**Organic matter and nutrient availability in Australian grains soils – a focus on supply and loss of Nitrogen and Sulfur and implications for industry fertilizer strategies**

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1. Executive summary

**The Australian grains industry has traditionally relied on the mineralization of soil organic matter and plant residues to provide a source of nitrogen (N) and sulfur (S) that can be utilized during the cropping phase of a rotation, with the balance to meet crop needs supplied by annual fertilizer applications. However, as soil organic matter continues to decline, despite adoption of stubble retention and reduced/zero tillage, and grain cropping regions continue to intensify production by shifting to continuous cropping rather than mixed cropping/grazing systems, the reliance on synthetic fertilizer inputs to maintain productivity and balance nutrient removal in harvested grain is increasing. The cost of nutrients like N already dominate most fertilizer budgets, with evidence of shortfalls in S availability increasingly evident in some regions, along with supply of mineral nutrients like phosphorus (P) and potassium (K). The increasing demand for nutrient inputs is accompanied by growing uncertainty about the capacity of microbially-mediated soil supply processes to make a reliable contribution to meeting N and S demand, especially as cropping and tillage systems change. This uncertainty about likely soil N (and to a lesser extent S) availability, the greater need for costly fertilizer inputs and the imperatives for efficient nutrient use have collectively sparked this review.**

**The review consists of three distinct components – (i) a review of published and grey literature (where available) outlining the technical understanding relating to soil N and S supply processes and the environmental losses that can reduce plant-available N and S from both soil and fertilizer sources; (ii) a survey of >300 (primarily) advisers and agribusinesses nationally, to determine how N fertilizer recommendations are made and the assumptions underlying the decisions themselves; and (iii) a documentation of the key Decision Support Systems (DSS) and their underlying assumptions that are used to help practitioners arrive at an N or S fertilizer recommendation.**

**In each component of the review, the strengths, weaknesses and knowledge gaps underpinning the fundamentals supporting N and S fertilizer decisions were documented. The review then attempted to contrast the technical and industry perspectives on priorities and gaps, and collectively develop a set of priorities to guide future R, D and E investment for the grains industry.**

**From the technical perspective, the review notes that while there has been considerable research conducted on soil N supply processes, much of that research is now quite dated and conducted in mixed cropping/grazing systems that are no longer representative of the reduced/zero tillage, more intensive cropping systems that are currently employed. In addition, changing rainfall patterns are influencing the relative importance of fallow and in-crop organic matter mineralization, with implications for both the timing and availability of nutrients for crop uptake. While similar comments can be made for S, the overall level of research and process understanding of S cycling and release for plant availability are poorly developed.**

**There are substantial knowledge gaps relating to environmental losses of N and S and the loss quantum in response to different environmental conditions. Leaching losses on lighter textured soils have only been explored to any extent in western regions. The gaseous losses of N via denitrification and volatilization are less well quantified across all regions. The former is especially relevant on clay soils and duplex soils or those with elevated soil C status (i.e. after a pasture phase), while the latter are increasingly important given the trends to move to in-crop top dressing of fertilizer N in southern and western areas. The recent national focus on N2O emissions via the NANORP project, especially when combined with 15N isotope studies, has shown that while N2O is important from an greenhouse gas emissions perspective, the major denitrification product is N2.**

**The review has also noted a lack of integrated, long term studies to look at the interaction between fertilizer application strategies, nutrient losses, crop recoveries and system nutrient budgets. Where these have occurred, the results of partial nutrient balances are often at odds with more quantitative isotope studies showing significant fertilizer losses. This suggest that ‘apparent’ nutrient balance for a locally relevant N fertilizer rate may have been achieved by mining the soil organic matter pool of nutrients, rather than balancing nutrient inputs to removal rates.**

**Advisors are using a combination of methods to derive N fertilizer recommendations, with the majority using ‘rules of thumb’ and local knowledge rather than elaborate DSS systems. Few DSS even consider S availability or derive application rates. Advisors are increasingly concerned about the accuracy of the simple N decision methods, and even the more elaborate DSS, given the major changes in soil fertility and cropping systems that have occurred since those tools were developed. The resulting uncertainty in fertilizer recommendations exists for both advisors who are well trained and familiar with the research on which tools were developed, as well as those newer to the industry who have not lived through the era of N workshops and training packages, and are using a DSS ‘black box’ without understanding the embedded assumptions and caveats.**

**The smaller relative contributions of both N and S derived from soil organic pools compared to that from synthetic fertilizer inputs on a crop by crop basis is increasing the pressure on advisors to achieve a ‘correct’ fertilizer decision. Given the uncertainty in seasonal forecasting, and hence likely nutrient demand, advisors are less interested in fine tuning recommendations than they are in ensuring there is an adequate nutrient buffer to meet any unexpected crop demand. Similarly, better understanding the characteristics of events that generate N or S losses, the soil properties which amplify or minimize the risks and the appropriate management response are areas of concern.**

 **Much of the information on soil N supply has been integrated into the main Decision Support Systems and some ‘rules of thumb’ used by industry to derive a fertilizer recommendation. However few DSS or advisors factor in environmental losses or even consider S. There is considerable resistance to developing ever more detailed, process-driven DSS’s for use by time-poor advisors, but building on existing DSS used by commercial providers and improving the ways of delivering that information in real time offer opportunities.**

**The integrated review, advisor survey and DSS overview have been distilled into a set of regionally-focussed recommendations for future R, D and E investment (Table 8), with recommendations across the R, D and E spectrum. The balance between investments in N and S should be heavily skewed in favour of N, given the impact that it has on productivity and the importance it plays in both the costs of production and the profitability of grains cropping. However it is very obvious that a level of basic investment is required to improve S management in these systems.**

**The R and D investment should be focussed on both definitive research around the nature and extent of N (and S) losses from both soil and fertilizer sources, and more applied research to test the validity and robustness of current N and S mineralization assumptions in more intensive, cereal and oilseed-dominated farming systems under reduced or zero tillage. The interaction between fertilizer application strategies, nutrient losses and crop recovery should also be addressed. In terms of E investment, there is a clear need to train the advisor and reseller community in the basics of N (and S) management and fertilizer decision making processes, given the significant generational turnover in both the reseller and advisor community, combined with the general absence of succession planning and on the job mentors for younger staff. There are many new advisors who have not undergone basic training and who are working on the basis of a poorly understood set of assumptions that may or may not be still relevant.**

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1. Introduction

Effective nutrient management strategies underpin the productivity and profitability of all Australian grain production systems, with the removal of nutrients in harvested product a significant challenge to the long term sustainability of cropping industries. Historically, nutrient removal has been buffered to varying extents by the reserves of organic and inorganic nutrients in the soil, with synthetic fertilizer inputs generally not employed to counter removal until an economic response to applied nutrients can be achieved, and even then applications typically only target economic rates rather than countering crop removal or rebuilding soil reserves. The result of such practices has been a steady decline in in soil nutrient reserves and an increasing reliance on synthetic fertilizer nutrients to meet seasonal crop demands, such that fertilizer inputs now commonly comprise the single largest variable input costs for many growers. Despite this increasing fertilizer use, there is growing evidence that much of Australia’s crop production continues to exploit soil nutrient reserves. For example, Lake (2012) has hypothesized that much of the stagnation in temperate cereal production can be related to inadequate nitrogen (N) inputs in the cropping system, while Bell *et al.* (2010) have highlighted the negative balances for other nutrients (phosphorus [P], potassium [K] and sulfur[S]), as well as N, in subtropical grains systems in NE Australia.

In addition to this declining background fertility, there have been a number of fundamental changes to grain cropping systems that have altered the historical supply and demand paradigms upon which many of the nutrient management strategies had been developed. These include a move towards more intensive/continuous cropping, the adoption of stubble retention and zero tillage systems and the declining frequency of legume species in farming systems. These trends have resulted in rapid increases in regional diversity that have yet to be reflected in nutrient management advice at appropriate scales.

One of the key factors in developing effective and efficient fertilizer application strategies for crops lies in understanding the availability of soil nutrient reserves in relation to crop nutrient demand, with the deficit or surplus of plant available nutrient linked to a decision to either apply fertilizer or not. To further refine that decision into a rate of a specific fertilizer product and an application strategy requires more in-depth understanding of the efficiency with which that applied fertilizer can be recovered by the crop and utilized internally to produce grain yield. The former is particularly important, and can be considered a function of the distribution and activity of plant roots in the fertilized zone (with that zone including profile layers where nutrient has been moved by soil water) during the period of crop nutrient acquisition, modified by any environmental losses. Clearly, a good understanding of both supply of plant available nutrients, the effectiveness of different fertilizer application strategies and knowledge of potential losses are fundamental to achieving profitable and productive cropping systems.

Plants acquire most nutrients they need in mineral form from the soil solution. For nutrients such as N and S, where generally the overwhelming majority of soil nutrient stores are held in organic form, the concentration of the mineral forms in the soil solution is determined by the net effect of microbially-mediated immobilization or mineralization processes. This biological nutrient cycling of N and S add a level of complexity to prediction of nutrient release dynamics and plant-available reserves which, despite considerable research effort, continues to limit the ability to accurately predict the N and S available to a crop in the coming season. The uncertainty in predictions is increased by the vulnerability of both soil and fertilizer-derived N and S to a variety of loss processes (leaching through the soil profile and gaseous loss to the atmosphere) when in their plant-available mineral forms in the soil solution. It is therefore not surprising that the Australian grains industry continues to grapple with ways to improve fertilizer N and S decisions.

Against a backdrop of low commodity prices and rising costs of crop inputs, there is continuing pressure to better define availability of essential nutrients in order to rationalize fertilizer investment. This pressure is greatest with N, which is by far the dominant component of the fertilizer budget of Australian grain growers. The emergence of other nutrient constraints (like S) is requiring growers to either increase their overall investment in fertilizer inputs or develop ways to diversify nutrient investment across a rotation or farming system. This increasing complexity in nutrient management has driven the undertaking of this review, which seeks to identify knowledge gaps and suboptimal management strategies that are collectively limiting the ability of the Australian grains industry to maximize N and S use efficiency and derive productivity gains from expensive fertilizer investment.

1. Review aims and structure

The aims of this review have been –

* To undertake a technical review of the factors determining relationships between soil organic matter (OM) and nutrient availability (particularly N), including the rates of N mineralisation and potential losses of mineral N via different pathways, and to identify opportunities for improved fertilizer N management.
* To understand the strengths and weaknesses of processes used in commercial industry (especially advisors and the fertilizer industry) to derive N fertilizer recommendations, and to identify both perceived knowledge gaps and any inconsistencies between existing DSS and rules of thumb used by advisors and the technical understanding from the literature.
* To compile a list of (regionally-based) recommendations for future GRDC investment to improve the understanding of N and S dynamics in the Australian grains industry and to deliver a framework for better fertilizer decisions for growers.

This review has been undertaken from two different perspectives, both of which aim to identify knowledge gaps and future R, D and E priorities for future investment. The first component of the review was undertaken from a technical perspective, and focussed on the level of understanding of the processes influencing N and S availability to crops (from both soil and fertilizer sources) in the published and grey literature, primarily with an Australian focus. This component identified knowledge gaps and priorities for future research investment.

The second was a national assessment of the industry approach to N fertilizer management decisions through a detailed survey of advisors who are responsible for delivering fertilizer advice, with some limited benchmarking of this process against grower clients. This involved survey questionnaires and follow up in depth interviews with a subset of participants, with a focus on the level of understanding (and uncertainty) surrounding different components of that fertilizer decision. Information from this process was used to derive a set of perceived gaps in knowledge and extension/training needs to better equip the industry for getting fertilizer decisions ‘right’. Due to the limited use of S in most fertilizer programs, this survey focussed exclusively on N.

A final integrative section of this review then examined the consistency (or otherwise) of perceived knowledge gaps between the research and agricultural advisor communities, as well as looking at the effectiveness of the current decision support tools, processes and rules of thumb used to make N and S recommendations. This analysis is focussed on deriving an industry roadmap that can be used to prioritize investment (on a regional basis) that will lead to improved N and S recommendations and greater returns from fertilizer investment.

1. Review of existing scientific knowledge

The following technical reviews seek to document our understanding of the key processes that impact on soil N and S supply and off-site losses, document how well this understanding is reflected in industry decision support tools and identify key knowledge gaps for future research investment. There has been a focus on studies from Australia, but where these are limited, reference to overseas information has been sourced. There has also been a clear emphasis on sources of peer reviewed/independently verified information.

* 1. Processes affecting soil N supply

Current approaches for predicting N fertilizer applications require the producer to estimate the likely crop N requirement (target yield, based on seasonal outlook, and grain protein content) and then determine to what extent the soil will meet this need from the mineral N pool and soil organic matter mineralisation, with fertilizer then used to meet any shortfall. Consequently, decision support models for predicting N fertilizer requirements rely on a number of quantitative and qualitative assessments each season including:

• Measurement or estimation of the available mineral N in the soil profile at planting;

• Estimation of the likely net mineralisation of N from soil organic matter and/or crop residues during the season that will contribute to the available N pool;

• The efficiency of recovery of soil- applied N by the crop; and

• Net off-site losses of N or immobilisation in the soil organic matter pool.

Variability in any or all of these components has the capacity to significantly alter an N fertilizer decision, and so have a major impact on the profitability of that fertilizer investment. We argue that a major cause of the current lack of confidence in existing approaches to managing N in grains is the uncertainty surrounding the magnitude and seasonal variability of these key processes at a local scale, in addition to a poorly developed understanding of how these processes are likely to vary across different agro ecological regions and soil types.

* + 1. **Nitrogen mineralisation**

Historically ley cropping systems in dryland Mediterranean systems built-up SOM during an extended pasture phase, with mineralisation and nutrient release occurring in subsequent cropping phases (Barrow 1969; Probert 1993). With the transition to more intensive cropping systems and prior to the adoption of legumes and fertilizer in cropping systems, depletion of soil organic matter (SOM) stocks was identified as a major cause of declining soil fertility and wheat yields in Australia (Hamblin and Kyneur 1993). Adoption of improved pastures and the use of superphosphate in newer farming systems helped mitigate this loss of carbon (C) and nitrogen (N) in some regions, with soil C reportedly increasing from 0.8 to 2.0%, and soil N from 0.04 to 0.12% on a sandy soil in Western Australia after implementation of improved pasture management (Barrow 1969). In South Australia, significant depletion of total N stores in topsoils under continuous cropping (11 kg ha-1 yr-1 were reversed by the inclusion of just 1 pasture year in a 3 year rotation (Grace and Oades 1994 ). McDonald (1989) found annual increments in soil N from legume based pastures ranging from 19-117 kg N ha-1 (average 63 kg N ha-1) from 15 studies across southern Australia. Subsequently, increasing affordability and use of N fertilizer has also supplemented SOM reserves – but SOM remains a major store and source for plants to obtain the nutrients needed for growth (Smith *et al.* 2000).

The historic decline in SOM in many cropping systems means that peak demand for N often exceeds the capacity of the soil to supply N in well managed, high yielding environments. The need to provide adequate nutrition is apparent in realising potential grain yields across a range of environments. It is therefore critical to, as accurately as possible estimate the requirement for N in crops (based on yield potential) and the net supply of N that results from several processes including but not limited to N mineralisation resulting from the breakdown of SOM and plant residues. While legume-based systems replenish nutrients via N2 fixation and suggest sufficient N for plant requirements (Myers *et al.* 1997; Anderson *et al.* 1998b; Fillery 2001; Crews and Peoples 2005), this is not always the case (Hossain *et al.* 1996). For low input Australian farming systems in particular, up to 80% of N supply to wheat can be derived from soil (Angus 2001).While this can include small amounts of N generated from free-living fixation (Gupta *et al.* 2006) and environmental deposition –non-legumes rely dominantly on decomposition of SOM and fresh residues for N (Smith *et al.* 2000).

Nitrogen in an organic form is either insoluble or held in the organic material itself and not plant available. The amount of organic N being returned to the soil across Australian grains systems is equivalent to half of the nitrogen fertilizer applied on an annual basis (Gupta *et al.* 1994b). To gain access to these nutrients, the organic matter has to be mineralised to a form that the plants can use and be surplus to microbial requirements. Nitrogen mineralisation is the decomposition of chemical compounds in organic matter to plant-available forms such as ammonium (NH4+) and nitrate (NO3-) by microorganisms. Nitrogen consumption pathways including microbial immobilisation, leaching and gaseous losses occur simultaneously and reduce the amount of N available for plant uptake. Thus the strategic use of fertilizers (Rowland *et al.* 1988; Mason and Rowland 1990; Angus 2001) to offset plant N uptake is required.

Soil organic matter (SOM) stores approximately 95% of N held in soils (total N) with annual turnover of SOM in Australian dryland systems measured at 2% (Angus *et al.* 2000), though this varies depending on soil depth and seasonal conditions - in particular soil moisture and temperature (Xu *et al.* 1996). In well managed, high yielding environments peak demand for N often exceeds or is ill-timed to meet the capacity of the soil to supply N and during peak demand of the growing season, estimates suggest less than 40% of the modelled maximum crop demand of 5.6 kg N ha-1 d-1 is available from non-fertilizer sources (Angus *et al.* 1998). It is therefore critical to, as accurately as possible estimate the requirement for N in crops (based on yield potential) and the net supply of N that results from several processes including but not limited to N mineralisation resulting from the breakdown of SOM and plant residues (Ladd *et al.* 1983; Amato *et al.* 1987; Xu *et al.* 1996).

Soil total N content for Western Australian cropping soils averages 2236 kg N ha-1 (n=1319 sites, 0–30 cm, from www.soilquality.org.au) and 2898 kg N ha-1 in subtropical Queensland (Dalal *et al.* 2013). Assuming an annual SOM turnover of 2%, 45 kg N ha-1 is mineralised on average from the surface soil (0–30 cm) in Western Australia. This could supply the equivalent of approximately 80% of the N requirement for an average 2 t/ha wheat crop achieving 11% grain protein (56 kg N/ha calculated using straw N content equivalent to 33% of grain N, root N equivalent of 10% of above ground N; Angus 2001). Using the average fertilizer N application rate in Western Australia of 30 kg N ha-1 (Angus 2001; Brennan and Bolland 2007), between 60 to 90% of N available for plant uptake can therefore be derived from SOM. In Western Australia the amount of N cycling annually through soils would suggest sufficient N supply for crop growth without the requirement for fertilizer (Murphy *et al.* 1998a; Fillery 2001; Hoyle and Murphy 2011). However accumulation of high levels of mineral N during autumn (Table 1), clearly illustrates asynchrony between supply and demand. Understanding the processes that determine the magnitude and timing of soil N supply, enables placement and timing of mineral N fertilizers to be better managed to match plant demand (Murphy *et al.* 2009).

Factors influencing the ability of soil to supply N include the amount of organic N, the mineralisation rate and rate limiting factors such as carbon availability, moisture and temperature (Campbell *et al.* 1981). Seasonal longevity in terms of actively growing plants, soil disturbance and residue loads also serve to vary the amount of N mineralisation. Laboratory assays of soils from southern NSW (Gupta *et al.* 1994a) have confirmed that potentially mineralisable N stores are dependent on residue retention ranging from 8% of the total N in burnt systems to 22% after 15 years of residue retention. Under non-limiting field conditions in southern NSW Angus et al. (1998) predicted 0·092% of total N could be mineralised daily, though rates declined at lower temperature and soil water content. Daily rates of mineralisation during the wheat growing season in Western Australia of 0·056 and 0·108% of total soil N (Murphy *et al.* 1998a) depending on rotational sequence were not dissimilar. Changes in N cycling are often not reflected in total soil pools due to the slow rate of change and large background - but to within (and between) season variance associated with process rate drivers such as temperature, transient influences on soil water and yield potential. Subsequently these values differ somewhat from the average mineralisation rate constants (*k)* for potential N mineralisation in surface soils of Queensland given by Campbell et al. (1981) of 0.058, 0.031, and 0.018 week-1 at 35°C, 25°C and 15°C respectively.

The sensitivity of the microbial community to environmental drivers, together with the composition and lability of organic matter in soils, determine the decomposition rate and thus the supply of nutrients (Macdonald and Baldock 2010; Murphy 2015). In many Australian soils (particularly in no till systems), organic matter and associated soil biota are dominant in topsoil and a strong negative gradient exists with increasing depth (Murphy *et al.* 1998b). Over 85% of N mineralised in soils to a depth of 20 cm originates from the top 10 cm, and 40-70% of this from the top 2 cm (Young *et al.* 1995; Purnomo *et al.* 2000), suggesting the organic horizon is a primary source of mineralised N and that maintenance of the top 2 cm of soil is critical to N supply. This may contribute to differences in N supply, with less than 20% of N in root material and 30% of freshly added residues available to subsequent crops in southern Australia (Ladd and Amato 1986; Russell and Fillery 1996; Russell and Fillery 1999).

At low temperature and under dry conditions there is limited microbial demand for mineralisable N, while at high temperature where moisture is not limiting SOM is mineralised rapidly and limitations to substrate availability can slow N release (Wang *et al.* 2004). Low temperatures in southern Australia often limit early season mineralisation and several studies have shown N demand within season to exceed supply by as much as 2–3 times, with maximum supply occurring several weeks later than peak demand (Angus 2001). This suggests the need for better understanding of the processes leading to accumulation of mineral N before sowing (between-season mineralisation) and the amount remaining at maturity (in-crop net mineralisation). Net mineralisation rates and N accumulation (kg N ha-1) for a range of Australian soils are presented in Table 1.

