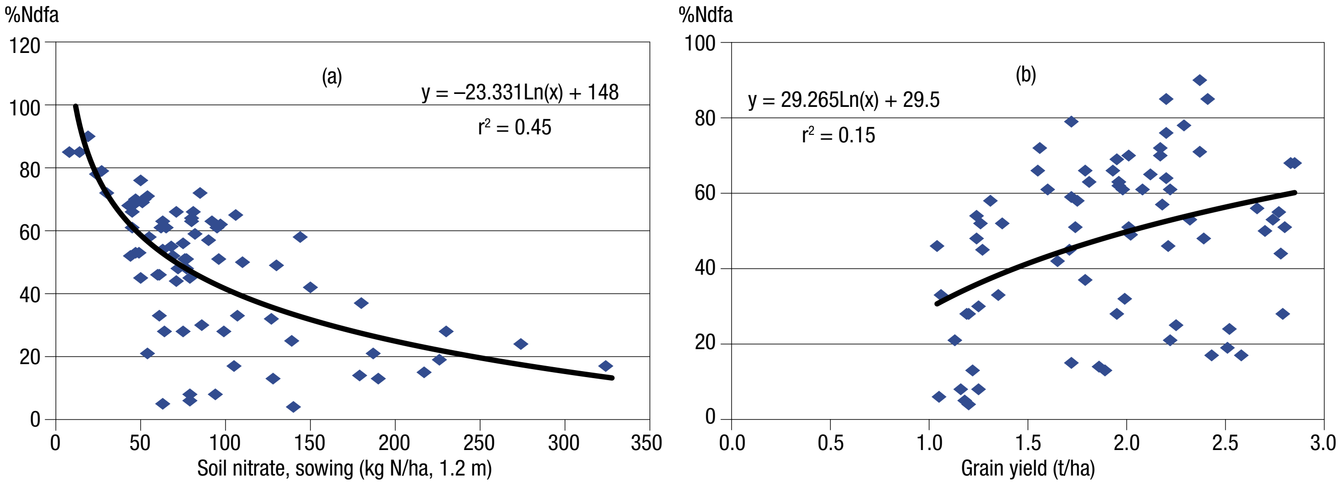
Crop	Functions[1] or values for HI and NHI	References
Bread, durum wheats	HI = 0.3602 + 0.0148*Grain Yield NHI = 0.70	Strong 1982, 1986 Strong *et al.* 1986 Angus and Fischer 1991 Marcellos *et al.* 1998 Felton *et al.* 1998 Turpin *et al.* 2002 Kirkegaard *et al.* 2004 Ryan *et al.* 2008 GD Schwenke, personal communication W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data
Barley	HI = 0.2923 + 0.0506*Grain Yield NHI = 0.75	Pala *et al.* 2008 W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data
Chickpeas	HI = 0.3489 + 0.0224*Grain Yield NHI = 0.67	Herridge *et al.* 1995 Dalal *et al.* 1997a Schwenke *et al.* 1998 Turpin *et al.* 2002 Elias 2009 W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data
Faba beans	HI = 0.2724 + 0.0550*Grain Yield NHI = 0.64	Turpin *et al.* 2002 W Felton, H Marcellos, DF Herridge, GD Schwenke, unpublished data
Canola	HI = 0.28 NHI = 0.55	Hocking and Stapper 2001a, b Hocking *et al.* 2002
Sorghum	HI = 0.335 + 0.0192*Grain Yield NHI = 0.979 - 0.0406*Grain Protein	Doughton and McKenzie 1984 Holland and Felton 1989 Herridge and Holland 1992 Kamoshita *et al.* 1998a, b, c Armstrong *et al.* 2003 GD Schwenke, personal communication
Sunflowers	HI = 0.44 NHI = 0.923 - 0.0172*Grain Protein	Hall *et al.* 1989 Herridge and Holland 1992 Connor *et al.* 1985
Mungbeans	HI = 0.37 NHI = 0.70	Herridge and Holland 1992 Herridge and Peoples 2002b Herridge *et al.* 2005
Soybeans	HI = 0.36 NHI = 0.73	Herridge *et al.* 1990 Herridge and Holland 1992 Herridge and Peoples 2002b Salvagiotti *et al.* 2008

[1] Functions all significant at $P<0.01$

Appendix 9 Relationships between soil nitrate at sowing, grain yield and %Ndfa for chickpeas and faba beans