* Net N mineralisation

Net mineralisation either reported in or between growing seasons, is the net balance between N supply (SOM and plant derived) and N losses which includes both biotic (e.g. immobilisation, denitrification) and abiotic processes (e.g. leaching, volatilisation). Between growing seasons, mineralisation is most often measured and reported as the difference (kg N ha-1) in soil mineral N between harvest and the subsequent break of season to a depth of up to 2.0m using cores extracted at variable depth increments (Table 1). Murphy *et al.* (1998a) showed that similar net mineralisation values may result from very different summations of different gross N mineralisation and immobilisation rates (Table 1). In-season methods generally use *in-situ* incubation of intact cores (Raison *et al.* 1987; Stein *et al.* 1987) or a variation of this method (Anderson *et al.* 1998b). In-season measures are generally for periods of between 2 and 6 weeks at a time and either run continuously or are repeated at intervals. Net N mineralisation rates are generally calculated using the net amount of N mineralised over a specified time and represented on a daily basis per unit area. In some studies measures have been reported in-field for periods of up to 2 years (Anderson *et al.* 1998b). In others it can be as short as weeks. In some studies in-season net mineralisation has also been calculated using changes in soil N plus crop N uptake (Angus *et al.* 2000).

Legume contributions to soil N supply, N fertilizer efficiency and plant N uptake dominate nitrogen studies in Australian cropping soils. A total of 28 publications report net N mineralisation resulting from SOM turnover or provide sufficient information to calculate mineralisation rates (Table 1) across a larger number of sites. Much of what has been reported was conducted between 1986 and 2000, and in some instances for sites sampled decades earlier. Only 13 Australian studies on N mineralisation were identified to have taken place in the past 15 years, nine of which were conducted in WA (Table 1, Table 2). Nationally New South Wales dominates study sites (16) with Western Australia (13), Queensland (10), Victoria (4), South Australia (2) and the ACT (1) with lesser numbers of sites. Xu et al. (1996) presented data for 123 sites across southern Australia. Predominantly studies are reported for slightly acid to acid soils where either low or no fertilizer N was applied, with only seven studies (with multiple treatments and sites) reported for alkaline soils (Table 1). Nitrogen losses resulting from the removal of organic N as harvestable products, microbial immobilisation, leaching, denitrification and gaseous loss which occur simultaneously to mineralisation and influence net N available were either not determined or are not reported here.

Net N mineralised varied significantly from -28 to 140 kg N ha-1 (Table 1) with net immobilisation of N noted in some northern and Western Australian systems (Doughton *et al.* 1993; Anderson *et al.* 1998b; Marcellos *et al.* 1998; Schwenke *et al.* 1998). Significant amounts of between-season mineralisation (Table 1) and low plant N demand result in accumulation of mineral N before sowing. The length of the fallow season, summer rainfall events and any losses resulting from plant uptake strongly influence the contribution of between-season mineralisation to annual net N mineralised. N mineralisation often occurs at a rate faster than is measured within season and while short-lived can strongly influence N mineralisation and accumulation prior to sowing. For example in Western Australia dry fallow conditions lessened the contribution of between season mineralisation to 14-21% of total net N mineralised, while higher mineralisation during a wetter fallow period could increase this to between 25 and 53% (Anderson *et al.* 1998b). Differences in estimates for in-crop net mineralisation have been linked to more extended periods of soil moisture associated with length of cropping phase, cultivation and stubble management (Angus *et al.* 1998). Angus et al. (2000, 2006) subsequently determined changes in net N mineralisation per unit rainfall of 0.37 to 0.62 kg N ha-1 mm-1 and 0.51 kg N ha-1 for each additional mm of available water during the fallow period. An average increase in N mineralisation of 0.054 kg N ha-1 d-1 was determined for each 1% rise in soil volumetric water below 15% soil water (Angus *et al.* 2006).

Table 1. Net N mineralisation rates (kg N ha-1 d-1) reported in-season and between-season for dryland crop and pastures across a range of Australian soils.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop (previous) | Location and annual rainfall (mm)a | Climate | Topsoil texture | SOCb(%) | Lower sample depth(cm) | Study period | In-season(kg N ha-1 d-1) | Between-season (kg N ha-1 d-1) | Reference |
|  |  |  |  |  |  |  | Daily | Cum. | Daily | Cum. |  |
| Wheat (legume) | Moora, WA; 360 | Mediterranean | Sandy | 1.21 | 21 | Nov.94-Jun.95 |  |  | 0.1 | 13-24 | Anderson et al. (1998b) |
| Wheat (legume) | Moora, WA; 360 | Mediterranean | Sandy | 1.21 | 21 | Nov.95-Jun.96 |  |  | 0.2 | 30-63 | Anderson et al. (1998b) |
| Wheat (legume) | Moora, WA; 360 | Mediterranean |  Sandy | 1.21 | 21 | Jul.95-Nov.95 | 0.3-0.5 | 64-78 |  |  | Anderson et al. (1998b) |
| Wheat (pasture), F | Harden, NSW; 600\* | Temperate | Loamy to clay | ND | 150 | Jun-Dec |  | 55 |  | ND | Angus et al. (1998) |
| Wheat (pasture), F | Harden, NSW; 600\* | Temperate | Loamy to clay | ND | 10 | Jun-Dec | 0.2-0.5e |  |  |  | Angus et al. (1998) |
| Wheat (pasture), F | Junee Reefs, NSW; 530 | Temperate | Loamy to clay | 1.33 | 150 | Aug-Oct |  | 43 |  | 148 | Angus et al. (1998) |
| Wheat (pasture), F | Junee Reefs, NSW; 530 | Temperate | Loamy to clay | 1.33 | 10 | Aug-Oct | 0.1-0.9e |  |  |  | Angus et al. (1998) |
| Wheat (pasture), F | Gininderra, NSW; 696 | Temperate | Sandy to loam | 1.92 | 150 | Jun-Nov |  | 74 |  | 122 | Angus et al. (1998) |
| Wheat (pasture), F | Gininderra, NSW; 696 | Temperate | Sandy to loam | 1.92 | 10 | Jun-Nov | 0.3-1.2e |  |  |  | Angus et al. (1998) |
| Wheat (pasture), F | Ariah Park, NSW; 470 | Temperate | Loam | 1.34 | 150 | Jul-Nov |  | 90 |  | 195 | Angus et al. (1998) |
| Wheat (pasture), F | Ariah Park, NSW; 470 | Temperate | Loam | 1.34 | 10 | Jul-Nov | 0.1-1.1e |  |  |  | Angus et al. (1998) |
| Wheat (pasture), F | Galong, NSW; 689 | Temperate | Loamy to clay | 0.89 | 150 | Jul-Dec |  | 60 |  | 121 | Angus et al. (1998) |
| Wheat (pasture), F | Galong, NSW; 689 | Temperate | Loamy to clay | 0.89 | 10 | Jul-Dec | 0.1-0.8e |  |  |  | Angus et al. (1998) |
| Wheat (wheat), F | Reefton, NSW; 482 | Temperate | Loam | 1.13 | 150 | Aug-Nov |  | 75 |  | 67 | Angus et al. (1998) |
| Wheat (wheat), F | Reefton, NSW; 482 | Temperate | Loam | 1.13 | 10 | Aug-Nov | 0.2-0.9e |  |  |  | Angus et al. (1998) |
| Wheat (lucerne) | Junee, NSW; 490 | Temperate | Loam | 0.85 | 200 | Nov.95-Apr.96, |  |  | 0.3-0.9 | 58-190 | Angus et al. (2000) |
| Wheat (lucerne) | Junee, NSW; 490 | Temperate | Loam | 0.85 | 200 | May.96-Dec.96 | 0.1-0.2 | 14-39 |  |  | Angus et al. (2000) |
| Canola (wheat) | Junee, NSW’; 490 | Temperate | Loam | 0.85 | 200 | Dec.96-May.97 |  |  | 0.3-0.5 | 46-85 | Angus et al. (2000) |
| Canola (wheat) | Junee, NSW; 490 | Temperate | Loam | 0.85 | 200 | May.97-Nov.97 | 0.5-0.6 | 85-110 |  |  | Angus et al. (2000) |
| Wheat (canola) | Harden, NSW; 608 | Temperate | Clay loam | 1.30 | 60 | Feb.02-Apr.02 |  |  | 0.7 | 34 | Angus et al. (2006) |
| ND (wheat) | Harden, NSW; 608 | Temperate | Clay loam | 1.30 | 10 | Sep.03-Nov03 | 0.3 |  |  |  | Angus et al. (2006) |

**Table 1 (cont.)** Net N mineralisation rates (kg N ha-1 d-1) reported in-season and between-season for dryland crop and pastures across a range of Australian soils.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop (previous) | Location and annual rainfall (mm)a | Climate | Topsoil texture | SOCb(%) | Lower sample depth(cm) | Study period | In-season(kg N ha-1 d-1) | Between-season (kg N ha-1 d-1) | Reference |
|  |  |  |  |  |  |  | Daily | Cum. | Daily | Cum. |  |
| Wheat (ND) | Harden, NSW; 608 | Temperate | Clay loam | 1.30 | 10 | Sep.04-Nov04 | 0.4 |  |  |  | Angus et al. (2006) |
| Wheat (canola) | Old Junee, NSW; 505 | Temperate | Kandosol | ND | 60 | Dec.96-Jul.97 |  |  | 0.4 | 88 | Angus et al. (2006) |
| Sorghum (fallow) | Emerald, QLD; 553 | Subtropical | Cracking clayc | 0.97 | 75 | Jan.92-Jan.94 | 0.24 |  | 0.07 |  | Armstrong et al. (1996) |
| Sorghum (sorghum) | Emerald, QLD; 553 | Subtropical | Cracking clayc | 0.97 | 75 | Jan.92-Jan.94 | 0.18 |  | 0.04 |  | Armstrong et al. (1996) |
| Chickpea () | QLD; ND | Subtropical | NDd | ND |  |  |  |  | 0.3 |  | Dalal et al. (1994) |
| Wheat () | QLD; ND | Subtropical | NDd | ND |  |  |  |  | 0.2 |  | Dalal et al. (1994) |
| Lucerne () | QLD; ND | Subtropical | NDd |  |  |  |  |  | 0.6 |  | Dalal et al. (1994) |
| LT Cropping | Glenmoral, QLD; 720 | Subtropical | Cracking clay | 1.63 | 40 | Sep.84-Nov.05 | 0.3d | 94d |  |  | Dalal et al. (2013) |
| LT Pasture | Glenmoral, QLD; 720 | Subtropical | Cracking clay | 1.93 | 40 | Nov.82-Nov.05 | 0.2d | 53d |  |  | Dalal et al. (2013) |
| Wheat (wheat) | Longerenong, VIC; 415 | Semi-arid | Cracking clay | ND | 120 | ND.12 |  | 41 |  |  | Dunsford et al. (2015) |
| Wheat (canola) | Longerenong, VIC; 415 | Semi-arid | Cracking clay | ND | 120 | ND.12 |  | 40 |  |  | Dunsford et al. (2015) |
| Wheat (canola/lucerne) | Longerenong, VIC; 415 | Semi-arid | Cracking clay | ND | 120 | ND.12 |  | 113 |  |  | Dunsford et al. (2015) |
| Wheat (fallow) | Longerenong, VIC; 415 | Semi-arid | Cracking clay | ND | 120 | ND.12 |  | 48 |  |  | Dunsford et al. (2015) |
| Wheat (various) | Walpeup, VIC; 334 | Semi-arid | Sandy loamc | ND | 120 | ND.12 |  | 24-35 |  |  | Dunsford et al. (2015) |
| Wheat (wheat) | Mingenew, WA; 402 | Mediterranean | Sand | 0.6 | 10 | Jun.10-Jul.10 | 0.3 |  |  |  | Flower et al. (2012) |
| Wheat (wheat) | Cunderdin, WA; 296 | Mediterranean | Sandy clay loamc | 1.0 | 10 | May.10-Jun.10 | 0.1 |  |  |  | Flower et al. (2012) |
| Wheat (lupin) | Wagga, NSW; 523 | Temperate | Clay loamd | 1.5 | 15 | Apr.89-Dec.89 (90) |  | 165 |  |  | Heenan and Chan (1992) |
| Wheat (pasture) | Wagga, NSW; 523 | Temperate | Clay loamd | 1.5 | 15 | Apr.89-Dec.89 (90) |  | 239 |  |  | Heenan and Chan (1992) |

**Table 1 (cont.)** Net N mineralisation rates (kg N ha-1 d-1) reported in-season and between-season for dryland crop and pastures across a range of Australian soils.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop (previous) | Location and annual rainfall (mm)a | Climate | Topsoil texture | SOCb(%) | Lower sample depth(cm) | Study period | In-season(kg N ha-1 d-1) | Between-season (kg N ha-1 d-1) | Reference |
|  |  |  |  |  |  |  | Daily | Cum. | Daily | Cum. |  |
| Wheat (wheat) | Wagga, NSW; 523 | Temperate | Clay loamd | 1.5 | 15 | Apr.89-Dec.89 (90) |  | 96 |  |  | Heenan and Chan (1992) |
| Wheat (lupin) – SR | Wagga, NSW; 523 | Temperate | Clay loamd | 1.5 | 15 | Apr.89-Dec.89 (90) |  | 174 |  |  | Heenan and Chan (1992) |
| Wheat (lupin) – SB | Wagga, NSW; 523 | Temperate | Clay loamd | 1.5 | 15 | Apr.89-Dec.89 (90) |  | 156 |  |  | Heenan and Chan (1992) |
| Fallow (cereal) | Bethungra, NSW; 536 | Temperate | Loam | 0.83 | 10 | Jan.94-Apr.94, Dec.94-Jan.95, Jan.96-Jun.96 |  |  | 0.3 | 31 | Kirkegaard et al. (1999) |
| Fallow (legume) | Bethungra, NSW; 536 | Temperate | Loam | 0.83 | 10 | Jan.94-Apr.94, Dec.94-Jan.95, Jan.96-Jun.96 |  |  | 0.4-0.6 | 50 | Kirkegaard et al. (1999) |
| Fallow (canola) | Bethungra, NSW; 536 | Temperate | Loam | 0.83 | 10 | Jan.94-Apr.94, Dec.94-Jan.95, Jan.96-Jun.96 |  |  | 1.0 | 94 | Kirkegaard et al. (1999) |
| Wheat (pasture) | Ginninderra, NSW; 696 | Temperate | Sandy loam | 1.40 | 10 | Feb.97-Apr.97 |  |  | 0.3 | 12 | Kirkegaard et al. (1999) |
| Canola (pasture) | Ginninderra, NSW; 696 | Temperate | Sandy loam | 1.40 | 10 | Feb.97-Apr.97 |  |  | 0.6 | 24 | Kirkegaard et al. (1999) |
| Wheat (wheat) | Tarlee, SA; 470 | Semi-arid | Loam | 1.0 | 10 | Jun.91-Sep.91 | 0.49 |  |  |  | Ladd et al. (1994)  |
| Wheat (wheat), F | Tarlee, SA; 470 | Semi-arid | Loam | 1.0 | 10 | Jun.91-Sep.91 | 0.63 |  |  |  | Ladd et al. (1994)  |
| Wheat (pasture) | Tarlee, SA; 470 | Semi-arid | Loam | 1.0 | 10 | Jun.91-Sep.91 | 0.64 |  |  |  | Ladd et al. (1994)  |

**Table 1 (cont.)** Net N mineralisation rates (kg N ha-1 d-1) reported in-season and between-season for dryland crop and pastures across a range of Australian soils.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop (previous) | Location and annual rainfall (mm)a | Climate | Topsoil texture | SOCb(%) | Lower sample depth(cm) | Study period | In-season(kg N ha-1 d-1) | Between-season (kg N ha-1 d-1) | Reference |
|  |  |  |  |  |  |  | Daily | Cum. | Daily | Cum. |  |
| Wheat (chickpea) | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 | May-Oct.89, 90, 92, 93 | 41 |  |  |  | Marcellos et al. (1998) |
| Wheat (chickpea) | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 | Nov-Feb.89, 90, 92, 93 |  |  |  | 89 | Marcellos et al. (1998) |
| Wheat (wheat) | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 | May-Oct.89, 90, 92, 93 | 26 |  |  |  | Marcellos et al. (1998) |
| Wheat (wheat) | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 | Nov-Feb.89, 90, 92, 93 |  |  |  | 56 | Marcellos et al. (1998) |
| Cont. fallow  | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 |  |  |  | 0.08-0.16 |  | Marcellos et al. (1998) |
| Fallow (chickpea) | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 | Oct.89-Apr.90 |  |  | 0.17-0.21 |  | Marcellos et al. (1998) |
| Fallow (wheat) | North Star, NSW; 616 | Subtropical | Clayey, clay loamc | ND | 120 | Oct.90-Apr.91 |  |  | 0.07-0.12 |  | Marcellos et al. (1998) |
| Wheat (wheat) | East Beverley, WA; 387 | Mediterranean | Loamy sand duplex | ND | 10 | May.94-Nov.94 | 0.25 | 43 | 0.1-0.2 |  | Murphy et al. 1998a |
| Wheat (lupin) | East Beverley, WA; 387 | Mediterranean | Loamy sand duplex | ND | 10 | May.94-Nov.94 | 0.34 | 59 |  |  | Murphy et al. 1998a |
| Wheat (pasture) | East Beverley, WA; 387 | Mediterranean | Loamy sand duplex | ND | 10 | May.94-Nov.94 | -0.16 | -28 |  |  | Murphy et al. 1998a |
| Pasture (pasture) | East Beverley, WA; 387 | Mediterranean | Loamy sand duplex | ND | 10 | May.94-Nov.94 | 0.70 | 122 |  |  | Murphy et al. 1998a |
| Wheat (Fallow, legume) | Dooen, VIC; 415 | Grassland | Grey crack clay | ND | 200 | Fallow.87-91 |  |  |  | 66-220 | O’Leary and Connor (1997) |
| Wheat (fallow, legume) | Walpeup, VIC; 334 | Temperate | Sandy loam | ND | 150 | Fallow.87-91 |  |  |  | 130-222 | O’Leary and Connor (1997) |
| Wheat (1L-2C) | Wagga, NSW; 523 | Temperate | Loamy | 1.80 | 20 | May.93-Nov.93 | 0.0-0.67 | 60 |  |  | Purnomo et al. (2000) |

**Table 1 (cont.)** Net N mineralisation rates (kg N ha-1 d-1) reported in-season and between-season for dryland crop and pastures across a range of Australian soils.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop (previous) | Location and annual rainfall (mm)a | Climate | Topsoil texture | SOCb(%) | Lower sample depth(cm) | Study period | In-season(kg N ha-1 d-1) | Between-season (kg N ha-1 d-1) | Reference |
|  |  |  |  |  |  |  | Daily | Cum. | Daily | Cum. |  |
| Wheat (pasture) | Harden, NSW; 598 | Temperate | Loamy | ND | 10 | Jun.83-Dec.83, 84 | 0.3-0.68 | 55-113 |  |  | Stein et al. (1987) |
| Fallow (legume) | Formartin, QLD; 634 | Temperate | Cracking clayc | ND | 120 | Dec.76-May.77 |  |  | 0.36 | 53-85 | Strong et al. (1986) |
| Fallow (Cereal) | Formartin, QLD; 634 | Temperate | Cracking clayc | ND | 120 | Dec.76-May.77 |  |  | 0.19 | 21-27 | Strong et al. (1986) |
| Fallow (Oats) | Formartin, QLD; 634 | Temperate | Cracking clayc | ND | 120 | Dec.76-May.77 |  |  | 0.21 | 40 | Strong et al. (1986) |
| Wheat (wheat) | Wagga, NSW; 524 | Temperate | Loam | 1.42 | 10 | Jun.93-Nov.93 | 0.53 | 53 |  |  | Smith et al. (2000) |
| Cereal (various) | 123 sites, SA | Temperate | Variousd | 0.4-2.4 | 10 | 4 weeks pre-sow.90-92 | 0.5-4.3g | 14-121g |  |  | Xu et al. (1996) |
| Cereal (various) | 123 sites, SA | Temperate | Variousd | 0.2-2.0 | 20 | 4 weeks pre-sow.90-92 | 0.2-1.5g | 5-42g |  |  | Xu et al. (1996) |
| Cropping (various) | 6 sites, southern QLD; 480-670 | Subtropical | Clayeyc, Sandy loam | 0.77-2.23 | 10 | 30 weekse | 0.15-0.42e, g |  |  |  | Dalal and Mayer (1987) |
| Various (wheat) | Euston, SA; 321 Waikerie, SA; 268 | Semi-arid | Loamy sand | 0.8 | 10 | Annuale |  | 46-79e |  |  | Sadras and Baldock (2003) |
| Sorghum (cereal) | Narayen, Qld; 543 | Subtropical | Clay  | 2.31 | 10 | Annual |  | 55 |  | 185 | (Robertson *et al.* 1994) |
| Wheat (pasture) | Wagga, NSW; 572 | Temperate | Clay loam | 1.7 | 15 | Oct.97-May.97 |  |  | 1.1 |  | (Paul *et al.* 2001; Paul and Conyers 2001 ) |
| Fallow (pasture) | Wagga, NSW; 572 | Temperate | Clay loam | 1.7 | 15 | Oct.97-May.97 |  |  | 1.3 |  | (Paul *et al.* 2001; Paul and Conyers 2001 ) |
| Wheat (fallow) | Dooen, Vic; 420 | Temperate | Clay | ND | 60 |  |  | 50g |  |  | (Officer *et al.* 2009) |
| Fallow (wheat) | Birchip, Vic; 375 | Temperate | Sandy loam | ND | 60 |  |  | 48g |  |  | (Officer *et al.* 2009) |

aLong term average annual rainfall (mm); \*Long term data obtained from <http://www.bom.gov.au/climate/data/index.shtml> for length of records at each site.

b0–10 cm

cAlkaline soil

dSoil pH not reported

eCalculated annually

fEstimated from graph

gN mineralisation determined from defined laboratory incubation under controlled conditions

ACT, Australia Capital Territory, F, nitrogen fertilizer added; Inc., incubated under controlled conditions; QLD, Queensland; ND, Not determined; NSW, New South Wales; SA, South Australia; V, various; VIC, Victoria; WA, Western Australia.

Armstrong et al. (1996) also suggest that for cropping systems in central Queensland, opportunistic planting of a second crop can lower rates of N mineralisation associated with lower soil water content and help minimise net losses of N in soils prone to leaching. Clay soils demonstrated lower short term (10 day) net mineralisation rates in subtropical Queensland reportedly associated with greater microbial utilisation of N under pasture (3.1 µg N g soil-1) compared to cropping systems (5.9 µg N g soil-1) - though differences to 10cm depth were minimal (Robertson *et al.* 1993). Longer incubation resulted in lower net N mineralisation under the cropping soils due to depletion of C, whereas mineralisation rates continued to increase in pasture soils (Robertson *et al.* 1993).

In southern cropping systems, variations in soil moisture and temperature influenced both within-season (Hoyle *et al.* 2006) and between-season mineralisation rates (Anderson *et al.* 1998b; Austin *et al.* 2004; Phillips *et al.* 2015). In Western Australia, the balance of N mineralisation, immobilisation and nitrification rates as well as other loss pathways measured at discrete points in time demonstrate the seasonal influence on net N accumulation (Hoyle and Murphy 2006; Cookson *et al.* 2008). Net mineralisation rates determined under controlled conditions are unlikely to be directly related to in-field rates which experience significant diurnal and temporal changes in moisture and temperature. Thus net N mineralisation rates for the same soil sampled in consecutive years from the field can vary significantly (Ladd *et al.* 1994). This temporal and spatial variability in net N mineralisation which can vary by a factor of two between sites within season and pre-season by a factor of three under different crop/pasture systems (Angus *et al.* 1998), make it difficult to interpret the balance between N supply and losses (Barraclough *et al.* 1998; Murphy *et al.* 1998b).

Rotation (Campbell *et al.* 1981; Heenan and Chan 1992; Anderson *et al.* 1998b), tillage (Stein *et al.* 1987; Heenan and Chan 1992; O'Leary and Connor 1997; Angus *et al.* 2006; Cookson *et al.* 2008; Herridge 2011) and stubble retention (Stein *et al.* 1987; Armstrong *et al.* 1996; O'Leary and Connor 1997; Chan *et al.* 2003; Angus *et al.* 2006; Hoyle *et al.* 2006) can have small but variable influences on soil N across soil types and environments through its influence on substrate availability (Ladd *et al.* 1994; Hoyle *et al.* 2006; Fisk *et al.* 2015). Under pasture management systems, mineralisation rates have been measured up to 50% greater than in cropping soils (Kirkegaard *et al.* 1999; Angus *et al.* 2006) and in canola as much as two times greater than either lupin or wheat (Kirkegaard *et al.* 1999; Sadras and Baldock 2003; Osler *et al.* 2004). Nitrogen accumulation in autumn through mineralisation of organic-N from legume-based systems in southern Australia often exceeds 100 kg N ha-1 with N leakage losses of 15-35 kg N ha-1 (Ridley *et al.* 2004). Large errors and spatial variability (Sadras 2002; Sadras and Baldock 2003) often result in a lesser influence for rotational treatments with no significant change.

However accumulated N does not always result in enhanced plant N uptake, suggesting asynchrony between supply and demand. Up to 31 kg N ha-1 was ‘lost’ due to immobilisation of soil N at sowing (O'Leary and Connor 1997). While Angus *et al.* (2006) showed greater net N accumulation prior to sowing in direct drilled versus cultivated soil, there was no cumulative effect on soil total N after 14 years. Often no discernible change or variable changes in mineralisation rates were observed between tillage treatments (Heenan and Chan 1992; Armstrong *et al.* 1996; Cookson *et al.* 2008) between tillage treatments. The generally inconclusive results regarding the effects of management on soil C and N and the very strong influence of climate drivers, suggests the primary means of better utilising soil and fertilizer N is through increased understanding of the timing and magnitude of soil N release. Management influences are likely attributable to small changes in periods of soil moisture and exposure of more stable SOM to decomposition..

* Gross N mineralisation

Gross mineralisation where reported represents the conversion of organic matter to ammonia or ammonium. Measuring gross N mineralisation rates are generally less variable than net N mineralisation in arable soils (Murphy *et al.* 2000; Hoyle *et al.* 2006; Cookson *et al.* 2008; Fisk *et al.* 2015) as consumption processes are excluded when using this method. Gross N mineralisation studies– predominantly in Western Australia (Table 2) measured the rate of 15N decline over 24 h as determined by 15N isotopic dilution both in-field after a mixture of 15N-labelled ammonia (NH3) and air was injected into soil in the ﬁeld (Murphy *et al.* 1997), or under controlled conditions using 15N-labelled ammonium sulphate (NH4)2SO4 and a modified diffusion technique used to prepare samples (Brookes *et al.* 1989; Murphy *et al.* 2003).

Gross N mineralisation measured under controlled conditions demonstrates a logarithmic relationship with SOM turnover in Western Australian soils, the rate of which doubles for each 10°C increase in temperature between 5 and 40°C (Hoyle *et al.* 2006; Luxhøi *et al.* 2008) and substantially higher rates of N mineralisation between 30 and 50°C (Hoyle and Murphy 2006; Luxhøi *et al.* 2008; Table 2). Enhanced N mineralisation rates at high temperature are attributed to the turnover of dead microbial biomass and associated nutrient release (Luxhøi *et al.* 2008). The fate of this mineralised N is in part determined by controls on other N process rates. Nitrification under increasing temperature appears unconstrained, while immobilisation remains unresponsive above 20°C leading to accumulation of mineral N (Cookson *et al.* 2002; Hoyle *et al.* 2006; Luxhøi *et al.* 2008). Little to no build-up of NH4+ or NO3- may be observed at low temperatures (Anderson *et al.* 1998b; Hoyle *et al.* 2006) but due to low plant nutrient demand in summer and rapid mineralisation of SOM, mineral N accumulates and is at risk of being lost during subsequent rainfall events (Anderson *et al.* 1998b; Fillery 2001; Austin *et al.* 2004; Barton *et al.* 2008; Fisk *et al.* 2015).

Studies reporting gross N mineralisation (Table 2) showed no measureable effect of management including tillage (Cookson *et al.* 2008; data not presented) stubble retention (Hoyle and Murphy 2006) and nitrification inhibitors (Fisk et al. 2015) in grain production systems. Thus N fluxes are primarily controlled by climate and soil attributes which influence microbial activity, rather than agricultural management practices such as tillage, rotation and residue management (Murphy *et al.* 2003). Environmental factors also influence N demand and uptake from crops and pastures from season to season, adding complexity to the challenge in matching N supply with demand.

Table 2. Gross nitrogen (N) mineralisation rates (mg N kg dry soil-1 day-1) reported for dryland cropping soils in Western Australia under field and laboratory conditions.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Crop (previous) | Soil texture | Lower depth (cm) | Incubation Temp.(°C) | Gross N mineralisation rate (mg N kg soil-1 d-1) | Reference |
| Wheat (wheat) | Loamy sand duplex | 5, 10 | Field | 0.57 | Murphy et al. (1998a)a |
| Lupin (wheat) | Loamy sand duplex | 5, 10 | Field | 0.74 | Murphy et al. (1998a)a |
| Wheat (pasture) | Loamy sand duplex | 5, 10 | Field | 1.03 | Murphy et al. (1998a)a |
| Pasture (pasture) | Loamy sand duplex | 5, 10 | Field | 1.10 | Murphy et al. (1998a)a |
| Lupin | Sandy | 5 | 17 | 1.3, 1.4 | Osler et al. (2004)a |
| Wheat | Sandy | 5 | 17 | 2.6 | Osler et al. (2004)a |
| Canola | Sandy | 5 | 17 | 3.2, 6.0 | Osler et al. (2004)a |
| Permanent pasture | Loamy sand | 5 | 25/35 | 4.7–8.9 | Sparling et al. (1995)a  |
| Permanent pasture | Loamy sand | 10 | 25/35 | 0.9–2.4 | Sparling et al. (1995)a |
| Wheat (lupin) | Loamy sand | 5 | 20 | 7.5 | Cookson et al.(2008)a |
| Wheat (lupin) | Loamy sand | 10 | 20 | 6.0 | Cookson et al.(2008)a |
| Unsown  | Sand | 5 | 30-60 | 1.0–5.5, 0.6–1.3 | Luxhøi et al. (2008)a |
| Wheat-SR (lentils) | Red clay loam | 10 | 20 | 1.7–2.9 | Hoyle and Murphy (2006)b |
| Wheat-SB (lentils) | Red clay loam | 10 | 20 | 0.5-2.5 | Hoyle and Murphy (2006)b |
| Wheat-SR (lentils) | Red clay loam | 5 | 5-30, 40 | 1.0–2.5, 13.0 | Hoyle et al. (2006)b |
| Wheat-SB (lentils) | Red clay loam | 5 | 5-40 | 0–2.3 | Hoyle et al. (2006)b |
| Fallow (wheat) | Deep sand | 10 | 20, 40 | 2.7, 3.3 | Fisk et al. (2015)b |
| Fallow (wheat+OM) | Deep sand | 10 | 20, 40 | 2.6, 7.0 | Fisk et al. (2015)b |
| Fallow (wheat)-dry | Loamy sand duplex | 10 | Field – 24h | 0c | Murphy et al. (1998a)a |
| Fallow (pasture)-dry | Loamy sand duplex | 10 | Field – 24h | 0c | Murphy et al. (1998a)a |
| Fallow (wheat)-wet | Loamy sand duplex | 10 | Field – 24h | 0.93c | Murphy et al. (1998a)a |
| Fallow (pasture)-wet | Loamy sand duplex | 10 | Field – 24h | 2.64c | Murphy et al. (1998a)a |

aField conditions

bLaboratory conditions

cReported in kg N ha-1 d-1

OM, plus organic matter; SB, stubble burnt; SR, stubble retained,

* Mineralization of N from plant residues

Mineralisation of plant residues can be up to seven times more decomposable than inherent SOC (Hoyle *et al.* 2011) and can decrease the risk of loss from existing SOM pools (Angus *et al.* 2006; Herridge 2011). Thus crop and pasture residues can have a large impact on plant-available soil N and the C-to-N ratio of these residues determine whether they will release or ‘tie-up’ plant-available nitrogen as they decompose (Table 3). Legume crops and pastures that convert atmospheric N2 into organic N at a rate of up to 20 kg N ha-1 per tonne shoot dry matter have a relatively narrow C-to-N ratio. The C-to-N ratio (Ladd *et al.* 1983; Kumar *et al.* 2003; Krull *et al.* 2004; Murphy *et al.* 2011; Table 3), location (Stevenson 1982; Hoyle and Murphy 2006; Hoyle and Murphy 2011) and soil disturbance (Hoyle and Murphy 2011) all influence decomposition of organic matter and subsequent N balance. Fox *et al.* (1990) reported net N mineralisation values after 12 weeks ranging from 11% of added N with cassia to 47% of added N for alfalfa, with the two legumes that contained less than 20 g N kg-1 (stylo and cassia) promoting net N immobilization for the first 6 weeks of the experiment. The legume (lignin+polyphenol):N ratio was found to be the best predictor of N mineralisation..

While higher N content in residues (e.g. legumes) increases the rate of mineralisation and can result in earlier mineral N supply – this N may be at risk of loss on coarse textured sandy soils. This is particularly the case when N is mineralised between growing seasons or where soil constraints restrict plant rooting growth to a depth shallower than the nitrogen profile in the soil. N release from crop residues can appear sufficient for crop demand as determined for a fine textured soil in Western Australia during the first 4 weeks of plant growth (Hoyle and Murphy 2011). However, measureable differences in tillering and N uptake at flowering suggest N was limited from an early stage where low N residues were used (Hoyle and Murphy 2011). This is consistent with previous studies noting N immobilisation and slower release of nutrients from poor quality residues (Amato *et al.* 1987). Thus strategies to meet early crop and pasture requirements suggest retention of N in soil and prevention of leaching losses, more rapid mineralisation when demand is greatest, or strategic application (split) of N fertilizer are required to better manage asynchrony between supply and demand.

Table 3. Influence of carbon and nitrogen content on decomposition of organic matter (modified from Praveen-Kumar et al., 2003; Herridge 2011; Hoyle et al. 2011, Murphy et al. 2011)

|  |  |
| --- | --- |
| Carbon-to-nitrogen ratio (C : N) | Decomposition and N supply |
| < 22:1 | Residues decompose rapidly. Microorganisms release plant available N surplus to requirements as the N content relative to C increases. |
| 22:1-30:1 | Sufficient N generally available for microbes to decompose residues without needing to use soil N stores, so they are relatively N neutral. |
| > 30:1 | Residues with a low N content relative to C such as wheat stubbles immobilise or ‘lock-up’ N. Microorganisms require more N than they release to the soil solution, resulting in less plant-available N. |
| > 60:1 | Least decomposable material. Immobilisation of soil N often observed.  |

For crops to achieve their water-limited potential yield, particularly in high yielding environments crops must be supplied with an amount of N greater than can be expected from mineralisation during the growing season, either from fertilizer or from mineral N accumulated earlier. While up to 80% of N supply to wheat in Australia can be derived from soil (Angus 2001), particularly in low input farming systems both the supply and demand for N in subsequent crops varies depending on crop type, residue biomass and N content, potential yield of the following crop and environmental drivers (particularly soil water) both during the fallow and in-season (Angus *et al.* 1998; Angus *et al.* 2006). Improving production in these systems is therefore reliant on improving the prediction of N release which Xu et al. (1996) suggested could be relatively well estimated from SOC, soil C to N ratio, pH, bulk density and field capacity; and the efficiency of use for N derived from SOM mineralisation and biological N ﬁxation. In many areas, conservation tillage and surface retention of organic matter results in a decline in SOM and N mineralisation with depth (Purnomo *et al.* 2000; Hoyle and Murphy 2006)

* + 1. Nitrogen loss from cropping soils
* Ammonia volatilisation

Volatilisation is the loss of N to the atmosphere as ammonia gas (NH3) from fertilizer applied to soil surfaces. All fertilizers that contain NH4+, or can produce NH4+ (e.g., urea) are susceptible to NH3 volatilisation when applied to the soil surface (Freney *et al.* 1983). Ammonia volatilisation from urea requires the hydrolysis of the urea by the enzyme urease (Bremner and Douglas 1971). The extent of the losses varies depending on fertilizer placement, soil type, soil pH and pH buffering capacity, crop residue management and environmental conditions (Sommer *et al.* 2004; Fillery and Khimashia 2016) .

In Australia there have been 94 NH3 volatilisation measurements reported from irrigated and non-irrigated cropping field sites in three states (Table 4). Losses have generally been estimated using field-based and non-intrusive micrometeorological methods (e.g., integrated horizontal passive flux), with some earlier studies utilising chambers (Wright and Catchpoole 1985; Bacon *et al.* 1986). Studies have predominately been conducted on neutral to alkaline soils cropped to wheat, with either urea or ammonium-based N fertilizers surface applied to soils at rates up to 100 kg N ha-1. Cumulative NH3 losses have been calculated after 6 to 35 days of measurements depending on the study. Measurements from non-irrigated cropping soils are dominated by a series of studies conducted in northern New South Wales, where several fertilizer products were applied to bare-fallow soils (pre-seeding) and during the growing season (in-crop) (Schwenke *et al.* 2014).

Table 4. The location, timing and number of ammonia volatilisation measurements reported for irrigated and non-irrigated in Australian cereal cropping systems

|  |  |  |  |
| --- | --- | --- | --- |
| State | Irrigated | Non-irrigated | References |
|  | Pre-crop | Seeding | In-crop | Pre-crop | Seeding | In-crop |  |
| NSW | 0 | 0 | 17 | 36 | 3 | 32 | Bacon et al. (1986)Bacon & Freney (1989) Schwenke et al.(2014) |
| VIC | 0 | 0 | 0 | 0 | 0 | 3 | Smith et al. (1991)Turner et al. (2010) |
| WA | 0 | 2 | 0 | 0 | 0 | 1 | Fillery and Khimashia, (2016)Wright & Catchpool (1985) |
| TOTAL | 0 | 2 | 17 | 36 | 3 | 36 |  |

NSW, New South Wales; VIC, Victoria; WA, Western Australia.

Ammonia losses have represented less than 10% of the N fertilizer applied to Australian cropping systems (Figure 1). Although surface applying nitrogen fertilizers to fallow soil prior to seeding increased the risk of ammonia losses (8.4%, median) from non-irrigated cropping systems in comparison to in-season applications (4.7%, median), losses were still conservative. Instead greater losses have been reported from irrigated wheat, and when N fertilizer was applied to particularly alkaline soils or soils with low pH buffering capacity (Bacon *et al.* 1986; Schwenke *et al.* 2014; Fillery and Khimashia 2016). For example, Schwenke *et al*. (2014) reported 34% of ammonium sulphate was volatilised when applied to a fallow, alkaline (pH=8.9) cropping soil containing 10% CaCO3. Another particularly high NH3 loss (29% of N fertilizer applied) was reported for a study conducted on an acidic soil with a low pH buffering capacity in central wheat belt of Western Australia (Fillery and Khimashia 2016). Others have demonstrated NH3 losses can increase if stubble management increase surface soil pH (stubble burning) or retains the fertilizers on the surface (Bacon *et al.* 1986).

A variety of strategies to decrease NH3 losses from cropping soils have been investigated in Australia. This has included irrigation following seeding, decreasing stubble retention and using urea coated with N-(n-butyl) thiophosphoric triamide (NBPT) to inhibit the enzyme urease (Bacon and Freney 1989; Turner *et al.* 2010; Schwenke *et al.* 2014). Applying NBPT-coated urea decreased NH3 losses by up to 89% in comparison to applying urea, but the results are not consistent across all Australian studies (Turner *et al.* 2010; Schwenke *et al.* 2014) (Figure 1).



Figure 1. Distribution of NH3 volatilisation fluxes from N fertilizer applied to non-irrigated soils before seeding (Pre-crop), seeding and during crop growth (In-crop) as reported by studies listed in Table 4. The number of studies conducted for each category is listed in brackets. AS, ammonium sulphate; UAN, urea ammonium nitrate, GU, green urea; LAN, liquid ammonium nitrate; LU, liquid urea.

* Nitrous oxide and dinitrogen gas emissions

Nitrous oxide (N2O) and dinitrogen (N2) emissions represent another gaseous loss pathway for N fertilizer applied to cropping soils. Both gases are produced in soils by microorganisms under particular soil conditions (Firestone and Davidson 1989). Denitrification is the reduction of nitrate (NO3-) to di-nitrogen gas (N2), with N2O and nitric oxide (NO) intermediary gaseous products (Wrage *et al.* 2001). Denitrification occurs in anaerobic microsites in the soils when there is sufficient nitrate and available ‘labile’ carbon. Nitrification converts soil NH4+ to NO3- under aerobic conditions, and like denitrification, incomplete conversion results in soil N2O emissions (Wrage *et al.* 2001). Applying N fertilizers, whether synthetic or organic, enhances soil microbial production of N2O and N2 (Davidson 2009; Smith *et al.* 2012) when the appropriate conditions are met e.g. denitrification occurs at high moisture contents. Consequently, interest in measuring these gaseous emissions from soils originated from a desire to better understand the fate of soil N (Denmead 1979; Hutchinson and Mosier 1981). Efforts to measure soil N2O fluxes were increased when N2O was recognized as a potent greenhouse gas (GHG) that also contributes to depletion of stratospheric ozone (Crutzen 1981; Ravishankara *et al.* 2009).

Quantifying N2O and N2 emissions from soils is challenging. Losses vary spatially, and differ from day-to-day (and within the day) in response to multiple factors that regulate production, consumption and emission of these gases (Butterbach-Bahl *et al.* 2013). Soil N2O emissions are most often measured in the field using manual (static) or fully automated chambers (Butterbach-Bahl *et al.* 2013). Chamber measurements are short-term (e.g., hourly), repeated usually in intervals of hours (automated systems) to weeks (manual systems), and are in turn integrated across time to finally calculate an annual losses. The ability of chambers methods to adequately quantify N2O losses relies on the user characterising N2O emissions during the year, in particular peak emissions following N fertilizer applications, and irrigation and soil re-wetting, , e.g. the latter of which may contribute up to 70% of the total annual flux (Barton *et al.* 2008; Wolf *et al.* 2010). Measurements of *in situ* N2 emissions are uncommon, and is best measured using 15N tracer methods (McGeough *et al.* 2012; Kulkarni *et al.* 2013)

In Australia, there have been over 70 published values of cumulative N2O emissions measured from grain cropping field sites (Table 5). Losses have been estimated using field-based chambers, with a large proportion (*ca* 65%) of the data obtained using automated chamber systems that measured emissions on a sub-daily basis. Studies have been conducted in all the major grain growing states of Australia except South Australia, on soils ranging from deep sands to heavy clays. Nitrous oxide emissions have been reported from soils planted to grain legumes, cereals and oil seeds where urea has been applied at a range of application rates depending on the crop and year (0–300 kg N ha-1). Nitrous oxide emissions have been measured from both irrigated and non-irrigated cropping soils, although losses have mainly been reported for non-irrigated grain crops (Table 5). Cumulative N2O losses have been calculated for at least a growing season, but in some cases for over a year.