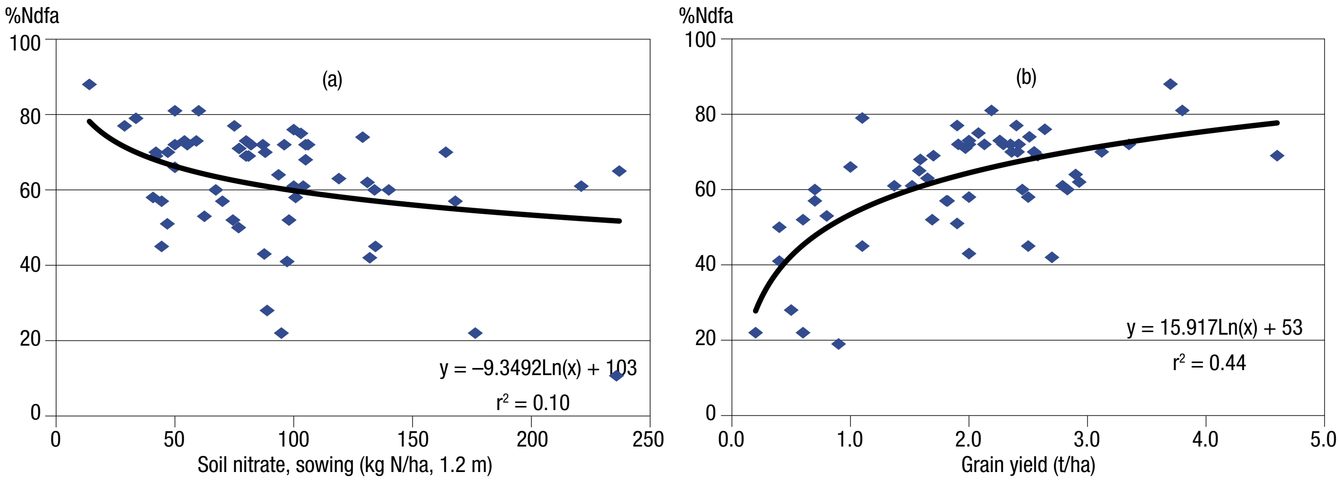
Chickpeas – sources of data: Doughton *et al.* 1993; Herridge *et al.* 1995; Herridge *et al.* 1998; Schwenke *et al.* 1998.

Chickpeas



Faba beans – sources of data Schwenke *et al.* 1998; McNeill and Unkovich 2000; Turpin *et al.* 2002; Khan *et al.* 2003 and unpublished from the NSW DPI long-term farming systems experiments in northern NSW (W Felton, H Marcellos, DF Herridge and GD Schwenke).