Whilst N2O emissions from Australian grain cropping soils are relatively low and represent a small proportion of the N fertilizer applied (Table 5) in high rainfall southern Victoria, annual N2O emissions from cropped soils which have just come out of pasture have exceeded 35 kg N2O-N in the absence of N addition (Grace 2012). The extent of the losses in continuously cropped system are greatly influenced by annual rainfall or irrigation In the low-rainfall zones of Australia (<600 mm yr-1), annual losses have ranged from 0.04 to 0.49 kg N ha-1 (0.09 kg N ha-1, median), representing up to 0.22 % of the N fertilizer applied. Unpublished data from low-rainfall zones, which was collected as part of the National Australia Nitrous Oxide Research Program (NANORP), falls within this range of values and provides additional data for New South Wales (Wagga Wagga), Victoria (southern Wimmera) and Western Australia (Buntine) (Grace 2015). In the high-rainfall zones of Australia (>600 mm yr-1), annual losses have ranged from 0.06 to 1.61 kg N ha-1 (0.17 kg N ha-1, median), representing up to 1.78% of the N fertilizer applied. However, unpublished data from NANORP shows N fertilizer losses from high-rainfall zones may as great as 3.3% of N fertilizer applied (Grace 2015). There have been fewer published studies investigating N2O losses from irrigated than non-irrigated crops, with reported cumulative losses as great as 1.61 kg N ha-1 (0.27 kg N ha-1, median) and up to 2.8% of N fertilizer applied. A recent re-analysis of Australia’s fertilizer induced Emission Factors (EFs) by Grace and Shcherbak (2015) reported average values of 0.5, 0.84 and 0.85% of the N applied is emitted as N2O (after correcting for background emissions) for low, high and irrigated grains systems respectively.

Nitrous oxide is a useful indicator of N use inefficiency and potentially greater losses of N2. Direct field-based measurements of N2 losses from soils have not been possible due to the methodological constraints on the direct quantification of N2 in our N rich atmosphere. Indirect methods such as the (now unreliable) acetylene block technique (to stop the conversion of N2O to N2) were used. Weier *et al.* (1993) reported an annual loss of 31 kg N ha-1 from an unfertilised clay soil under black gram in central Qld using this method. The proportion of N2 produced compared to N2O emitted via denitrification increases rapidly as soils approach saturation (Friedl *et al.* 2014). The application of isotopically labelled 15N fertilizer has dominated the studies which have sought to study N2 losses from grain cropping either by direct measurements of the gas or by mass balance, the latter inferring N2 losses by difference i.e.

15N2 lost = 15N applied – 15N recovered in soil – 15N recovered in plants – 15N2O

In alkaline soils, inclusion of the NH3 loss pathway is also required in the mass balance approach unless the applied 15N has been sufficiently incorporated into the soil to minimise these losses, which is normally the case.

Total gaseous N losses via denitrification using the mass balance approach have been reported in the majority of studies prior to 2000 without distinguishing the relatively small losses of N2O. In wheat, Craswell and Martin (1975) reported 25% of the applied nitrate being lost from a saturated heavy clay in Queensland. These losses were significantly reduced when the N was placed at depth (Craswell and Strong 1976), which was confirmed by Strong *et al.* (1992). Avalakki *et al.* (1995) reported field denitrification rates on the Darling Downs of 0.18-1.95 kg N ha-1 d-1, with 47-71% of the N applied in April lost via denitrification. In sorghum, 35% of the N applied midseason to a clay soil in the North Burnett was lost over the next 64 days (Robertson *et al.* 1997). Mosier *et al.* (1986) reported that 20% of the 300 kg N applied in a split application to irrigated maize in Griffith (NSW) was lost via denitrification.

In Western Australia, Palta and Fillery (1993) reported only 38% of the urea that was applied to a duplex soil was recovered in aboveground biomass which is comparable to that reported for soils near Merredin (Fillery and Mcinnes 1992)where N losses ranged from 9-20%. These losses are comparable to those on duplex soils in south-eastern Australia reported by Smith and Whitfield (1990) but only one-half of the losses reported by Smith *et al.* (1989) who attributed these losses to denitrification. Direct measurements of gaseous N2 and N2O by Bronson and Fillery (1998) confirm that when duplex soils of Western Australia are waterlogged after fertilisation, the N lost via leaching (3.1-5.3% of applied urea) is less than denitrification (3.1-9.4%)

Direct gaseous measurements of 15N2 + 15N2O were first attempted by Chen *et al.* (1995) and Avalakki *et al.* (1995) in laboratory studies and then in a variety of sugarcane soils by Weier *et al.* (1996) who reported denitrification losses ranging from 3-20% of applied nitrate during the first 4 days after irrigation. When extended to 14 days, the total losses were equivalent to 13-29% of applied N. Scheer *et al.* (2012b)reported N2 emissions exceeding N2O emissions by up to 70:1 in irrigated cropping on a Vertisol near Dalby in Queensland with 28% of the applied N lost over 74 days with an average N2:N2O ratio of 20:1. Recent advances in the use of field based mass spectrometry Scheer *et al.* (2014) confirmed the highly dynamic nature of the N2:N2O ratio, with values approaching 300:1 during prolonged saturation in clay soils.

15N mass balance studies conducted through the NANORP (Grace 2015) confirm that nitrogen use efficiency (NUE) in the Australian grains industry is low, with consistently high losses of applied N via denitrification, specifically:

• 20-50% in Vertosols of the northern grains region.

• 20-40% in the High Rainfall Zone (HRZ) grains region of southern Victoria increasing to as 80-95% with early applications of urea.

• 20-40% in the Wimmera region of the southern grains zone.

• 12-45% from sorghum grown on Vertosols in NSW.

• 31-45% from winter cereals in southern NSW.

Nitrous oxide is an important indicator of much larger, economically significant losses of nitrogen to the atmosphere via denitrification. The 15N field studies within NANORP confirmed that losses of N2O are only a small fraction of total gaseous N losses via denitrification from the Australian grains industry.

Table 5. Nitrous oxide emissions (N2O-N ha-1) reported from Australian cropping soils.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop  | Location and annual rainfall (mm)a | Soil carbon (%) | Nitrogen fertilizer(kg N ha-1) | Study period and duration (days) | N2O emission (kg N ha-1)  | EF(%) | Reference |
| **Dryland cropping: Low-rainfall zone (<600 mm yr-1)** |
| Wheat | Rutherglenn, VIC; 598 | ND | 83b | 1/4/2004-21/3/2005; 354c | 0.18 | 0.06 | Barker-Reid et al. (2005) |
| Wheat | Rutherglenn, VIC; 598 | ND | 0 | 1/4/2004-21/3/2005; 354c | 0.13 | NA | Barker-Reid et al. (2005) |
| Wheat | Cunderdin, WA; 368 | 0.98 | 100b | 19/5/2005-18/5/2006; 354c | 0.11 | 0.02 | Barton et al. (2008) |
| Wheat | Cunderdin, WA; 368 | 0.98 | 0 | 19/5/2005-18/5/2006; 354c | 0.09 | NA | Barton et al. (2008) |
| Canola | Cunderdin, WA; 368 | 0.98 | 75b | 24/5/2007-14/5/2008; 356c | 0.13 | 0.06 | Barton et al. (2010)  |
| Canola | Cunderdin, WA; 368 | 0.98 | 0 | 24/5/2007-14/5/2008; 356c | 0.08 | NA | Barton et al. (2010) |
| Lupin | Cunderdin, WA; 368 | 0.98 | 0 | 14/5/2008-28/4/2009; 349c | 0.13 | NA | Barton et al. (2011) |
| Bare soil | Cunderdin, WA; 368 | 0.98 | 0 | 14/5/2008-28/4/2009; 349c | 0.13 | NA | Barton et al. (2011) |
| Wheat+lime | Wongan Hills, WA; 374 | 1.03 | 75b | 2/6/2009-8/6/2010; 371c | 0.05 | NA | Barton et al. (2013b) |
| Wheat | Wongan Hills, WA; 374 | 1.03 | 75b | 2/6/2009-8/6/2010; 371c | 0.06 | NA | Barton et al. (2013b) |
| Lupin+lime | Wongan Hills, WA; 374 | 1.03 | 0 | 2/6/2009-8/6/2010; 371c | 0.05 | NA | Barton et al. (2013b) |
| Lupin | Wongan Hills, WA; 374 | 1.03 | 0 | 2/6/2009-8/6/2010; 371c | 0.04 | NA | Barton et al. (2013b) |
| Wheat+lime | Wongan Hills, WA; 374 | 1.03 | 50b | 9/6/2010-8/6/2011; 364c | 0.04 | NA | Barton et al. (2013b) |
| Wheat | Wongan Hills, WA; 374 | 1.03 | 50b | 9/6/2010-8/6/2011; 364c | 0.07 | NA | Barton et al. (2013b) |
| Wheat+lime | Wongan Hills, WA; 374 | 1.03 | 20b | 9/6/2010-8/6/2011; 364c | 0.06 | NA | Barton et al. (2013b) |
| Wheat | Wongan Hills, WA; 374 | 1.03 | 20b | 9/6/2010-8/6/2011; 364c | 0.06 | NA | Barton et al. (2013b) |

**Table 5 (cont).** Nitrous oxide emissions (N2O-N ha-1) reported from Australian cropping soils.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop  | Location and annual rainfall (mm)a | Soil carbon (%) | Nitrogen fertilizer(kg N ha-1) | Study period and duration (days) | N2O emission (kg N ha-1)  | EF(%) | Reference |
| Wheat | Horsham, VIC; 430 | ND | 51b | 4/5/2011-14/12/2011; 224c | 0.49 | NA | Hill et al. (2012) |
| Wheat | Horsham, VIC; 430 | ND | 5 | 4/5/2011-14/12/2011; 224c | 0.47 | NA | Hill et al. (2012) |
| Wheat | Cunderdin, WA; 368 | 0.98 | 75b | 20/6/2006-23/5/2007; 337c | 0.09 | 0.01 | Li et al. (2011) |
| Wheat | Cunderdin, WA; 368 | 0.98 | 0 | 20/6/2006-23/5/2007; 337c | 0.08 | NA | Li et al. (2011) |
| Wheat | Horsham, VIC; 447 | ND | 50b | 5/6/2007-12/12/2007; 190c | 0.28 | 0.22 | Officer et al. (2015) |
| Wheat | Horsham, VIC; 447 | ND | 0 | 5/6/2007-12/12/2007; 190c | 0.17 | NA | Officer et al. (2015) |
| **Dryland cropping: High-rainfall zone (>600 mm yr-1)** |
| Canola | Tamworth, NSW; 681 | 1.9 | 80b | 19/6/2009-19/6/2010; 365d | 0.06 | NA | Schwenke et al. (2015) |
| Chickpea | Tamworth, NSW; 681 | 1.9 | 0 | 19/6/2009-19/6/2010; 365d | 1.27 | NA | Schwenke et al. (2015) |
| Canola | Tamworth, NSW; 681 | 1.9 | 80b | 19/6/2009-19/6/2010; 365d | 0.39 | NA | Schwenke et al. (2015) |
| Chickpea | Tamworth, NSW; 681 | 1.9 | 0 | 19/6/2009-19/6/2010; 365d | 0.17 | NA | Schwenke et al. (2015) |
| Faba bean | Tamworth, NSW; 681 | 1.9 | 0 | 19/6/2009-19/6/2010; 365d | 0.17 | NA | Schwenke et al. (2015) |
| Field pea | Tamworth, NSW; 681 | 1.9 | 0 | 19/6/2009-19/6/2010; 365d | 0.14 | NA | Schwenke et al. (2015) |
| Wheat-CT-SB | Warwick, QLD; 728 | 1.92 | 90b | 1/7/2006-30/6/2007; 365d | 0.73e | 0.72f | Wang et al. (2011)  |
| Wheat-CT-SB | Warwick, QLD; 728 | 1.9 | 0 | 1/7/2006-30/6/2007; 365d | 0.11e |  | Wang et al. (2011)  |

**Table 5 (cont).** Nitrous oxide emissions (N2O-N ha-1) reported from Australian cropping soils.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop  | Location and annual rainfall (mm)a | Soil carbon (%) | Nitrogen fertilizer(kg N ha-1) | Study period and duration (days) | N2O emission (kg N ha-1)  | EF(%) | Reference |
| Wheat-CT-SR | Warwick, QLD; 728 | 1.9 | 90b | 1/7/2006-30/6/2007; 365d | 0.73e | 0.72f | Wang et al. (2011)  |
| Wheat-CT-SR | Warwick, QLD; 728 | 2 | 0 | 1/7/2006-30/6/2007; 365d | 0.07e |  | Wang et al. (2011)  |
| Wheat-NT-SB | Warwick, QLD; 728 | 1.89 | 90b | 1/7/2006-30/6/2007; 365d | 0.80e | 0.39f | Wang et al. (2011)  |
| Wheat-NT-SB | Warwick, QLD; 728 | 1.91 | 0 | 1/7/2006-30/6/2007; 365d | 0.11e |  | Wang et al. (2011)  |
| Wheat-NT-SR | Warwick, QLD; 728 | 1.89 | 90b | 1/7/2006-30/6/2007; 365d | 0.62e | 0.51f | Wang et al. (2011)  |
| Wheat-NT-SR | Warwick, QLD; 728 | 2.03 | 0 | 1/7/2006-30/6/2007; 365d | 0.11e |  | Wang et al. (2011)  |
| Wheat-CT-SB | Warwick, QLD; 728 | 1.92 | 90b | 1/7/2007-30/6/2008; 365d | 0.87e | 0.76f | Wang et al. (2011)  |
| Wheat-CT-SB | Warwick, QLD; 728 | 1.9 | 0 | 1/7/2007-30/6/2008; 365d | 0.20e |  | Wang et al. (2011)  |
| Wheat-CT-SR | Warwick, QLD; 728 | 1.9 | 90b | 1/7/2007-30/6/2008; 365d | 1.17e | 1.09f | Wang et al. (2011)  |
| Wheat-CT-SR | Warwick, QLD; 728 | 2 | 0 | 1/7/2007-30/6/2008; 365d | 0.20e |  | Wang et al. (2011)  |
| Wheat-NT-SB | Warwick, QLD; 728 | 1.89 | 90b | 1/7/2007-30/6/2008; 365d | 0.80e | 0.69f | Wang et al. (2011)  |
| Wheat-NT-SB | Warwick, QLD; 728 | 1.91 | 0 | 1/7/2007-30/6/2008; 365d | 0.17e |  | Wang et al. (2011)  |
| Wheat-NT-SR | Warwick, QLD; 728 | 1.89 | 90b | 1/7/2007-30/6/2008; 365d | 0.80e | 1.18f | Wang et al. (2011)  |
| Wheat-NT-SR | Warwick, QLD; 728 | 2.03 | 0 | 1/7/2007-30/6/2008; 365d | 0.17e |  | Wang et al. (2011)  |
| Wheat-CT-SB | Warwick, QLD; 728 | 1.92 | 90b | 1/7/2008-30/6/2009; 365d | 0.88e | 1.25f | Wang et al. (2011)  |
| Wheat-CT-SB | Warwick, QLD; 728 | 1.9 | 0 | 1/7/2008-30/6/2009; 365d | 0.15e |  | Wang et al. (2011)  |
| Wheat-CT-SR | Warwick, QLD; 728 | 1.9 | 90b | 1/7/2008-30/6/2009; 365d | 1.61e | 1.78f | Wang et al. (2011)  |
| Wheat-CT-SR | Warwick, QLD; 728 | 2 | 0 | 1/7/2008-30/6/2009; 365d | 0.18e |  | Wang et al. (2011)  |

**Table 5 (cont).** Nitrous oxide emissions (N2O-N ha-1) reported from Australian cropping soils.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop  | Location and annual rainfall (mm)a | Soil carbon (%) | Nitrogen fertilizer(kg N ha-1) | Study period and duration (days) | N2O emission (kg N ha-1)  | EF(%) | Reference |
| Wheat-NT-SB | Warwick, QLD; 728 | 1.89 | 90b | 1/7/2008-30/6/2009; 365d | 0.51e | 0.49f | Wang et al. (2011)  |
| Wheat-NT-SB | Warwick, QLD; 728 | 1.91 | 0 | 1/7/2008-30/6/2009; 365d | 0.07e |  | Wang et al. (2011)  |
| Wheat-NT-SR | Warwick, QLD; 728 | 1.89 | 90b | 1/7/2008-30/6/2009; 365d | 0.70e | 0.60f | Wang et al. (2011)  |
| Wheat-NT-SR | Warwick, QLD; 728 | 2.03 | 0 | 1/7/2008-30/6/2009; 365d | 0.15e |  | Wang et al. (2011)  |
| **Irrigated cereal crops** |
| Wheat+DMPP | Taabinga, QLD; 776 | 1.47 | 80 | 6/7/2011-29/11/11; 146c | 0.25 | -0.01 | De Antoni et al. (2014) |
| Wheat | Taabinga, QLD; 776 | 1.47 | 80 | 6/7/2011-29/11/11; 146c | 0.40 | 0.19 | De Antoni et al. (2014) |
| Wheat | Taabinga, QLD; 776 | 1.47 | 20 | 6/7/2011-29/11/11; 146c | 0.19 | -0.29 | De Antoni et al. (2014) |
| Wheat | Taabinga, QLD; 776 | 1.47 | 0 | 6/7/2011-29/11/11; 146c | 0.25 | NA | De Antoni et al. (2014) |
| Maize+DMPP | Taabinga, QLD; 776 | 1.47 | 160 | 15/12/2011-20/6/2012; 188c | 0.50 | 0.24 | De Antoni et al. (2014) |
| Maize | Taabinga, QLD; 776 | 1.47 | 160 | 15/12/2011-20/6/2012; 188c | 1.61 | 0.93 | De Antoni et al. (2014) |
| Maize | Taabinga, QLD; 776 | 1.47 | 100 | 15/12/2011-20/6/2012; 188c | 0.65 | 0.53 | De Antoni et al. (2014) |
| Maize | Taabinga, QLD; 776 | 1.47 | 40 | 15/12/2011-20/6/2012; 188c | 0.22 | 026 | De Antoni et al. (2014) |
| Sorghum | Kingaroy, QLD; 776 | ND | 100b | 12/12/2012-19/9/2013; 281c | 1.43 | 1.17 | De Antoni et al. (2015) |
| Sorghum | Kingaroy, QLD; 776 | ND | 0 | 12/12/2012-19/9/2013; 281c | 0.27 | NA | De Antoni et al. (2015) |
| Sorghum | Kingaroy, QLD; 776 | ND | 100b | 12/12/2012-19/9/2013; 281c | 0.68 | 0.63 | De Antoni et al. (2015) |
| Sorghum | Kingaroy, QLD; 776 | ND | 0 | 12/12/2012-19/9/2013; 281c | 0.24 | NA | De Antoni et al. (2015) |

**Table 5 (cont).** Nitrous oxide emissions (N2O-N ha-1) reported from Australian cropping soils.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop  | Location and annual rainfall (mm)a | Soil carbon (%) | Nitrogen fertilizer(kg N ha-1) | Study period and duration (days) | N2O emission (kg N ha-1)  | EF(%) | Reference |
| Maize-SR | Griffith, NSW; 402 | ND | 300b | Not stated | Not stated | 1.6 | Galbally et al. (2005) |
| Maize-SB | Griffith, NSW; 402 | ND | 300b | Not stated | Not stated | 2.8 | Galbally et al. (2005) |
| Wheat | Horsham, VIC; 447 | ND | 50b | 5/6/2007-12/12/2007; 190c | 0.21 | NA | Officer et al. (2015) |
| Wheat | Horsham, VIC; 447 | ND | 0 | 6/6/2008-12/12/2008; 189c | 0.08 | NA | Officer et al. (2015) |
| Wheat | Horsham, VIC; 447 | ND | 0 | 6/6/2008-12/12/2008; 189c | 0.07 | NA | Officer et al. (2015) |
| Wheat | Horsham, VIC; 447 | ND | 0 | 6/6/2008-12/12/2008; 189c | 0.14 | NA | Officer et al. (2015) |
| Wheat- HI | Kingsthorpe, QLD; 630 | 16.1 | 200b | 15/6/2009-26/10/2009; 133c | 0.75 | NA | Scheer et al. (2012a) |
| Wheat-MI | Kingsthorpe, QLD; 630 | 15 | 200b | 15/6/2009-26/10/2009; 133c | 0.43 | NA | Scheer et al. (2012a) |
| Wheat-LI | Kingsthorpe, QLD; 630 | 15.5 | 200b | 15/6/2009-26/10/2009; 133c | 0.45 | NA | Scheer et al. (2012a) |

aLong-term annual rainfall as reported by authors

bUrea

cN2O fluxes measured on a sub-daily basis using automated chambers

dN2O fluxes measured using manual chambers

eN2O fluxes are estimated from graphical data

fEmission factor calculated by Wang et al. (2011) using data collected from manual and automated chambers, and cannot be estimated using data from previous column.

CT, conventional till; DMPP, 3,4-dimethylpyrazole phosphate; EF, emission factor; HI, high irrigation; LI, low irrigation; MI, medium irrigation; NA, not applicable; ND, not determined; NT, no till; NSW, New South Wales; OM, organic matter added; QLD, Queensland; SB, stubble burnt; SR, stubble return; VIC, Victoria; WA, Western Australia;

* Nitrogen leaching

Nitrogen leaching occurs from cropping soils when water drains through the soil and beyond the rooting zone. Leaching of N fertilizer is best minimised by applying it at a rate that the soil-crop system is able to assimilate or utilise N (Powlson 1988; Carpenter *et al.* 1998). This approach will vary depending on the crop N requirements, but also on the biological, chemical and physical attributes of the soil. Fertilizer N can be taken up by crop, immobilised in soil organic matter, denitrified or volatilised to gaseous N species. Any N not involved in these processes is susceptible to leaching when drainage occurs. Additional N may also become available if land management practises increase net soil N mineralisation rates or plant available N (Shepherd *et al.* 1996; Officer *et al.* 2015). Nitrogen can be leached as NO3-, NH4+ and as organic N. It has often assumed that NO3- is more susceptible to leaching than other forms of N as the solid phase of most soils has a net negative charge, and so repels negatively charged anions such as NO3-. However, organic N leaching can also be significant from agricultural soils (Murphy *et al.* 2000) .

The extent of N leaching will also be affected by the rate that dissolved N moves through the soil profile. Crop N uptake and soil biological processes often occur at greater rates in the surface- than the sub-soil. Nitrogen fertilizer (and irrigation management) practices that maximise the contact time between applied nutrients and the top soil should increase crop N uptake and soil ‘retention’, and therefore decrease the risk of N leaching. The extent of leaching beyond the top soil will vary depending on amount and intensity of rainfall or irrigation, the amount of N in soil solution, soil texture and structure, and the extent of the crop rooting zone. Nitrogen losses will be less in those soil types where soil drainage moves evenly through the entire soil profile (‘matrix’ flow) than in soil types were soil water moves through macropores such as down cracks, along old root channels and worm holes (‘preferential’ flow) (Barton *et al.* 2004).

Direct measurements of nitrogen leaching

Nitrogen leaching from soils is best quantified directly, and throughout the year to account for seasonal changes in soil N availability (Addiscott 1996). Measuring N leaching for an extended period will also account for any effects of establishing the experiment (e.g., soil disturbance) on N leaching. Techniques used to measure soil N leaching include porous (suction) cup lysimeters in combination with soil hydrological models and soil lysimeters (Addiscott 1990; Cameron *et al.* 1992; Addiscott 1996).

In Australia there have been 13 field-based measurements of N leaching reported from rain-fed cereal and grain legume crops. These studies have been conducted in two states, and mainly confined to deep sands cropped to wheat following a grain legume or pasture (Table 6). On only one study site was N fertilizer applied (157 kg N ha-1; Poss *et al.* 1995). Nitrogen leaching losses have been estimated by measuring NO3- losses that occurred beyond the rooting zone (0.9-1.5m, depending on the study) using either porous (suction) cup lysimeters in combination with soil hydrological models or soil lysimeters fitted with anion exchanges resin traps at the base (Table 6). Nitrate leaching measurements have mainly been confined to the growing season, with only three measurements based on approximately one year of measurements (Table 6). Nitrate leaching losses have ranged from <5 to 72 kg N ha-1 during the growing season, and from 4 to 14 kg N ha-1 after one year. Greatest losses have occurred from deep sands cropped to wheat following a grain legume (lupin) (Table 6). In the single study where NO3- leaching losses were measured from both a N fertilised and non-N fertilised soil, losses represented 1.2% of the N fertilizer applied (Poss *et al.* 1995).

Monitoring the changes in mineral N through the soil profile over time can be used to demonstrate the susceptibility of crop management systems and soil types to N leaching. Ideally the applied N fertilizer is “labelled” using 15N so that changes in mineral N can be attributed to the application of fertilizer. Although these measurements do not quantify N leaching losses, they can demonstrate if N leaching has occurred beyond the crop rooting zone. Such approaches have been most widely used to investigate the fate of N fertilizer applied to heavier textured soils.

Table 6. Nitrogen leaching (NO3-N ha-1) reported from Australian soils cropped to rainfed cereals or grain legumes.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop (previous crop) | Location and annual rainfall (mm)a | Soil texture | Nitrogen fertilizer(kg N ha-1) | Measurement method | Study periodand duration (days)  | Nitrogen leached(kg N ha-1) | Reference |
| Lupin (wheat) | Moora, WA; 460 | Sand | 0 | Anion exchange resin, 1m depth | 21/6/94–26/9/94; 97 | 24 | Anderson et al. (1998b)  |
| Lupin (wheat) | Moora, WA; 460 | Sand | 0 | Ceramic suction cups, 1.5m depth | 12/4/95–15/8/95; 125 | 35 | Anderson et al. (1998b) |
| Lupin (wheat) | Moora, WA; 460 | Sand | 0 | Ceramic suction cups, 1.5m depth | 18/6/96–15/8/96; 58 | 23 | Anderson et al. (1998b) |
| Lupin (wheat) | Moora, WA, 460 | Sand | 0 | Anion exchange resin, 1m depth | 27/6/95–14/6/96; 353 | 14 | McNeil and Fillery (2008) |
| Wheat (wheat) | Moora, WA; 460 | Sand | 0 | Anion exchange resin, 1m depth | 21/6/94–26/9/94; 97 | 24 | Anderson et al. (1998b) |
| Wheat (lupin) | Moora, WA; 460 | Sand | 0 | Ceramic suction cups, 1.5m depth | 12/4/95–15/8/95; 125 | 59 | Anderson et al. (1998b) |
| Wheat (lupin) | Moora, WA; 460 | Sand | 0 | Ceramic suction cups, 1.5m depth | 18/6/96–15/8/96; 58 | 42 | Anderson et al. (1998b) |
| Wheat (lupin) | Moora, WA, 460 | Sand | 0 | Anion exchange resin, 1m depth | 18/6/96–26/11/96; 161 | 72 | McNeil and Fillery (2008) |
| Wheat (pasture) | Moora, WA; 460 | Sand | 0 | Ceramic suction cups, 1.5m depth | 12/4/95–15/8/95; 125 | 34 | Anderson et al. (1998b) |
| Wheat (pasture) | Moora, WA; 460 | Sand | 0 | Ceramic suction cups, 1.5m depth | 18/6/96–15/8/96; 58 | 43 | Anderson et al. (1998b) |
| Wheat (wheat) | Wagga Wagga, NSW; 539 | Clay | 157 | Ceramic suction cups, 0.9m depth | 3/3/93– 28/2/94; 362 | 6 | Poss et al. (1995) |
| Wheat (wheat) | Wagga Wagga, NSW; 539 | Clay | 0 | Ceramic suction cups, 0.9m depth | 3/3/93– 28/2/94; 362 | 4 | Poss et al. (1995) |
| Wheat (wheat) | Wagga Wagga, NSW; 539 | Clay | 17 | Ceramic suction cups, 0.9m depth | 6/7/93– 26/11/93; 143 | 4.2 | Smith et al. (1998) |

aLong-term annual rainfall as reported by authors

The downward movement of N fertilizer tends to be limited in ‘cracking clays’ cropped to grain sorghum in Queensland and Western Australia (Wright and Catchpoole 1985; Armstrong *et al.* 1996; Armstrong *et al.* 1998), even in instances where the soil had received N fertilizer and then fallowed the next year to mimic crop failure (Armstrong *et al.* 1996). These observations are consistent with the view that N leaching is not important from Vertosol soils due to low drainage rates (Turpin *et al.* 1998). However, there have been incidences where N leaching has occurred from Vertosols due to increased soil mineral N concentrations resulting from N fertilizer applications and the burning of stubble, or where infiltration rates have been enhanced with introduction of zero tillage (Turpin *et al.* 1998). Better targeting N fertilizer applications to crop demand has been an effective approach to minimising N leaching from clay soils in high rainfall cropping systems (Ferric-Sodic Chromosol; Harris *et al.* 2013) or in years characterised by abnormally high drainage (Red Kandosol; Smith *et al.* 2000).

Modelled estimates of nitrogen leaching

Nitrogen leaching losses are site specific, and can vary from year-to-year depending on land management and rainfall distribution. Consequently crop models, with the ability to simulate soil water and nutrient availability, have been used to extrapolate field-based research findings to soil types, climatic regions and years where nitrogen leaching has not been measured. Modelling NO3- leaching from deep sands in the Western Australian grain belt has received the greatest attention. The Agricultural Production Systems Simulator (ASPIM) model simulated NO3- leaching losses to within 10% of measured losses collected during two growing seasons from a cropped, non-N fertilised deep yellow sand in the Western Australian grain belt whereby measured losses ranged from 24 to 55 kg N ha-1 per season depending on the year (Anderson *et al.* 1998b; Asseng *et al.* 1998a). However, some modelled results should be considered with caution as the often they do not account for preferential flow pathways in soils, and so can underestimate N leaching losses (Sadras 2002).

The risk of N leaching from deep sands may be greater than what measurement data indicates. Modelled NO3- leaching losses from deep sands in the Western Australian grain belt were up to 116 kg N ha-1 during the growing season in the absence of N fertilizer applications (Asseng *et al.* 1998a; Wong *et al.* 2006). Long-term simulations (1910–1990) showed the greatest risk of NO3-  leaching occurred in years when soil mineral N was elevated at the start of the cropping season (89.5 kg N ha-1 in surface 150 cm), with a 50% probability that 46 to 53 kg N ha-1 would be lost beyond 150 cm in a deep sand during the growing season (Asseng *et al.* 1998a). Elevated soil mineral N concentrations may occur following a grain legume crop or in response to summer rainfall when the soil is fallow (e.g., Anderson *et al.* 1998b; Barton *et al.* 2013a). Applying nitrogen fertilizer (50 kg N ha-1) to deep sands with a relatively low initial profile mineral N content (28.5 kg N ha-1 to 150 cm) also resulted in NO3- leaching, with long-term simulated losses ranging from 0 to 100 kg N ha-1, and a 50% probability of 29 kg N ha-1 being lost during the season (Asseng *et al.* 1998a). Similarly for another deep sand in the Western Australian grain belt, APSIM predicted NO3- leaching losses ranging from 0 to 25.5 kg N ha-1 per year depending on soil texture (Wong *et al.* 2006). Modelling has demonstrated ‘splitting’ N fertilizer applications between seeding and post-seeding is likely to decrease NO3-  leaching losses from deep sands (Asseng *et al.* 1998a; Wong *et al.* 2006). For example, dividing N fertilizer applications (50 kg N ha-1 ) between seeding and post-seeding lowered nitrate leaching from 29 to 26 kg N ha-1 from a sandy soils with a low mineral N content at the start of the season (28.5 kg N ha-1 in the surface 150 cm) (Asseng *et al.* 1998a).

Simulated NO3- leaching losses from other cropping soils in Australia is limited. Research conducted in Queensland and South Australia indicated NO3- leaching losses can be expected to be less from finer textured soils than from coarse-textured soils in Western Australia. Estimated cumulative NO3- leaching losses from a long-term simulation of a clay soil following land clearing for crop production in Queensland were <200 kg N ha-1 after 23 years in the absence of applied N fertilizer (Huth *et al.* 2010). Modelling NO3-  leaching from a sandy loam soil for 40 years (1960–2000) at three sites in the Mallee Region of south-eastern Australia suggested annual NO3- leaching losses should also be low (0.9–5.7 kg N ha-1 yr-1) when a typical N fertilizer rate is applied (5 kg N ha-1 yr-1) (Sadras 2002). Increasing the N fertilizer rate 10-fold (55 kg N ha-1 yr-1) increased predicted N leaching losses to 2.1 to 17.3 kg N ha-1 yr-1 depending on the study site (Sadras 2002).

* + 1. Knowledge gaps and priorities for N supply and loss processes
* Mineralization

In-field studies in Australia commonly report the net amount of N available to crops at the beginning of a growing season, but fewer have undertaken measures of process rates that determine when and how much is available (and its fate) during the growing season. In Australian dryland systems it is relatively well understood that N supply is linked to total soil N which exists in different SOM fractions with variable composition and turnover rate (Baldock and Skjemstad 1999, Krull et al. 2006, Baldock et al. 2013), thus it is important to better understand the plant inputs and rate limiting factors responsible for SOM turnover and N availability - in particular soil type, rainfall (Angus 2001), temperature (Hoyle *et al.* 2006, Luxhøi et al. 2008) and management (Gupta *et al.* 1994a). Improved methods of quantifying soil derived N and implementation of farming practices to manage and optimise N supply could result in a range of strategies where residues and SOM supply sufﬁcient N for a low crop demand early in the season but where supplementation of soil N with application of fertilizer N is required to meet the demand for optimum yield and protein, as the season progresses (Angus 2001); or where supplementary fertilizer N is added in high yielding environments with a dominance of high C to N residues.

* N losses

Volatilization

Further investigation of NH3 volatilisation losses from Australian cropping systems is warranted as losses can be as high as 30% of the applied N (Figure 1). Although a large number of field-based studies have measured NH3 losses in Australia, a large proportion (>90%; Table 4) of these have been confined to sites in New South Wales. The recent publication of a model for predicting NH3 losses from Australia’s agricultural soils provides an opportunity to strategically investigate and verify the risk of NH3 losses from Australian cropping systems using current fertilizer management practices (Fillery and Khimashia 2016). Indeed the developers of the aforementioned model highlighted the need for additional research to further improve the prediction of NH3 losses from agricultural soils. This includes measuring NH3 losses from fertilizers applied to crop canopies post Z30 (cereals) and V8 (maize) in those environments where N fertilizers are applied at the later stages of crop development, plus examining the interaction between time and amount of rainfall on NH3 volatilisation from a variety of soil textures (Fillery and Khimashia 2016).

Nitrous oxide and dinitrogen gas emissions

Nitrous oxide emissions from agricultural soils have been widely investigated in the key grain growing regions of Australia, and have been found to represent a small percentage of the N fertilizer applied to cropping soils (<5%). Further investigation of N2O emissions specifically from Australian grain cropping soils is not justified for the purpose of refining N fertilizer decisions given the low losses. However, further research is needed to quantify N2 losses (via denitrification) from Australian cropping soils as unpublished data consistently suggests that these losses may represent up to 50% of N fertilizer applied to soils in wetter environments on heavier textured soils. Currently there is a dearth of information on the potentially large losses of N2 losses from Australian cropping soils.

Leaching

Field-based measurement of N leaching from Australian cropping soils has largely been confined to rainfed cereal and grain legume crops studies in Western Australia. These studies have demonstrated N leaching losses can be significant from coarse-textured soils even when N fertilizer is not applied (e.g. 14 to 72 kg N ha-1 during the growing season; Table 6). Yet, justifying further field-based N leaching studies to assist with improving N fertilizer decisions is difficult in the absence of reliable weather forecasting. The extent of N leaching depends on the extent, duration and distribution of rainfall, which will vary from year-to-year. Without accurate weather forecasts the risk of drainage beyond the rooting zone or lateral movement will be difficult to predict and accommodate N leaching in fertilizer decision models. In southern grain growing regions the most pragmatic approach to limiting N leaching losses is to avoid applying N fertilizer immediately before heavy rainfall, especially on soil types prone to leaching (e.g. sands). If N leaching does occur, growers in southern regions can bring N fertilizer programs forward or apply additional fertilizer.

* 1. Processes affecting soil S supply

Sulfur (S) is an essential plant nutrient found in similar concentrations to P, which alongside N is necessary for the production of essential S-containing amino acids. Sulfur is also important for many enzymes and other important S-rich products such as co-enzyme A and chlorophyll. Nitrogen and S are main constituents of proteins, therefore, a shortage in the supply of S for crops also affects the utilization of N within the plants for the synthesis of proteins. Sulfur is also essential for biological N fixation by symbiotic bacteria in legumes (Divito and Sadras 2014).

Foliar symptoms of S deficiency are generally not specific enough for diagnosis by observation alone. Within the literature and from industry observations the symptoms of S deficiency can be both variable and transient from season to season with changing environmental conditions, soil and crop S requirements (for examples see Blair *et al.* 1983; Chisholm and Dowling 1985; Hocking *et al.* 1996; Lester and Dowling 2001; Anderson *et al.* 2006; Brennan and Bolland 2006). When S is deficient, protein synthesis is inhibited and plants become pale, with symptoms similar to those of N deficiency particularly in plants reliant on fixed N (Scherer 2001). While S can be remobilised within plants if a deficiency occurs, it is not as highly mobile as N so symptoms appear in young leaves, compared to older leaves with N deficiency. Crop responses to S fertilizers are highly variable and experiments comparing soil and tissue S testing with yields are often poorly correlated (e.g. Lester and Dowling 2001; Brennan and Bolland 2006).

In Australian farming systems, S in cropping soils has decreased significantly over the last 20 -30 years through a combination of decreased S addition, increased rates of S removal under intensified cropping cycles and declining reserves of organic matter (OM). Lower S additions have occurred as a consequence of the shift from higher S-containing fertilizers such as superphosphate used in mixed pasture/cropping systems to lower S-containing ammonium phosphates (MAP and DAP) favoured in cropping only systems, plus reductions in gypsum application for remediation of sodic topsoils.

Most farmers, particularly outside of WA, are slowly exhausting existing soil S pools in most soil types as S export via crop removal exceeds input. In most areas, S application largely occurs as part of starter fertilizer applied at seeding (1-10 kg/S ha) which is believed to have a largely negligible impact on soil S balance (National Land and Water Resources Audit 2001; Bell *et al.* 2010). Decreasing OM in cultivated soils that is reducing the size of the soil organic S pool and also lowering rates of S mineralisation (Dalal and Mayer 1986; Sakadevan *et al.* 1993; Banerjee and Chapman 1996). This has led to widespread reports of S deficiencies across a range of crops, growing environments and soils in cropping regions in WA, SA, NSW, VIC and QLD (Hocking *et al.* 1996; Lester and Dowling 2001; Anderson *et al.* 2006; Brennan and Bolland 2006).

In Australia, S deficiency has been observed to decrease yields of the major grain crops including wheat, canola and sorghum (Randall *et al.* 1981; Hocking *et al.* 1996; Lester and Dowling 2001). Rotational legumes such as lupins appear more resistant than cereals to yield decreases in low S soils (Robson *et al.* 1995; Anderson *et al.* 2006), however S deficiency can decrease N2 fixation and N inputs from the legume phase of rotations (Scherer and Lange 1996; Divito and Sadras 2014). Brassicas such as canola have high requirements for S (30 to 60kg S/ha) compared to cereals (10 to 20 kg S/ha) (Zhao *et al.* 2002) and accordingly, S deficiencies have commonly been extensively reported in canola crops grown in NSW and WA (Hocking *et al.* 1996; Brennan and Bolland 2006; Grant *et al.* 2012). In addition, S fertilization can improve apparent N-use efficiency in canola, an N-inefficient crop compared to cereals (Fismes *et al.* 2000). Despite the incidence of S deficiencies in wheat being less common than for canola (due to lower crop S requirements), researchers and farmers have observed wheat S deficiencies intermittently for over 30 years across a range of growing areas (Wrigley *et al.* 1980; Randall *et al.* 1981; Anderson *et al.* 2006; Brennan and Bolland 2006). Work overseas has found that barley yields are negatively affected by S deficiencies, however this hasn’t been widely reported in Australia (Withers *et al.* 1995). Results from field surveys suggest that the incidence of S deficiency in lupin crops in Western Australia is low, but 15% of wheat crops in some areas may be S-deficient or marginally supplied with S (Robson *et al.* 1995). Grain yield increases with S application for cereal and fibre crops in the northern region have tended to be not from S application solely, but from applying multiple nutrient combinations of either P and S, or PK and S (Lester and Bell 2011, 2013; Bell *et al.* 2015). Responsive sites have tended to be in areas of central Queensland and on the higher rainfall areas of the eastern Darling Downs. In canola and wheat, S deficiency also has a negative impact on oil and/or grain quality (Moss *et al.* 1981; Hocking *et al.* 1996; Zhao *et al.* 1999b; Fismes *et al.* 2000). More recently, other work done in WA also observed low wheat grain S in their analysis (all <0.12% except for highest S fertilizer treatments at 30 kg ha-1) which is low enough to have important implications for grain quality (Moss *et al.* 1983; Zhao *et al.* 1999a; Anderson *et al.* 2006). Similarly for wheat in the northern grains region, low grain S concentrations and N:S ratios wider than the suggested critical values have been outlined in industry updates (Lester and Bell 2010) following a nutrient survey program.

* Crop S demand and soil S supply

Similar to N, there can be considerable asynchrony in crop S requirements and patterns of S mineralisation within soils. Typically, soil analysis has shown that soil sulfate (SO4-S) levels are highest at the end of summer, fall to low levels in winter and spring, then rise again after crop growth ceases (Barrow 1966). Fertilizers containing soluble SO4-S provide S that is readily useable by plants, but the plants have to compete with soil microbes and loss processes for the pool of available S.

In most Australian soils outside of WA there is little understanding of these interactions, particularly in heavier clay soils where there historically haven’t been S deficiency issues, with the exception of extreme events such as years of very high annual rainfall (Chisholm and Dowling 1985). If S levels are insufficient at seeding, then mineralisation of organic S will generally not provide sufficient S for crop growth during the growing season (Anderson *et al.* 2006).

Heterogeneity of nutrient supply in the soil with time and depth can have important effects on both nutrient distribution in some plants and the identification of nutrient deficiencies (Robson *et al.* 1992). It is not uncommon for SO4-S to either be high in the top 20cm soil layers due to fertilizer application and depleted in lower soils layers with deficiency symptoms slowly developing as the season progresses. In soils prone to leaching, S may be low in upper soils layers inducing an early deficiency that is overcome as roots grow into more S-rich layers from 50 to 75cm (Bole and Pittman 1984).

The reverse distribution of soil SO4-S increasing with depth is more likely to be encountered in the northern growing region with significant gypsum occurring naturally with depth in the soil (Hubble *et al.* 1983). With grain production in this region more dependent on stored soil moisture, investigation of the profile sampling approach of Hue and Cope (1987) is warranted.