Faba beans



Appendix 10 Linked N budgeting functions for winter cropping

		C	D	E	F	G
6	Yield of -	Chickpeas	Faba beans	Wheat	Barley	Canola
7	Crop yield in tonnes/ha	INSERT	INSERT	INSERT	INSERT	INSERT
8	Grain protein of wheat, barley, canola			INSERT	INSERT	24.0
9						
10	Receivals grain protein (%)*			=E8	=F8	=G8
11	Grain protein (% @ 0% moisture)	=21.8	=23.9	=(1.12*E10)	=E10	=G10
12	Grain yield (t/ha @ 12% moisture)	=C7	=D7	=E7	=F7	=G7
13	HI	=0.35+(0.02*C12)	=0.27+(0.06*D12)	=0.36+(0.02*E12)	=0.29+(0.05*F12)	=0.28
14	Shoot biomass (t/ha)	=C12/C13	=D12/D13	=E12/E13	=F12/F13	=G12/G13
15	Total crop biomass (t/ha)	=C14*2	=D14*1.4	=E14*1.4	=F14*1.4	=G14*1.4
16	Residue biomass (t/ha)	=(C15*0.95)-(C12*0.89)	=(D15*0.95)-(D12*0.89)	=(E15*0.95)-(E12*0.89)	=(F15*0.95)-(F12*0.89)	=(G15*0.95)-(G12*0.89)
17	Residue %N	=0.0724*C11	=0.0724*D11	=0.0724*E11	=0.0724*F11	=0.0724*G11
18	Residue C:N	=40/C17	=40/D17	=40/E17	=40/F17	=40/G17
19	Sowing soil nitrate, 1.2m (kg N/ha)	INSERT	INSERT	INSERT	INSERT	INSERT
20	In-crop N mineralisation (kg N/ha)	Table 6.1	Table 6.1	Table 6.1	Table 6.1	Table 6.1
21	Grain N (kg/ha)	=(C12*0.89)*(C11/6.25)*10	=(D12*0.89)*(D11/6.25)*10	=(E12*0.89)*(E11/5.7)*10	=(F12*0.89)*(F11/6.25)*10	=(G12*0.89)*(G11/6.25)*10
22	NHI	=0.67	=0.64	=0.70	=0.75	=0.55
23	Shoot N (kg/ha)	=C21/C22	=D21/D22	=E21/E22	=F21/F22	=G21/G22
24	Total crop N using NHI (kg/ha)	=C23*2	=D23*1.4	=E23*1.4	=F23*1.4	=G23*1.4
25	Total crop N from biomass (HI) (kg/ha)	=(C16*C17*10)+C21	=(D16*D17*10)+D21	=(E16*E17*10)+E21	=(F16*F17*10)+F21	=(G16*G17*10)+G21
26	Residue N (kg/ha) (from biomass)	=(C25*0.95)-C21	=(D25*0.95)-D21	=(E25*0.95)-E21	=(F25*0.95)-F21	=(G25*0.95)-G21
27	Residue N (kg/ha) (difference)	=(C24*0.95)-C21	=(D24*0.95)-D21	=(E24*0.95)-E21	=(F24*0.95)-F21	=(G24*0.95)-G21
28	N volatilised from crop (kg/ha)	=C24*0.05	=D24*0.05	=E24*0.05	=F24*0.05	=G24*0.05
29	%Ndfa	=131-23*LN(C19)+29.*LN(C12)	=87-7.6*LN(D19)+15.3*LN(D12)	=0	=0	=0
30	Total N fixed (kg/ha)	=((C24+C25)/2)*(C29/100)	=((D24+D25)/2)*(D29/100)	=0	=0	=0
31	Crop uptake of nitrate-N (kg/ha)	=((C24+C25)/2)-C30	=((D24+D25)/2)*(D29/100)	=((E24+E25)/2)-E30	=((F24+F25)/2)-F30	=((G24+G25)/2)-G30
32	Net C retained in SOM (%)	=35	=35	=30	=30	=35
33	Net C retained in SOM (kg/ha)	=C16*0.4*1000*(C32/100)	=D16*0.4*1000*(D32/100)	=E16*0.4*1000*(E32/100)	=F16*0.4*1000*(F32/100)	=G16*0.4*1000*(G32/100)
34	N required for SOM-C (kg/ha)	=C33/11	=D33/11	=E33/11	=F33/11	=G33/11
35	N released/immobilised (kg/ha)	=((C26+C27)/2)-C34	=((D26+D27)/2)-D34	=((E26+E27)/2)-E34	=((F26+F27)/2)-F34	=((G26+G27)/2)-G34
36	N incorporated into nitrate pool (kg/ha)	=C35*0.9	=D35*0.9	=E35*0.9	=F35*0.9	=G35*0.9
37						
38	Soil nitrate-N spared (kg/ha)	=(C19+C20-C31)	=(D19+D20-D31)	=(E19+E20-E31)	=(F19+F20-F31)	=(G19+G20-G31)
39	Spared N adjusted (CP and FB only)	=(0.91*C38)+14.2	=(0.65*D38)+9.4	=E38	=F38	=G38
40	Soil nitrate-N at harvest (kg/ha)	=C39	=D39	=E39	=F39	=G39
41	Nitrate mineralised/immobilised	=C36	=D36	=E36	=F36	=G36
42	Native SOM nitrate mineralised in fallow	Table 6.1	Table 6.1	Table 6.1	Table 6.1	Table 6.1
43	Total N mineralised during fallow (kg/ha)	=C41+C42	=D41+D42	=E41+E42	=F41+F42	=G41+G42
44	**Total nitrate at sowing**	**=C40+C43**	**=D40+D43**	**=E40+E43**	**=F40+F43**	**=G40+G43**

*Receivals % grain protein (barley @ 0%; wheat, sorghum @ 12% moist; sunflowers @ 9%)