* + 1. Mineralisation
* Soil S supply pathways

Sulfur occurs in the soil in both inorganic and organic forms, and crops primarily take up S as sulfate (SO42--S) from soil. Within the soil, S cycles through five main pools: available S consisting of inorganic soil solution SO4-S and adsorbed SO4-S (3-10%); and organic S consisting of plant S, microbial S, labile S (mostly ester sulfates with fairly rapid turnover) and resistant S (carbon bonded S, slow turnover pool comprising 50 to 90% of total soil S) (Blair *et al.* 1991; Till 2010). In the upper layers of most soils, greater than 90% of soil S is present in organic forms largely unavailable to the plant (Germida and Schoenau 1992). These organic forms include crop residues and humus. Organic S must undergo microbial decomposition or mineralisation to a soluble inorganic form such as SO4-S before plant uptake can occur.

Scherer (2001) provides an overview of soil S transformations, forms of organic S in soils and processes associated with S mineralisation that release SO4-S from soil OM. Mineralisation processes are enzymatic, biochemical, or microbially mediated depending on the form of organic S present in the soil. The rate of organic S mineralisation is influenced by a range of factors such as carbon, nitrogen and sulfur content of OM and plant residues, existing S pools within soil, environmental conditions such as rainfall and temperature, soil pH and rate of S uptake by plants (Blair *et al.* 1997; Anderson *et al.* 2006; Till 2010; Page *et al.* 2013). As a general rule, most organic S is in the resistant form so this breakdown is a slow process (T1/2 = 1-3 years) and does not provide adequate S in the growing season for most crops (Blair *et al.* 1991; Eriksen and Mortensen 1999; Till 2010).

The general decline of soil OM observed under cropping systems, reduces both total soil organic S pools and soil microbial biomass (Dalal and Chan 2001). While soil microbial biomass is only 5% of OM, it performs critical functions in the soil and environment, including that it is a labile source of S, an immediate sink and the main mechanism for nutrient transformation such as the production of SO4-S (Dalal 1998). The soil microbial biomass S fraction of total organic S in soil is considered to be relatively labile and the most active S pool for S turnover in soil. Microbial S values showed direct relationships with both microbial C and with total soil organic S (Banerjee and Chapman 1996; Chowdhury *et al.* 1999). While the management change to zero-till and reduced-till cropping systems has slowed the decline of OM in cropping soils (see Page *et al.* 2013), there is little evidence of replenishment or increase in OM in the short-to-medium term, thus increasing future reliance on fertilizers to supply crop nutrition requirements.

There is limited work done on rates of S mineralisation in the field, with most of the previous work being done in lab conditions (Till 2010) which significantly limit its application in developing understanding of S dynamics in the paddock. There is also limited to no understanding of the relationship between rates of S mineralisation and N mineralisation, which would potentially be useful in fertilizer management. Another limitation of most of the S mineralisation studies is that they are done on incubated soil without plants. Plants have been shown to actively influence microbial activity, rates of S mineralisation and the dynamics of S cycles within the soil (Castellano and Dick 1991; Eriksen *et al.* 1995). Many of these studies are also done under conditions where the composition of the soil microbial biomass responsible for fixation and mineralisation is not clearly identified. This is particularly important as both the plant and the microbial biomass actively compete for mineralised SO4-S, leading to unrealistic estimates of the availability of the mineralized S and net S gained from studies without plants. This is not a problem exclusive to Australia with most work in Europe also being done under lab conditions. However, it does lead to a significant lack of understanding about S mineralisation and S chemistry under field conditions with crops globally. In Australia this is exacerbated by most work on S being done in low fertility sandy soils in WA (Anderson *et al.* 2013), and a significant need for research to be done on S cycling between pools and its relationship with mineralisation/immobilisation and adsorption/desorption processes in heavier clay soils under temperate, sub-tropical and tropical growing environments.

Work done in WA has found that the existing pool of S in the soil directly influences the net SO4-S mineralised in coarse sandy soils. For example, Anderson *et al.* (2006) illustrated the importance of continued application of S fertilizer for sustaining net SO4-S mineralisation in course sandy soils prone to leaching, which has also been observed in other studies (Sakadevan *et al.* 1993). The measured rates of total growing season net SO4-S mineralised were 2.2-8.0 kg S/ha with the rate being unaffected by previous S fertilisation (Anderson *et al.* 2006). However, previous S fertilisation did significantly influence net S mineralisation if considered over a longer time period when active crop uptake wasn’t occurring, such as a summer fallow period (0-5.8 kg S/ha) or a longer time period such as 18 months (7-17 kg S/ha) (Anderson *et al.* 2006). Wheat yields were also higher in treatments with a prior history of gypsum use, suggesting the dynamics of existing soil S pools could play an important role in soil S mineralisation processes. Mineralisation of organic S was seasonally dependent, with very low rates of net mineralisation, and in some cases net S immobilisation apparent soon after seeding (Anderson *et al.* 2006). This pattern of mineralisation is common in dryland soils where stubble retention and minimum tillage is practiced, with the delay being attributed to longer periods of stubble decomposition (Gupta *et al.* 1994a; Anderson *et al.* 2006). Rates of mineralisation increased in spring with increasing soil temperatures but for most crops the rate of mineralisation within the growing season is insufficient to meet crop S demand (for example Anderson *et al.* 2006). Growing season mineralisation rates for sandy soils ranged from 3.5 to 8.0 kg S/ha when S fertilizers were applied at 0 to 30 kg S/ha, with fallow S mineralisation rates ranging from -0.2 to around 6.0 kg S/ha (Anderson *et al.* 2006).

In addition to being a source of both labile and resistant S, decomposing plant residues also influence the rate of mineralisation/immobilisation with the return of low-S plant residues to low-S soils leading to decomposition processes being limited by S availability. Chapman (1997) found that adding barley straw low in S to low S soils, limited decomposition due to the low straw S content.Net S mineralisation occurred at a straw S content of 0.15% irrespective of any additional S added to the system. Depending on the soil type, in S-deficient areas, the incorporation of plant residues low in S may lead to reduced plant growth and retarded residue decomposition if the S content is low enough (< 0.11%) (Chapman 1997).

In a laboratory incubation experiment with canola, lentil and wheat stubble, decomposition and mineralisation of S from crop residues was primarily a function of their nutrient concentration in the residue rather than biochemical compositions of the crop species (Janzen and Kucey 1988). Canola, with a much higher tissue S concentration, showed much higher S mineralisation than lentil or wheat residues. This also means that agronomic practices which influence soil and stubble fertility in one crop will profoundly influence the rate of residue decomposition and amounts of nutrients available for the subsequent crop. For example, canola crops following wheat will have lower S availability and mineralisation than canola-canola cropping rotations with high S plant stubble and increased mineralisation rates.

* Soil sampling protocols and sulfur analysis methods

One of the issues with our prediction of S supply and losses in soils is the inability of soil S tests to reliably indicate S responsive soils. In addition, soil S testing is often poorly correlated with yield responses which significantly limits the usefulness of testing. Within the literature there is a range of factors that influence the accuracy of S testing, and more importantly the usefulness of soil testing in predicting farmer’s S fertilizer needs. These include, but are not exclusive to, accuracy of soil S tests commonly used, depth of soil testing required, leaching risk, unknown microbial / S pool interactions and soil adsorption properties. In soils where there is a high probability of leaching (low soil S sorption and high intensity rainfall events) it is likely that soil testing cannot used to determine paddocks requiring fertilizer S, because of S leaching below the root-zone, with rainfall determining the extent of leaching and magnitude of the decrease in production resulting from S deficiency (Bolland and Russell 2010).

The most common soil S test methods used in Australia for measuring plant available soil S (SO4-S) are KCl40 (Blair *et al.* 1991; Blair *et al.* 1997) and two variants on the extraction with MCP (Barrow 1967; Peverill 1977; Blair *et al.* 1997; Anderson *et al.* 1998a). The two variations on MCP extraction, are inorganic MCP which measures straight soil SO4-S or total MCP which measures soil SO4-S plus a small pool of labile organic S ---small compared with the amount extracted by the KCl-S method (Blair *et al.* 1991). The adoption of ICP AES analysis by commercial soil testing labs has improved their ability to reliably measure low concentrations of S extraction solutions because the ICP measures the total concentration of S in the soil extract. This is important, since KCl-S and MCP-S methods extract different amounts of organic S depending on the soil type and concentration of organic carbon (Blair *et al.* 1991). However, one of the key problems with utilising S soil testing as a way of testing for S deficiencies is that as S is an element that is required in relatively low concentrations (compared to N and P), so the threshold for detecting a deficiency is often close to the limit of analytical testing. This, in addition to the complexity and dynamic nature of the soil S cycle, high propensity of SO4-S to leach, differing crop S requirements, the transient nature of S availability between seasons, and a lack of understanding about S mineralisation in non-sandy soils in Australia, means that it is difficult to find consistent relationships between field soil S tests results and crop responses (Blair *et al.* 1997; Lester and Dowling 2001; Anderson *et al.* 2006; Bolland and Russell 2010). Consequently, the current critical soil test ranges (CSTR) for S for wheat and canola, have limited applicability and large confidence intervals. In addition, as most of the S research has been done in WA (80% of datasets analysed by Anderson *et al*. 2013) these CSTRs are not applicable for most growing regions outside of WA. There is is insufficient data currently available to develop these relationships for other crops and soil types.

The importance of increased sampling depth for S soil testing is highlighted in the meta-analysis of S fertilizer research done by Anderson *et al.* (2013) examining the relationships between soil S tests and yield responses for historical studies of wheat and canola. They found that increasing sampling depth to at least 30cm for wheat/canola in WA and up to 60cm for canola in NSW, significantly increased the ability of soil S testing to predict yield responses. Considering that uptake of S from the soil profile is driven by the distribution of roots and S availability within the soil profile in relation to seasonal conditions, deeper sampling helps take these complex processes into account (Bole and Pittman 1984; Brennan and Bolland 2006). Increasing sampling depth beyond 50 cm is unlikely to further increase accuracy of the soil tests for wheat and canola, with root length density within the soil profiles declining exponentially with soil depth (Bole and Pittman 1984; Zhang *et al.* 2004).

Deeper sampling depths are also important for non-sandy soil types, high rainfall areas, and other crops where root and S distribution in the soil layers is likely to be deeper than in sandy soils. For example, in tropical cropping systems, rapid crop uptake in conjunction with high rainfall events can lead to low levels of extractable S in soil surface layers. Using a weighted profile mean to take into consideration increased sampling depth for S testing was useful for predicting responses to S when establishing pasture legumes, as a consequence of both soil S distribution and crop rooting profile (Probert and Jones 1977). In VIC and NSW soils considered in the meta-analysis by Anderson et al. (2013), the adsorption/desorption properties of the soils also appeared to play a role in S availability, with KCl-S being poorly correlated with yield in the top 15cm. Soil MCP-S test values were able to be used to establish critical soil test ranges for S in the upper part of the soil suggesting that for the soils considered in this dataset, the adsorbed S is a more significant contributor to the S supply in the topsoil than mineralised organic S (Anderson *et al.* 2013). This is similar to results for sorghum in Qld where MCP analysis produced more robust results than KCl-40 (Lester and Dowling 2001).

* + 1. Sulfur loss from cropping soils
* Sulfur leaching

Leaching of SO4-S below the rooting depth of crops is driven by a range of factors including fertilizer history and application (Heng *et al.* 1991), SO4-S status of soil (Sakadevan *et al.* 1994), soil water-holding capacity and/or soil water drainage (Heng *et al.* 1991), soil adsorption capacity for SO4-S (Bolan *et al.* 1986; Lefroy *et al.* 1995), and soil S immobilisation potential (Scherer 2001). For most Australian soils, the amount of leaching is largely unknown, but it is reasonable to conclude that very high annual rainfall, extreme rainfall events and course sandy soils can be considered as high risk factors for leaching to occur (Barrow 1974). It is for this reason that S inputs on sandy soils such as commonly occur in WA, under wheat and canola production need to be maintained for wheat quality and grain quality (Moss *et al.* 1983; Zhao *et al.* 1999b; Anderson *et al.* 2006; Gallejones *et al.* 2012).

Similarly to nitrate, in soils of neutral and alkaline pH SO4-S is mobile and high rainfall events have the potential to leach considerable amounts of available S (> 2kg/ha) from the upper part of the soil profile (Blair and Nicolson 1975; Peverill and Douglas 1976). In addition to native soil chemical properties (Blair *et al.* 1997), soil OM also plays an important role in soil S retention through increasing adsorption of S (Anderson *et al.* 1998a; Barton *et al.* 1999). In light-textured soils with low S sorption capacity, the frequency and intensity of rainfall/drainage and soil sorption properties directly influence the availability of SO4-S to crops during the growing season (Anderson *et al.* 2006; Bolland and Russell 2010). Intense rainfall early in the growing season can cause leaching of soil S beyond the root zone and create S deficiencies later in the growing season (Anderson *et al.* 2006; Ercoli *et al.* 2012). Alternatively, in soils with leached SO4-S, deficiencies may be alleviated later in the season when roots reach deeper soil layers high in S (Bole and Pittman 1984).

Work in sandy WA soils found that SO4-S in the top 0.2m of soil decreased rapidly in the first and second year after gypsum applications stopped with a concomitant build-up evident between 0.3 and 0.5m (Anderson *et al.* 2006). It appears likely that outside of the area of crop uptake (top 20-30cm), plant available S was slowly leaching into the deeper soil layers. Accumulation of SO4-S at 0.3m to 0.5m in sandy soils, is supportive of historical leaching of SO4-S occurring, however S budgets suggested that most of the leached SO4-S remains above 0.5 m where it can still be accessed by crops (Anderson *et al.* 2006). This redistribution and accumulation of SO4-S at depth has been observed elsewhere (Chen *et al.* 1999). Blair *et al.* (1997) profiled S content in soils across 28 sites in Victoria, New South Wales, South Australia, Queensland and Western Australia and found that soils with S accumulated above 50cm generally received <700mm rainfall annually. Of these eight soils, five also had low S adsorption properties. In soils with S accumulations deeper than 50cm, over half were in areas with rainfall > 700mm and 70% had low S sorption (Blair *et al.* 1997). Of particular concern, of the 15 soils with S at depth, one-third actively desorbed S. The retention of SO4-S in the upper soil layers increased with soil clay content with the increased adsorption capacity of the clay aiding in preventing S leaching into deeper layers of the soil (Bolan *et al.* 1986; Lefroy *et al.* 1995). Not unexpectedly, the less the adsorptive capacity in the surface layers of the soil the more risk there is of substantial movement of SO4-S into deeper layers occurring.

Leaching events can also occur in heavier soils as a consequence of unusually high annual rainfall, with S deficiency symptoms being widespread in winter cereals in the Darling Downs after unusually high annual rainfall (Chisholm and Dowling 1985). The S deficiency observed in these winter crops could be influenced by a combination of factors including; S immobilisation due to high stubble loads from the previous summer, a lack of S mineralisation due to high cropping intensity, and seasonal conditions not allowing root activity deeper in the profile to access subsoil S. In pastures in NSW (Armidale), long-term annual fertilisation with superphosphate on phalaris and white clover pastures led to S leaching, with a large amount of SO4-S stored deeper in the soil profile and paddock drainage water high in S (Chen *et al.* 1999). Long term application of superphosphate resulted in high KCl-S being observed in the top 20cm of the profile, together with an increase in SO4-S sorption capacity at lower soil depths, resulting in a large amount of SO4-S stored at greater depth (Chen *et al.* 1999). However, use of 35S labelling illustrated that the movement of SO4-S through the profile was very slow (Chen *et al.* 1999). The movement of nitrate through this soil was also examined in this study with results suggesting that synchronisation of pasture growth with N mineralisation and nitrification, together with ammonium domination of the soil N system prevented N leaching in this environment (Chen *et al.* 1999). As SO4-S is slowly utilised in small amounts by most pastures and crops, the likelihood of leaching occurring is increased compared to nitrate which is required in large amounts over a short time period.

As a consequence of the high leaching risk in sandy soils, studies have shown the residual value of the previously applied SO4-S fertilizer is short-lived, with as little as 15% of applied SO4-S retained in the soil as SO4-S at the start of the growing season after S application (Anderson *et al.* 2006). If these sandy soils occur in high rainfall areas (>750mm), the rate of leaching can be even faster with current season fertilizer S leached three to four months into the growing season (Barrow 1966). As a consequence, soils with high S test values that have low plant-available water capacity (e.g. Tenosols and Sodosols) will have higher critical soil test ranges for S compared to soils that are less prone to leaching (Blair *et al.* 1997; Anderson *et al.* 2013). Unsurprisingly, the retention rates are much higher in clay loam soils (31%) with the increased adsorptive capacity of the soil holding residual amounts of applied SO4-S fertilizer (McCaskill and Cayley 2000). Residual values of applied SO4-S fertilizer are influenced by a range of factors including timing of application (seeding vs. post seeding), rate of application and seasonal conditions. For example, in S fertilizer trials in WA wheat crops were unresponsive to current season S fertilizer application due to the residual effect of the post-seeding S application made in the previous year (Anderson *et al.* 2006). In contrast, in following seasons at this site when S fertilizer was not applied in season there was no residual effect from the previous season observed, due to > 90mm drainage observed in the previous two growing seasons.

* + 1. Factors hindering the development of better understanding of S processes

One of the major problems in developing a better model of S availability to crops is the lack of understanding regarding S cycling in soils and the poor relationship between soil S tests and crop grain yield responses. Studies relating soil S and yield are dependent on a range of factors, such as soil depth tested, type of soil test (most commonly KCl-S and MCP-S), seasonal conditions and OM content. Within Australia, soils where relationships have been observed are largely limited to coarse sandy soils such as occur in WA, where stored nutrients, rainfall and OM matter/microbial activity is generally low. More commonly, S fertilizer trials only observe an increase in yield under very high levels of S applications to the paddock. Confounding factors such as soil type, clay content, S fertilizer history, existing soil S pools, microbial content and competition for applied S, OM and seasonal conditions have a significant impact on the responses, or in most cases lack responses to S fertilizers.

Anderson *et al.* (2013) used the BFDC national database to look at the potential for developing calibration relationships between soil S tests using various soil depths and relative grain yields, but with limited success. The applicability of this analysis is severely limited by the fact that most of the historical research has been done in WA (82%), depth and type of soil test used was variable, and S response trials are limited to canola and wheat.Interpretations were based on 60 wheat and 131 canola S studies in WA, 10 wheat and 25 canola studies in NSW and nine wheat S studies in VIC. Critical soil test ranges (CSTR) were defined at a relative yield of 90%. Across all the datasets (WA, NSW and VIC) the KCl-S test-wheat crop response relationship was poorly defined. However, reducing the focus of the analysis improved the accuracy, illustrating the importance of growing condition and soil type to crop S response. In WA wheat the CSTR for wheat was 2.4 to 3.2 mg / kg (R = 0.87) with soil sampling at 30cm. These CSTR values also held for wheat grown on Ferrosols in NSW. The authors suggested that these CSTR values can be used more widely to predict S responses on soil types where soil SO4 is not leached during the growing season (therefore excluding high rainfall areas in northern NSW, southern QLD and parts of SA). For canola grown in WA, the CSTR was defined as 6.8–7.5 mg/kg (R = 0.70), which was slightly higher than the range of 3.1–4.9 mg/kg defined for canola grown in NSW. Accuracy of the CSTR values for both wheat and canola was significantly improved by sampling to 30cm instead of 10cm and for canola in NSW increasing the sampling depth to 60cm was required for relationships to be established. Increasing sampling depth was generally more critical for canola compared to wheat.

* + 1. **Knowledge gaps and priorities for S supply and loss processes**
* Lack of in-field studies measuring process rates that determine when and how much S is available during the growing season
* As a consequence of most S research in Australia being (a) done on combined pasture / cropping systems with higher OM levels than currently exist in most cropping soils (Blair and Nicolson 1975; Blair *et al.* 1991; Blair *et al.* 1997), (b) done in nutrient poor, low water-holding capacity coarse sandy soils in Western Australia (e.g. Anderson *et al.* 2013), and (c) mostly done > 20 years ago before the widespread adoption of no-till and reduced-till cropping systems, the information available for process rates determining when and how much S becomes available during the growing season in most Australian cropping soils is either non-existent, limited or out-of-date.
* In addition, the ability to assess the impact of seasonal environmental conditions, including extreme rainfall events on these process rates and S availability is non-existent
* This leaves farmers and agronomists largely in the dark about the availability of S within their soils, which, combined with the observed decreases in grain S content in widespread studies (Bell *et al.* 2015), is cause for future concern.

* Inability to identify S responsive soils from soil S tests against a background of declining soil S fertility and poor understanding of fate of applied S fertilizers in most soils
* There is a current inability to effectively characterise S responsive soils using current soil S tests as a consequence of lack of knowledge regarding S cycles and competition with microbial biomass for applied S. The dynamics of the S cycle in Australian soils is largely unknown, particularly in terms of the mineralisation/immobilisation and the dynamics/kinetics of applied S fertilizer. There is a significant lack of understanding about the way in which the size and state of different S pools within the soil directly influence the availability of S even when added as fertilizer. There is some evidence (Anderson *et al.* 2006) that suggests previous fertilizer history and/or current state of S within the different soil S pools may influence the mineralization and availability of S to crops after fertilizer is applied. However, there is not sufficient information currently availability for most soils that effectively characterises the state of S within the different pools and how this background interacts with the availability of applied S fertilizers.
* There is evidence within the literature (Anderson *et al.* 2006) and anecdotal industry experience of S fertilizer trials often failing to generate a crop S response (M.Bell, D.Lester pers.comm) despite paddocks showing S strong deficiencies in the prior year. In addition, many sites that theoretically should be S deficient based on low soil S test results are also non-responsive. There is a lack of understanding of the fate of applied S fertilizers, soil S pool dynamics, and microbial interactions, the latter of which are largely uncharacterised and potentially very significant.
* Lack of understanding about rates of S mineralisation in relation to soil type and SOM, and most usefully the relationship between S and N mineralisation (useful for fertilizer applications)
* From a crop perspective, most of the S acquired early in the crop’s life cycle is derived from the immediate release of S from crop residues that remains in the surface soil, and mineralisation of S from organic matter over the fallow period. Sulfur behaves in a similar manner to N with respect to fallow build up as an anion (sulfate) but it is generally less mobile than nitrate. As micro-organisms consume labile organic matter, they release excess S as sulfate into the soil solution which is available for plant uptake and/or leaching. This is the same process that releases N as ammonium which then nitrifies it to nitrate. From a fertilizer management perspective, it would be useful to develop some understanding of the relationships between N and S mineralisation to be able to develop some “rules of thumb”
* There is also little understanding of where the ‘cliff’, with respect to labile organic matter depletion, and slow mineralisation of S reserves actually is. As labile organic matter is used and more recalcitrant, resistant organic material remains, the replenishment of surface S reserves will decline and increasing S responses will more likely be observed. Investment in carbon research needs to address the links with S supply to benefit to producers in the long term.
* Mobilisation of S out of fertilizer bands and subsequent ability / inability of crop roots to utilise banded S

There is little to no understanding of the mobilisation of S out of fertilizer bands and the ability/inability of crop roots to utilize S in a band.

1. Decision support models for nitrogen and sulfur
	1. Nitrogen fertilizer decision models

There are seven main decision support models used for determining N fertilizer recommendations for dryland grain production in Australia (NCalc, NitrogenARM, NUlogic®, Select Your Nitrogen, SoilMate, WhopperCropper and Yield Prophet), although a number of more regionally-focussed tools are also available (e.g. N Budget in the northern region and N Balance in southeast NSW). The assumptions used for predicting N fertilizer requirements are dependent on the time-step used by the model. The models used for decision support for N fertilizer in Australia fall into two groups: annual or daily time-step.

Annual time-step models predict grain yield and quality (protein) response based upon an estimate of net N supply from soil and residues and an estimate of crop N demand based on a potential yield. The relationships between total plant available N, potential yield and actual yield are derived empirically in all annual time-step models, but there are important differences between the models. NCalc uses a budgeting approach where the amount of N fertilizer required is the crop N demand (based on potential yield) minus estimated soil N supply. Select Your Nitrogen and NUlogic® (Neuhaus and Bowden 2014) use a response-curve approach, where empirically-derived functions are used to predict grain yield and profit as a function of the rate of N fertilizer applied. All annual time-step models determine soil N supply by estimating the amount of N likely to be mineralised from soil organic carbon (SOC) in the surface soil (0–10 cm), and combining this with the amount of mineral N (NO3- + NH4+) already available prior to planting. The amount of soil mineral N available at seeding is based on soil testing or, in the case of Nbudget, the nitrate is estimated based on crop history, local climate data and background soil fertility—soil testing for mineral N or soil organic C is not required (Herridge 2011). N budget used several decades of research data to derive functions that account for the effects of legumes on cereal diseases and soil nitrate levels, as well as 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 N2 fixed by legume crops were also included. Select your Nitrogen, NUlogic® and NCalc also include net N supply from residues from previous crops or pastures. The NitrogenARM model does not account for N supply from the previous crop, but does allow the effect to be included using soil N test results.

All annual time-step models derive the amount of N supplied by soil N mineralisation empirically. Firstly, SOC is used to predict total organic N (SON) based upon the soil carbon to nitrogen ratio (C:N); and secondly, a proportion of the SON is assumed to mineralise to plant available mineral N. NCalc allows the user to specify a C:N ratio while Select Your Nitrogen uses a default value. There is some agreement between the annual time-step models on the percentage of SON that will mineralise in a year. NCalc has a default mineralisation rate of 3% based on previous studies (Baldock 2004). NUlogic® has a default mineralisation rate of 2% which can increase up to 3% where summer rainfall has occurred. Select Your Nitrogen calculates soil mineral N availability in the 15 weeks prior to anthesis and has a potential mineralisation rate of 3% (0.002 per week x 15 weeks x 100). The relationship between soil N supply and SOC is a key assumption in annual time-step models, which limits the application of each model to the environment where it has been validated. There may be scope to improve this prediction by accounting for soil organic matter fractions and soil pH (pers. comm. A. Neuhaus).

APSIM is a daily time-step model used in Australia for modelling N dynamics in crops and is the engine behind the decision support models Yield Prophet and WhopperCropper. APSIM differs from the annual time-step models as it is process-based rather than empirical. However, the inclusion of soil processes requires assumptions about relationships between soil properties and an estimate of parameter values. For example, nitrification rate (mg N kg-1 day-1) is calculated based upon a potential nitrification rate and scalars for soil; water content, temperature and pH ([https://www.apsim.info/Documentation/Model,CropandSoil/SoilModulesDocumentation/SoilN.aspx](https://www.apsim.info/Documentation/Model%2CCropandSoil/SoilModulesDocumentation/SoilN.aspx) ). These assumptions are validated by comparison of model outputs with observations (Asseng *et al.* 1998a; Asseng *et al.* 1998b), however the validation is typically based on the integrated effect of all model assumptions on grain yield rather than assessing model performance for individual processes. Where a growth factor is affected by a number of processes, e.g. radiation use efficiency is modified by scalars for temperature and leaf nitrogen concentration ([https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Wheat.aspx](https://www.apsim.info/Documentation/Model%2CCropandSoil/CropModuleDocumentation/Wheat.aspx) ), the minimum of these scalars is used to calculate actual growth. The key assumptions for APSIM are: i) the sub-models used for discrete soil processes are adequately described by the function used, ii) parameter values are sound, and iii ) the interactions between processes are adequately captured using the minimum scalar approach.

Although all models account for the supply of mineral N from the soil, only Yield Profit accounts for all the potential loss pathways such as NH3 volatilisation, denitrification and leaching in detail (Table 7).

Table 7. Soil N supply and loss pathways accounted for by various decisions support models used for N fertilizer recommendations in rainfed cropping systems.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model | N mineralisation | NH3 volatilisation | Denitrification | N leaching | Reference |
| NCalc | Yes | No | No | No | Baldock (2003) |
| NitrogenARM | Yes | No | No | No | http://armonline.com.au/#/ncalc |
| NUlogic®, | Yes | No | No | No | Neuhaus and Bowden (2014),  |
| Select Your Nitrogen | Yes | No | No | Yes | Burgess *et al.* (1992) |
| WhopperCropper |  |  |  |  |  |
| SoilMate | Yes | No | No | Yes | Pers. comm. C. Dowling, |
| Yield Prophet (APSIM) | Yes | Noa | Yes | Yes | Keating et al. (2003); Vogeler et al. ; Holzworth et al. (2014); Graydon et al. (2012); Giltrap et al. (2015) |
| Nbudget | Yes | ­­­Yes\* | Yes\* | Yes\* | Herridge (2011) |

a Only for flooded conditions, and urine patches in pasture

b Provides a retrospective assessment from the previous crop and season using rules of thumb, rather than any dynamic seasonal estimate

\*no direct modelling, assumed 80% fertilizer N plant available based on previous research.

* 1. Sulfur fertilizer decision models

Nutrient balances are the most common approach to S management in Australian farming systems as a consequence of poor relationships between soil S testing and crop yields, the lack of research and understanding of S mineralisation in most Australian soils (with the exception of WA) and transient seasonal S deficiencies being observed in most grain growing regions. A common approach is to apply fertilizer at seeding to supply 1-10 kg S/ha depending on the fertilizer used and the risk of S deficiency within the growing region. The National Land and Water Resources Audit (2001) determined that this practice is likely to result in a neutral (-2 to 0 kg S/ha) to moderately positive (5-10 kg S/ha) S balance in WA wheat belt, as long as leaching does not occur. There is a lack of information available for assessing the long-term outcome of this practice for wheat growing areas outside of WA so the current practice of 1-10kg S/ha at seeding is common in areas where S deficiencies have been observed with the rate increased for crops of high S requirement such as canola.

One of the considerable challenges with further research in this area is the inability of researchers, agronomists and farmers to correctly identify sites outside of WA that are S responsive. Outside of WA, it is not uncommon in the grains industry to identify areas showing symptoms of S deficiency only to do S fertilizer trials the following year and get no responses (M. Bell pers. comm.). There are a range of factors including seasonal impacts on mineralisation, soil immobilisation/mineralisation dynamics, largely uncharacterised microbial competition for applied S fertilizers, soil adsorption/desorption properties, crop S requirements, and changing organic S pool dynamics that all may be playing a role in creating these transient S shortages within cropping soils. Irrespective of this, the circumstantial evidence largely points towards S deficiency becoming more common in all grain growing areas within Australia. Development of soil S testing procedures that characterise net S mineralisation in different soil types / growing conditions and determine residual SO4-S within deeper soils layers is essential.

1. Consultant and grower approaches to nitrogen fertilizer decisions

A series of targeted interviews and surveys were conducted in each region to assess:

* The broad approach used for N fertilizer recommendations by growers and consultants, and how accurate they believe recommendations.
* The types and usefulness of information and tools growers and consultants use to make N fertilizer recommendations.
* How growers the consultants account for soil N mineralisation and other factors that influence fertilizer N efficacy
* What additional information and tools growers and consultants might consider valuable.

In total, approximately 200 consultants, advisors and others providing fertilizer recommendations to growers were surveyed using either on line polls or questionnaires completed during industry workshops. The number of questions ranged from a minimum of 7 to a maximum of 21, with the less detailed questionnaires and the more diverse sets of responses resulting in detailed follow up interviews with >25 consultants nationally.

In the West, growers from the Mingenew-Irwin and Liebe grower groups were also consulted, with a subset of the advisor questions receiving contributions from >120 participants.

The synopsis form each state/regional report is attached to this report in Appendices, with the detailed datasets available as required. The key findings on a national basis are outlined below, with specific regional differences or peculiarities outlined under the relevant sections.

* 1. The context within which nitrogen fertilizer decisions are being developed

While the project did not specifically set out to canvas grower communities about how they made their fertilizer decisions, the information derived from the WA cohort showed that more than 75% of growers sought fertilizer advice from a consultant or fertilizer reseller, and anecdotal experience suggests this is likely to be similar in most other grain growing regions. This justifies our focus on the agronomists, consultants and advisors and the tools and knowledge they are using to make such recommendations.

Moving to the advisor/consultant cohort, there was a clear emphasis from respondents in all regions that fertilizer recommendations were influenced by a myriad of factors other than biophysical issues, with each client’s unique combination of financial, managerial, aspirational and logistical circumstances resulting in the development of a recommendation that tries to be both agronomically sound as well as likely to be implemented. This often results in some significant compromises that are not necessarily consistent with the agronomic optimum.

In all growing regions the advisors surveyed covered a broad range of rainfall and productivity zones, although there was a tendency for greater coverage from the more reliable cropping areas. In the case of Vic/SA this was from those operating with >375mm annual rainfall (67%), in NSW this was 66% >450mm and a further 16% irrigated, and in Qld >70% were in the 550-650mm zone with more than half also advising on irrigation blocks. There was care exercised in selecting advisors for more in depth interviews, to ensure this broad representation was maintained. In the west, the cropping regions covered the 225–450 mm (May–Oct) span, with the Mingenew-Irwin and Liebe grower groups and the consultants interviewed covering the upper and lower ends of that range, respectively.

Soil types and farming systems varied greatly. Across the northern region there was a gradient from almost exclusively alkaline clays in Qld and NNSW, transitioning through a variable region in central NSW (acid loams – alkaline clays) to more acidic and lighter textured loams and sandy soils in southern NSW. The soils in Vic and SA were very mixed although predominantly neutral-alkaline in pH, with everything from siliceous white sands through duplex clay loams and clay loams to grey cracking clays. Soils in WA were almost exclusively light textured.

Farming systems again varied regionally, with NNSW and Qld almost exclusively cropping but an increasing proportion of mixed farming enterprises further south and in the west. The reliance on synthetic fertilizer inputs to meet crop N demands was reported as very high in Qld through to central NSW, despite a rotation frequency of pulse crops typically 1:4 or 1:5. However the impact of mixed cropping enterprises further south (typically with mixed swards or lucerne pastures grown in phases) meant the fertilizer N inputs increased through the cropping phase as mineralisable N reserves were depleted. In areas where cropping intensity had increased, fertilizer reliance was again high. In the west, systems were also heavily reliant on synthetic N inputs, as legume frequency was low (some lupins and field peas, but at relatively low frequency) and continuous cropping of cereal-canola rotations is increasingly the norm.

* 1. Approaches used to determine N fertilizer requirements for clients

This topic and related questions produced a variety of responses, with clear regional nuances. Perhaps the most consistent response at a national level was a strong reliance on nutrient budgeting (in various guises) and ‘rules of thumb’ developed from a mish-mash of technical advice, local experience and ‘calibrated gut feeling’. Various sources of information (models/DSS, soil testing, seasonal forecasting, paddock history) were used to inform/tweak the application of those approaches and to occasionally ground truth/validate/recalibrate the underlying assumptions. The contribution of various tools and measurement techniques to the development of a fertilizer recommendation, and the uncertainties associated with them, are highlighted below –

* Using a nitrogen budget/balance approach to determine crop N demand

Various methods are being used to estimate crop N demand, typically based on potential yield estimates, a grain protein target and a partitioning factor to account for N remaining in crop residues. In many cases these individual components are rolled into a single, fairly coarse rule of thumb like ’20 units of N/t wheat grain’. All regions reported that estimating seasonal yield potential was by far the greatest uncertainty in determining an N application strategy. Factors such as stored soil water at planting (especially in Qld and NSW) and seasonal forecasts were reported to figure prominently in this estimate, along with factors related to crop rotation, weed and disease risks. Interestingly, there were some observations that the latest seasonal forecasting tools were being poorly utilized in this regard due to their perceived uncertainty. Even when the majority of N inputs were being provided as in-season top-ups, the fertilizer recommendations were often developed at a point in time prior to sowing, rather than updated as the season unfolded.

Approximately half of all advisors thought yield potential estimates at the time of making a fertilizer decision needed to be with 10-15% of actual yields, but a further 35-45% suggested a broader 15-25% range. This was quite consistent nationally. The broader ranges were commonly related to lower yielding regions, and interestingly both ranges often resulted in a similar margin for error in target yield of approx. 0.5 t/ha. This uncertainty in the yield target, and hence crop N demand, has influenced advisors attitude towards the need to fine tune other components that relate to fertilizer N requirement (e.g. in season mineralization).

* Accounting for soil N supply

Most advisors considered the contribution from soil mineralization when making a fertilizer recommendation, with models/DSS and soil testing supporting broader rules of thumb estimates based on soil type and paddock history. The strategies and tools used to estimate this contribution differed significantly between regions. Responses were primarily related to accounting for pre-season and in-season N mineralization, with a general acknowledgement that the understanding of N mineralization in relation to soil and climatic factors was quite limited, especially in relation to modern farming systems.

* Accounting for pre-sowing/fallow mineralization

Pre-season mineralization was typically estimated using models/DSS and local ‘rules of thumb’, with soil testing used to validate assumptions in fields with contrasting management of histories. However, the reliance on soil test information differed markedly, depending on region and the client group. In Qld and NNSW advisors place considerable confidence in soil testing towards the end of a fallow as a measure of available soil N, especially for winter crops and long fallow situations, from the perspective that the majority of N mineralisation is likely to have occurred by this time. The situation for summer crops can be more variable, given the cooler temperatures and less reliable winter rainfall, although this caveat predominantly relates to spring plantings. Regardless, more than 85% of advisors surveyed rated soil testing as their most effective tool in developing a fertilizer recommendation, with the quantities of available N in the crop root zone used to discount fertilizer N requirements. Unfortunately many farmers have much lower confidence in soil testing, seeing it as an expensive option for which quicker and cheaper means of estimating soil mineral N need to be developed. This contrast has resulted in a relatively low frequency of soil testing. Experienced advisors tend to use it as a means of indicating relative differences between paddock histories and ages of cropping, or to validate their local rule-of-thumb estimates, rather than as a regular requirement to estimate soil N supply.

The situation in Vic and SA was less emphatic, although a high proportion of advisors considered soil testing to be an important tool in making a fertilizer recommendation and while 60% said they accounted for pre-sowing soil N mineralization in their fertilizer recommendations, the proportion actually using soil testing to quantify this was not immediately obvious. While advisors recommended their clients conduct soil testing on representative paddocks each year, the difficulty in sample collection and the costs per sample are limiting the number of samples taken. In these situations advisors typically reverted to past experience and rules of thumb for different paddock histories and seasonal scenarios, or relied on estimates from various decision support systems. Those using the DSS tools were typically in the minority, with comments suggesting greater confidence in the output from more process-level tools like Yield-Prophet but a reluctance to devote the time or resources into doing the detailed site parameterisations to gain the perceived additional accuracy.

There was even less reliance on soil testing in the west. Consultants typically saw soil sample results each year, and may have used results as the starting point for developing recommendations, but most noted that the actual results had little impact on their fertilizer recommendations. This may reflect the more transient nature of mineral N in those lighter textured soil types, as well as the large seasonal variability in fallow mineralization. Interestingly, the soil organic matter content was valued more than soil mineral N in those situations as an indicator of the degree of buffering provided to fertilizer N supply in seasons where yield potential is higher than expected, rather than as a factor modifying fertilizer recommendations.

* + *In season N mineralisation*

Most advisors reported they accounted for in-season N mineralization, but the extent and impact on a fertilizer recommendation was highly variable and there were distinct regional differences. In Qld and parts of northern NSW, where fallow mineralization typically dwarfs that recorded in crop, factors such as paddock history and organic matter level/age of cropping will already have been accounted for in starting soil N measurements or estimates. Even when estimates are provided by the relevant DSS, in season mineralization is often discounted or ignored when developing fertilizer recommendations as it is typically considered as a seasonal buffer (to allow for a higher yielding season than expected) rather than to discount fertilizer requirements.

In the rest of southeast Australia, the contribution of in-season mineralization was generally considered much more significant and is a factor that often influences seasonal fertilizer recommendations, although there was considerable variation in the confidence with which these estimates were used. Advisors in NSW reported using model estimates from DSS like Soil Mate and the Angus spreadsheet, with key modifiers being soil carbon and rainfall, but there were comments that figures were ‘rubbery’ and were again more useful as a seasonal N buffer than to fine tune fertilizer recommendations. These comments about a desire for N buffering in the farming system were common nationally, and probably reflected the uncertainty in estimating yield potential and N demand at the time when fertilizer recommendations were being made. There was also a link made between soils with higher soil C, elevated rates of N mineralization and (generally) higher yield potential, so the in-season mineralization buffer provided greater confidence in N fertilizer recommendations rather than a means to reduce N inputs.

In Vic and SA, few advisors seemed to use DSS estimates, but preferred ‘rules of thumb’ approaches developed in the 1990s. There was general acknowledgement that changing soils (lower carbon) and farming systems (earlier sowing, stubble retention, zero till, less pasture and more intense cropping and greater reliance on in-season N applications) were not reflected in these mineralization estimates. Advisors strongly supported the packaging up of more recent information from these systems and management strategies to provide clear and simple messages about key mineralization drivers and how these interact under a range of climate scenarios, and advocated further research be targeted at validating the hypotheses derived from this data harvesting.

In the west, gut feel and rules of thumb were the main ways of accounting for N mineralization, with little interest in more refined estimates unless they were ‘quick and easy’. These responses may relate to the admitted dearth of knowledge about mineralization rates and N processes amongst the consultant group, but also tended to reflect how fertilizer N was managed. Fertilizer strategies were developed prior to sowing on the basis of likely soil contributions from different paddock histories and soil carbon contents. Any in-season top-up applications were done more in response to changing yield targets rather than to any fine tuning of in-crop mineralization rates. The advisors were uncertain how they would use more refined data on N mineralization even if it were to become available.

* Assumptions about efficiencies of use of soil and fertilizer N

There appeared to be considerable confusion between groups in relation to the terminology ‘efficiency of use’, and this resulted in some conflicting messages. In some cases this was interpreted as a de facto N harvest index (i.e. for each 1 t grain containing 20 kg N ha-1 the crop requires another 20 kg N ha-1) while in other cases it seemed to be based on the efficiency with which available N was converted into grain yield (an amalgam of N uptake efficiency and internal partitioning of N into grain). Regardless, the answer was typically 50%, with no distinction between soil and fertilizer N. While there was some recognition that this figure could vary significantly between soil types, inherent soil fertility, seasonal conditions and time of N application, few advisors seemed to have codified how they adjust fertilizer application rates in response to different situations and rely on rules of thumb.

Feedback from a number of groups and regions was that there was again a clear need to integrate more recent research findings that better reflect current cropping systems and N application strategies, and use the information to update extension methods and information sources that can be accessed by industry, especially for younger advisors who may not have had mentoring from more experienced colleagues in an organization. A particular example would be some sort of codification of how to adjust fertilizer N application rates for differential crop recovery efficiencies at different application times (pre-sowing, at sowing and at various times in crop).