Appendix 11 Linked N budgeting functions for summer cropping

		C	D	E	F
6	Yield of -	Sorghum	Sunflowers	Mungbeans	Soybeans
7	Crop yield in tonnes/ha	INSERT	INSERT	INSERT	INSERT
8	Proteins (@ 12% moisture)	INSERT	=16.0	=24.0	=38.0
9					
10	Grain proteins	=C8	=D8	=E8	=F8
11	Grain protein (% @ 0% moisture)	=(1.12*C10)	=(1.12*D10)	=(1.12*E10)	=(1.12*F10)
12	Grain yield (t/ha)	=C7	=D7	=E7	=F7
13	HI	=0.34+(0.019*C12)	=0.44	=0.37	=0.36
14	Shoot biomass (t/ha)	=C12/C13	=D12/D13	=E12/E13	=F12/F13
15	Total crop biomass (t/ha)	=C14*1.4	=D14*1.4	=E14*1.4	=F14*1.4
16	Residue biomass (t/ha)	=(C15*0.95)-(C12*0.89)	=(D15*0.95)-(D12*0.89)	=(E15*0.95)-(E12*0.89)	=(F15*0.95)-(F12*0.89)
17	Residue %N	=0.0724*C11	=0.0724*D11	=1.67	=1.90
18	Residue C:N	=40/C17	=40/D17	=40/E17	=40/F17
19	**Soil nitrate, 1.2m (kg N/ha)**	INSERT	INSERT	INSERT	INSERT
20	In-crop N mineralisation (kg N/ha)	Table 6.2	Table 6.2	Table 6.2	Table 6.2
21	Grain N (kg/ha)	=(C12*0.89)*(C11/6.25)*10	=(D12*0.91)*(D11/6.25)*10	=(E12*0.89)*(E11/6.25)*10	=(F12*0.89)*(F11/6.25)*10
22	NHI	=0.98-(0.041*C8)	=0.92-(0.017*D8)	0.70	0.73
23	Shoot N (kg/ha)	=C21/C22	=D21/D22	=E21/E22	=F21/F22
24	Total crop N using NHI (kg/ha)	=C23*1.4	=D23*1.4	=E23*1.4	=F23*1.4
25	Total crop N from biomass (HI) (kg/ha)	=(C16*C17*10)+C21	=(D16*D17*10)+D21	=(E16*E17*10) +E21	=(F16*F17*10) +F21
26	Residue N (kg/ha) (from biomass)	=(C25*0.95)-C21	=(D25*0.95)-D21	=(E25*0.95)-E21	=(F25*0.95)-F21
27	Residue N (kg/ha) (difference)	=(C24*0.95)-C21	=(D24*0.95)-D21	=(E24*0.95)-E21	=(F24*0.95)-F21
28	N volatilised from crop (kg/ha)	=C24*0.05	=D24*0.05	=E24*0.05	=F24*0.05
29	%Ndfa	=0	=0	=37-0.25*(E19+E20)+20*(E12)	=37-0.25*(F19+F20)+20*(F12)
30	Total N fixed (kg/ha)	=0	=0	=((E24+E25)/2) *(E29/100)	=((F24+F25)/2) *(F29/100)
31	Crop uptake of nitrate-N (kg/ha)	=((C24+C25)/2)-C30	=((D24+D25)/2)-D30	=((E24+E25)/2)-E30	=((F24+F25)/2)-F30
32	Net C retained in SOM (%)	=30	=30	=35	=35
33	Net C retained in SOM (kg/ha)	=C16*0.4*1000*(C32/100)	=D16*0.4*1000*(D32/100)	=E16*0.4*1000*(E32/100)	=F16*0.4*1000*(F32/100)
34	N required for SOM-C (kg/ha)	=C33/11	=D33/11	=E33/11	=F33/11
35	N released/immobilised (kg/ha)	=((C26+C27)/2)-C34	=((D26+D27)/2)-D34	=((E26+E27)/2)-E34	=((F26+F27)/2)-F34
36	N incorporated into nitrate pool (kg/ha)	C35*0.9	D35*0.9	E35*0.9	F35*0.9
37					
38	Soil nitrate-N spared (kg/ha)	=(C19+C20-C31)	=(D19+D20-D31)	=(E19+E20-E31)	=(F19+F20-F31)
39	Spared N adjusted (CP and FB only)	=C38	=D38	=E38	=F38
40	Soil nitrate-N at harvest (kg/ha)	=C39	=D39	=E39	=F39
41	Nitrate mineralised/immobilised	=C36	=D36	=E36	=F36
42	Native SOM nitrate mineralised in winter fallow	Table 6.2	Table 6.2	Table 6.2	Table 6.2
43	Total N mineralised during winter fallow (kg/ha)	=C41+C42	=D41+D42	=E41+E42	=F41+F42
44	**Total nitrate at sowing next summer**	**=C40+C43**	**=D40+D43**	**=E40+E43**	**=F40+F43**

Appendix 12 Rainfall statistics for winter cropping

In-crop (May – October) rainfall (mm) data – recalculated using BoM data

	10th	30th	50th	70th	90th
Coonamble	102	172	208	249	336
Gunnedah	152	207	243	296	352
Croppa Creek	145	187	232	279	374
Moree	132	184	230	289	359
Narrabri	144	214	265	327	403
Walgett	90	152	189	226	281
Dubbo	150	219	271	321	406
Warialda	155	221	257	314	392
Tam/Quirind/Inverell/Coonabarabran	171	258	302	353	444
Tamworth	172	268	312	360	431
Quirindi	162	247	291	340	425
Inverell	178	256	306	347	444
Coonabarabran	173	262	299	365	474
Goondiwindi	128	175	218	263	362
Dalby	123	158	215	243	308
Roma	83	136	162	203	264
St George	85	141	184	226	326

Fallow (November – April) rainfall (mm) data – recalculated using BoM data

	10th	30th	50th	70th	90th
Coonamble	144	213	285	342	424
Gunnedah	215	268	370	430	525
Croppa Creek	214	306	384	459	573
Moree	207	282	371	455	552
Narrabri	193	287	363	425	521
Walgett	144	212	269	344	445
Dubbo	149	246	298	356	484
Warialda	230	334	393	476	611
Tam/Quirind/Inverell/Coonabarabran	269	352	425	501	585
Tamworth	291	364	410	487	553
Quirindi	237	308	382	446	546
Inverell	320	406	502	578	643
Coonabarabran	228	329	404	494	598
Goondiwindi	231	290	347	414	509
Dalby	288	334	390	487	588
Roma	207	284	360	423	516
St George	155	228	279	400	491

Average monthly rainfall (mm) – BoM data

	Nov	Dec	Jan	Feb	Mar	Apr
Coonamble	43	47	61	55	45	36
Gunnedah	68	69	86	73	42	40
Inverell	86	98	99	98	67	40
Moree	65	69	79	75	51	36
Narrabri	59	67	80	73	54	39
Walgett	38	44	75	62	42	35
Dubbo	52	50	61	53	48	44
Warialda	69	71	85	80	64	41
Tamworth	86	94	74	77	41	43
Quirindi	65	80	81	66	53	42
Croppa Creek/North Star	64	72	83	72	57	40
Coonabarabran	64	69	91	82	62	53
Gilgandra	47	52	64	54	46	40
Goondiwindi	62	70	76	71	57	36
Dalby	75	89	74	74	50	37
Roma	55	70	74	77	55	34
St George	45	50	67	61	52	35

Appendix 13 Rainfall statistics for summer cropping

In-crop (November – February) rainfall data (mm) – recalculated using BoM data

	10th	30th	50th	70th	90th
Coonamble	103	150	190	260	320
Gunnedah	117	182	268	309	428
Croppa Creek	138	192	245	300	462
Moree	120	196	225	300	400
Narrabri	171	186	273	323	440
Walgett	80	129	207	230	346
Dubbo	104	146	216	258	381
Warialda	144	240	275	340	472
Tam/Quirind/Inverell/Coonabarabran	168	246	304	367	457
Tamworth	168	227	290	342	378
Quirindi	147	236	286	340	434
Inverell	209	288	340	417	510
Coonabarabran	146	233	300	370	504
Goondiwindi	139	215	260	336	440
Dalby	184	241	274	336	466
Roma	136	207	253	301	394
St George	82	150	201	262	375

Average monthly rainfall (mm) – BoM data

	May	Jun	Jul	Aug	Sep	Oct
Coonamble	40	37	36	32	32	42
Gunnedah	45	40	42	35	40	59
Inverell	49	44	48	44	47	77
Moree	40	38	44	34	33	51
Narrabri	49	51	45	37	39	51
Walgett	40	30	33	27	26	44
Dubbo	47	50	44	44	43	49
Warialda	44	45	45	39	44	59
Tamworth	40	50	62	48	53	60
Quirindi	45	51	48	45	47	61
Croppa Creek/North Star	41	33	42	37	37	53
Coonabarabran	54	57	55	53	50	60
Gilgandra	43	45	43	40	39	47
Goondiwindi	41	40	40	32	33	47
Dalby	40	32	33	26	28	59
Roma	34	28	29	23	21	45
St George	40	34	33	26	26	39

Short Fallow (March – October) rainfall (mm) – recalculated using BoM data

	10th	30th	50th	70th	90th
Coonamble	197	269	296	324	366
Gunnedah	254	321	358	380	381
Croppa Creek	234	298	306	335	370
Moree	265	302	330	332	384
Narrabri	250	334	373	420	460
Walgett	181	232	276	322	316
Dubbo	265	330	362	391	418
Warialda	300	333	382	429	430
Tam/Quirind/Inverell/Coonabarabran	309	368	409	435	465
Tamworth	290	342	382	404	460
Quirindi	300	356	392	414	453
Inverell	345	378	411	440	464
Coonabarabran	300	394	452	482	482
Goondiwindi	172	248	313	385	495
Dalby	157	238	288	334	416
Roma	138	201	232	270	388
St George	144	212	257	333	447

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