* Accounting for N losses

This was another topic where there was a general awareness of the processes involved (in some cases more informed than others), but a relatively poor understanding of the key triggers for a significant loss event (e.g. what constitutes a significant rainfall event?), how to develop an appropriate N management response or indeed whether such a response is even warranted. For example, somewhere between 40 and 60% of advisors in the eastern states did not make specific allowance for N losses in their fertilizer recommendations, with a number of advisors commenting that losses were thought to be already specifically accounted for by the 50% N recovery efficiency factor discussed earlier. In the west, a typical response to a loss event (substantial rainfall in a light textured soil resulting in the crop looking N deficient) is to bring forward the next scheduled N application and to apply some extra N. However, without any idea of how to determine the quantum of N losses from an event the amount of additional/catch-up fertilizer applied is based on guess work and gut feeling rather than any sound knowledge base.

That said, advisors in the south and north estimated surprisingly similar estimates of available N (there was no distinction between soil or fertilizer N sources) lost in an average growing season. With the exception of the winter crop in Qld (46%), 70-90% of respondents thought average losses exceeded 10% of available N, and 20-30% (50% for Qld summer cropping) thought average losses exceeded 20% of available N. The distinction between summer and winter cropping in Qld again probably reflects the experiences from the recent NANORP summer sorghum focus. Advisors in the west were not comfortable quantifying a loss fraction.

There were very different perspectives on the main loss pathways in different soils and regions, and in a number of cases this may be a reflection of the extension activities surrounding recent research initiatives (NANORP and the volatilization work of Schwenke et al.). In the case of NANORP, the broad exposure from this program has resulted in considerable awareness of denitrification as a potentially significant N loss pathway, but the level of detailed understanding is limited (i.e. prominence given to N2O rather than N2, and a lack of distinction between soil types). The more limited exposure of the volatilization work of Schwenke et al. in NNSW and Qld has resulted in much less concern with that loss pathway for in-crop applications in NSW than across the border in Vic and SA.

Whilst noting the above caveats, there seems to be a relatively general perception across the industry that volatilization losses from in crop applications are relatively insignificant, especially in the west and in NSW. However volatilization is still considered the major N loss pathway in Vic and SA (with the exception of very sandy soils), with the lack of significant in-season rain events in late winter and spring (when tactical N applications are made) in recent years keeping these concerns to the fore. Interestingly, there is also concern expressed in Qld where in crop application is insignificant but more growers are moving to top dressed N applications prior to sowing to cover larger areas more efficiently.

Leaching losses were considered the main loss pathway in the west, with the greatest risk on the lighter soils, while denitrification was considered the most important loss pathway on the alkaline clays in the eastern states – especially for summer cropping. However in all instances the episodic nature of loss events, and the uncertainty around how to characterise the severity (e.g. does soil have to be waterlogged or just wet, and for how long?) and the quantum of losses (e.g. will N be leached out of the root zone or just deeper into the profile) is limiting the ability of advisors to develop a measured and timely management response. Even when events have occurred outside the seasonal window (e.g. 2010 floods) with ample time for a soil sampling exercise to quantify the impact and adjust fertilizer rates for the following season, the lack of awareness of the potential severity of the losses resulted in one of the ‘occasional misses’ when many advisors got N recommendations wrong.

* 1. What sort of job do advisors think they are doing with respect to N recommendations?

The overwhelming response was ‘good to very good’ most of the time – with the occasional miss! The interpretation of a ‘good’ result was a little unclear, but perhaps should be related to the margin of error considered in determining a fertilizer N recommendation. This was considered to be getting N rates high enough to produce at least 85-90% of seasonal yield potential by ~60% of advisors, with a slightly lower target of 75-85% by a further 20-25% of advisors. This probably reflects the economics of N use in these variable rainfall environments, with comments from advisors in the west suggesting that operating on the flat part of the N response curve (>85% seasonal yield potential) meant that large amounts of profit were unlikely to be lost due to either under or over fertilization.

The references to ‘occasional misses’ were consistent with the general observations that the level of knowledge about seasonal impacts on N mineralization and the various N loss pathways were inadequate among the advisor community, and so an appropriate compensatory management response was not implemented. In each region these ‘misses’ typically related to unusual seasonal conditions (summer rainfall in the south and west, flooding in the north and south) where the usually reliable ‘rules of thumb’ have broken down.

A specific question asked in Qld related to the conduct of seasonal debriefs on the effectiveness of seasonal performance provided interesting insights. Parameters included in the review process are the key outputs (yield), inputs (applied N, mineralisation) and growing season conditions (weather and expected losses). Specific methods used to assess performance, particularly related to N management, included grain yield (92% of respondents) followed equally by zero strips, soil testing and post-crop nitrogen budgets (50%).

* 1. Conclusions and identification of knowledge gaps hindering better fertilizer recommendations
* Overview

There was real consistency nationally in the gaps and priorities identified by advisors, although the responses suggested as solutions (further research versus re-evaluation and packaging of existing but fragmented information) varied somewhat between regions. Regardless of this, there was a consistent message that any new information packages or products needed to be simple and easy to use (if targeting advisors), or designed for use by 3rd parties to feed outputs directly to the advisor group for discussion with their clients. Advisors were adamant they had a limited amount of time to focus on fertilizer decisions, versus everything else, and any additional time invested would need to have substantial benefits for client profitability. Until the widely fluctuating demand side of the ‘N equation’ can be narrowed through improved seasonal forecasting and yield prediction, perhaps through development of more dynamic tools that can provide updated (e.g. weekly) seasonal yield forecasts at a relevant scale (e.g. shires), consultants will be slow to invest more of their time and effort into fine-tuning other aspects of soil N management.

An interesting counterpoint to these feelings was evident in many comments from advisors in areas where cropping has intensified, pasture rotations are less common and soil organic matter levels are low, and it related to the growing productivity and profitability implications of ‘getting it wrong’. The reduction in buffering of N available to the crop from the soil is resulting in increasing pressure on advisors to apply the ‘right’ rate for that particular season, with little room for error. This is raising questions about how well the efficiency of recovery of fertilizer N in different seasons and from different application strategies is understood, and on how to quantify the impact of seasonal conditions on soil N supply as well as N losses. There is a clear lack of confidence in the advisor community in this space, and combined with the uncertainty in predicting seasonal yield potential, this is culminating in a proportion of advisors ignoring the more sophisticated attempts to fine tune soil N supply (e.g. by accounting for in-season N mineralization). Many are adopting a more conservative approach to ensure there are sufficient N supply buffers to enable a productivity response in a better than expected season.

* Extension and training needs

There was widespread articulation of a need to re-initiate some sort of formal training/skilling opportunities for advisors. At one level this was targeted at developing simple and practical extension guidelines to remind advisors of the principles behind existing ‘rules of thumb’ and to update these for aspects of N management to account for significant changes that have since occurred to farming system and climatic patterns. These guidelines needed to be simple with a focus on problem solving, recognising that on farm logistics and scale require estimations not precision.

At another level this involves a process to upskill younger advisors and retailers, who have often not received the mentoring and advice of experienced agronomists and advisors in their region or group. This group requires quality training in N decision-making, both understanding the background soil and plant science involved (including soil test interpretation) as well as gaining perspectives from highly experienced local agronomists. The feedback from more experienced advisors showed that while they were generally comfortable using rules of thumb and local experience in their decision making processes, they were only able to do this because they had been through a period where a lot of extension workshops and training opportunities were available and they had a reasonable understanding of the underlying science and assumptions inherent in these ‘shortcuts’. Those entering the industry were often picking up the rules of thumb without knowing why they worked and when they no longer applied, with the result that inappropriate advice could be delivered – especially in seasons where things were different to the norm.

There were also suggestions that it may be timely to revisit the various DSS available. While some are comfortable with the use of those in their local/regional scales, others suggested there may be opportunities to combine the best points of each into a single, more comprehensive package. Such an exercise could include making such a product available as an app to enhance usage, especially if the tool was able to produce grower-friendly reports.

1. Comparing the identified gaps and priorities from researchers and industry
	1. Nitrogen supply and loss processes
		1. Specific knowledge gaps identified in the technical review
* A systems perspective around N management research
* There is widespread recognition of the fragmentary nature of N research, with studies typically focussing on a supply process or loss pathway without a broader perspective relating to other processes and losses occurring simultaneously.
* There is also a clear recognition of the age of much of the N research, especially relating to N mineralization. Farming systems have changed dramatically in many areas (direct drill, intensified cropping and low legume frequencies) and the relevance of historical relationships to predict soil N dynamics and fertilizer requirements are questioned.
* Similarly, in at least some parts of the Australian grains industry, there have been noticeable shifts in temperatures and rainfall patterns that will impact on the relative importance of fallow and in-season N dynamics and the management tools used to quantify those processes and predict fertilizer N requirements.
* Finally, the increasing reliance on fertilizer N for a larger proportion of crop N supply applies much greater pressure to our the understanding of the fate of applied N, both within that crop season and in the subsequent fallow and later crop seasons. Ensuring adequacy of N supply, and utilizing more adaptive management responses to particular sets of climatic events, will become increasingly important for successful management of N in Australian cropping systems.
* Complementary analytical methods exist (e.g. 15N) which provide accurate representations of the fate of applied N in agricultural soils, including quantification and fate of native soil N through mineralisation of SOM and residues.
* Supply processes - Mineralization
* There is little published information quantifying rates of mineralization during the growing season in Australian dryland production systems. This information will be essential for determining when and how much N is available during the growing season.
* Soil N supply is linked to total soil N which exists in different SOM fractions with variable composition and turnover rates. There are currently poor links between improved SOM fraction measurement techniques and rate limiting factors responsible for SOM turnover. Such work would logically focus on response to variation in rainfall and temperature.
* The links between changing farming systems and management practices, the duration of cropping and the size and turnover rates of mineralisable N pools are poorly developed. There is an urgent requirement for research in this space to both update the technical basis for existing DSS and to capitalize on the move to in-season fertilizer N management.
* N losses

Volatilization

* This loss pathway warrants considerable attention, given that losses can be as high as 30% of the applied N.
* The only detailed sets of field measurements quantifying volatilization losses predominantly come from NSW, and in the case of rainfed production systems, the alkaline clay soils of NNSW. This work focussed on winter cropping, so there is also need for further work in the northern grains region to examine options for N fertilizer management in the summer cropping industries. There is also a demonstrable need to extend this work to other production regions, soil types and rainfall environments in the southern and western regions, especially given the broad shift to surface applications of N during the growing season in those cropping systems.
* The publication of a model for predicting NH3 losses from Australia’s agricultural soils provides an opportunity to strategically investigate and verify the risk of NH3 losses from Australian cropping systems using current fertilizer management practices.

Nitrous oxide and dinitrogen gas emissions

* Nitrous oxide emissions from agricultural soils represent a small percentage of the N fertilizer applied to cropping soils (<5%), and further research on minimizing N2O emissions is not justified for the purpose of refining N fertilizer decisions.
* However, there is substantial evidence emerging from a variety of soils (alkaline clays, duplex soils and soils high in organic matter) showing that substantial denitrification losses (largely as N2) do occur in Australian cropping soils. These losses typically represent 20-50% of N fertilizer applied in many environments.
* The current dearth of information on N2 losses from Australian cropping soils needs to be addressed to allow subsequent focusing on system/regional hotspots and management strategies to minimize the loss risk.

Leaching

* There is limited field based measurement of N leaching from Australian cropping soils, except for rain fed crops in Western Australia, where losses can be significant from coarse-textured soils. There is a need to extend these studies to encompass other lighter textured soils in SA/Vic, and into the high rainfall zones in Vic and NSW.
* Without improved weather forecasting to predict the risk of drainage beyond the rooting zone it will be difficult to convert a leaching risk on a sandy soil into modified fertilizer N management practices. Currently, pragmatic approaches include avoiding applying N fertilizer immediately before heavy rainfall and bringing N fertilizer programs forward or applying additional fertilizer after loss events have occurred.
* Research into the opportunities for improved fertilizer technology to reduce leaching losses in high risk situations could be profitable, although quite soil and climate-specific.

* + 1. Specific knowledge gaps identified by advisors
* Mineralisation

All regions were interested in better ways to estimate soil N mineralization, from both organic matter and recent crop residues (especially grain legumes). Even advisors who use the existing DSS tools note that the estimates are ‘rubbery’, with uncertainty around the impact of new farming systems (rotations, tillage and cropping intensity) on the underlying assumptions.

In the north and the south, there was a feeling that at least some of this information may be available but needed integration and incorporation into extension and promotional material. The focus would be to allow better estimates of quantity and availability based on soil type, temperature, rainfall pattern, season length and organic carbon, and should also include previous crop residue type, i.e. cereal, oilseed or grain legume.

Consultants were especially keen to better understand what influences soil N immobilisation and mineralisation in the previous season, pre-seeding and in-season. This was particularly relevant for the west, but was also of interest in areas with high stubble loads in eastern states. They feel that factors like N carryover, stubble load, stubble type and stubble management affect N requirements, largely by affecting N transformations, but they have not seen sufficient data to support their hunches. Recent challenging seasonal conditions, in which the current rough assumptions of N mineralization were clearly inadequate, have clearly driven this topic. They were unclear whether sufficient research data already exists and simply needs integration, or whether new research is required, but articulated a desire for N information in real-time, with spatial quantification of N transformations and losses..

* N losses

Advisors described a general lack of understanding around how to both quantify and respond to N loss events nationally. Whilst people could generally identify the likely loss pathways for their soils and regions, they were very unsure about how to quantify likely losses in response to particular climatic events and seasonal conditions. There was also a lack of knowledge about whether/how effectively current rules of thumb (e.g. 50% N recovery efficiency) deal with losses. There is a clear need for better knowledge, targeted to regional production environments, to clarify what situations and scale of different forms of N loss may occur. Leaching was perceived to be the main loss event for the west, and on some sandy soils in the south, but volatilization and denitrification (on less well drained soils and especially in summer cropping environments) are major priorities in the north and south.

* Crop N uptake efficiencies

Advisors described a need to better integrate and update the available information on crop N recovery (of both soil and applied N) based on time, method of N application and seasonal conditions in current farming systems. Some of this information is embedded in DSS used by a proportion of advisors, but this has not been explicitly promoted to those outside the DSS-using cohort. This is especially relevant given the increase in cropping intensity and the greater reliance on fertilizer N inputs (with typically lower N recovery efficiency) as opposed to background soil N supplies in most of the cropping regions.

There is also a clear need to develop better information and guidelines on the links between N application strategies (fallow, at planting or in crop), the resulting position of N in the soil profile, risks of different loss pathways and the efficiency of N recovery by the crop. These need to have a clear regional soil type and climate focus.

* Better estimates of seasonal yield potential

Advisors noted the uncertainty in yield estimates as a major constraint in attempts to fine tune crop N demand estimates. A variety of suggestions were made to improve this situation, ranging from better estimates of spatial variability in soil water contents/PAWC as a way of informing zonal N management within paddocks, to more comprehensive tools to develop relationships between historical yield and rainfall which are site and management specific. The pipe dream articulated by advisors in the west, was a better yield predictor based on real-time estimates of soil moisture availability and climate forecasts, linked to a decision tool that calculates optimal N rates and post-sowing application strategies.

* Variety-specific N management packages

This was specific question raised by advisors in NNSW and is more related to agronomic management of different wheat varieties than it is to uncertainty about N management. It is an area for continued research funding, as results from some new varieties have been quite different in terms of N uptake and protein outcomes.

* 1. Sulfur supply and loss processes
		1. Specific knowledge gaps identified from the technical review only
* Lack of in-field studies measuring process rates that determine when and how much S is available during the growing season
* Dynamics of S cycle in Australian soils is largely unknown, particularly in terms of the relationship to mineralisation / immobilisation of S from SOM and the dynamics / kinetics of applied S fertilizer
* Lack of understanding about the way in which the size and state of different S pools within the soil directly influences availability of S to plants, even when added as fertilizer
* Lack of understanding about rates of S mineralisation in relation to soil type and SOM, and most usefully the relationship between S and N mineralisation (useful for fertilizer applications)
* Impact of microbial competition for applied S fertilizers (largely uncharacterised and potentially significant). Circumstantial evidence suggests that microbes can completely immobilise added S fertilizer for years in some Australian soil types
* Mobilisation of S out of fertilizer bands and subsequent ability / inability of crop roots to utilise banded S
* Current inability to effectively characterise S responsive soils using current soil S tests as a consequence of lack of knowledge regarding S cycles and competition with microbial biomass for applied S
1. Conclusions and R, D and E investment priorities for N, S and W

Nutrient dynamics in farming systems are constantly changing in relation to shifts in input-output ratios, as well as day to day management approaches involving crop rotation, crop residue management and fertilizer management. The dynamics of N and S are further complicated given the importance of microbially-mediated organic pools governing the availability of inorganic forms of each nutrient for crop uptake, and so matching available nutrient reserves to an expected (and often uncertain) crop demand represents an on-going challenge for Australian grain growers and their advisors

As the technical review has highlighted, there has been a lot of research into factors affecting soil N supply but much less known about S – especially in cropping soils. However, what is known about both nutrients typically reflects the farming systems, age of cropping/background soil organic matter status and prevailing soil types and seasonal conditions under which the research was undertaken. While much of this information has been integrated into various Decision Support Systems and rules of thumb used by industry to derive a fertilizer recommendation, there is seen to be real uncertainty around the accuracy of these predictions for modern cropping systems. This uncertainty exists in both advisors who are well trained and familiar with the research on which tools were developed, as well as those newer to the industry who have not lived through the era of N workshops and training packages, and are using a DSS ‘black box’ without a thorough understanding of the embedded assumptions and caveats. These concerns are matched by those researchers conducting this review, as well as others in the broader research community.

Much of this uncertainty is derived from the changes that have happened to soils (declining soil organic matter) and farming systems (now characterised by zero tillage, a low legume frequency and a move towards more intensive cropping, rather than mixed cropping/grazing) over the last 20 years. The industry now sees smaller relative contributions of both N and S derived from soil organic pools compared to that from synthetic fertilizer inputs on a crop by crop basis, with the loss of nutrient buffering from that shrinking organic pool increasing the pressure on a ‘correct’ fertilizer decision. Given the uncertainty in seasonal forecasting, and hence likely nutrient demand, it is not surprising that examples of instances where the recommendations were found to be inadequate are increasing.

In contrast to factors affecting supply, the review has also shown there is a lot less known about the various loss processes that can affect plant available N and S reserves, although there is a general recognition (from limited data and advisor/industry experience) that these losses can be substantial in response to episodic events. Understanding the characteristics of events that generate these losses and the soil properties which amplify or minimize the risks require further assessment. Similarly, putting those losses into context with other mineralization/immobilization processes and developing management strategies to either reduce the risk of losses or respond retrospectively to a loss event are areas that are currently quite poorly developed.

In response to the increasing reliance on fertilizer N and S sources, and hence exposure to financial and productivity risk, the dynamics of N and S fertilizers added to soils, subsequent nutrient recovery by the target crop and the quantum of any off site losses have therefore assumed a far greater importance in achieving water-limited yield potentials than in previous eras. As with soil nutrient supply processes, the assumptions and rules of thumb developed to account for fertilizer recovery and use efficiency are increasingly being questioned, and while not a focus for this review, the interactions between fertilizer management strategies, soil nutrient dynamics, crop recovery and off site losses require on going RD&E investment.

The balance between investments in N and S will be heavily skewed in favour of N, given the impact that it has on productivity and the importance it plays in both the costs of production and the profitability of grains cropping systems. However it is very obvious that the level of understanding around S in grains cropping systems is quite poor, despite the increasing incidence of (albeit ephemeral) sulfur deficiency and the more frequent inclusion of S in fertilizer programs. There is a clear need for a level of basic investment to determine some of the fundamental processes influencing S availability in soils (especially the balance between mineralization and immobilization) and the availability of applied S fertilizers for crop uptake. This is most relevant for the finer textured soils in eastern Australia, where S dynamics have been poorly characterised and S-responsive field sites are difficult to identify.

There would also seem to be a clear need for investment across the R, D and E spectrum, particularly in the case of N. The R and D investment should be focussed on both definitive research around the nature and extent of N (and S) losses from both soil and fertilizer sources, and more applied research to test the validity and robustness of current N and S mineralization assumptions in more intensive, cereal-dominated farming systems under reduced or zero tillage. The interaction between fertilizer application strategies, nutrient losses and crop recovery should also be investigated at core locations representative of climate, soil type and productivity zones of consequence across the industry.

There should be a concerted effort to integrate these R&D findings, in addition to existing outcomes from recent initiatives like NANORP, into both existing DSS and also into simple ‘rules of thumb’ (perhaps as mobile apps) that are able to provide real time seasonal updates at relevant local scales. The objection to developing ever more detailed, process-driven tools for use by time-poor advisors was widespread, but building on existing, quite complex DSS used by commercial providers and improving the ways of delivering that information in real time offers the greatest opportunities.

There is also a rapidly emerging need to train the advisor and reseller community in the basics of N (and S) management and fertilizer decision making processes. This need has arisen due to the significant generational turnover in both the reseller and advisor community, combined with the general absence of succession planning and on the job mentors for younger staff. The experienced older advisors who went through the extensive training programs in the 90’s are generally comfortable with the approaches used and the pitfalls and assumptions underpinning the tools and rules of thumb being used. However there are many new advisors who have not undergone that training and who are working on the basis of a poorly understood set of assumptions that may or may not be still relevant. The rapidly changing farming systems and fertilizer application strategies have added to this need.

**Table 8.** Investment priorities to improve efficiency of use of N and S in viable and sustainable grains production systems in Australia

|  |  |  |  |
| --- | --- | --- | --- |
|  | **North** | **South** | **West** |
| **N supply** | * **Investigate the ability of popular decision support models to predict soil N mineralisation rates and assess the value to growers of improved estimates**
* **Explore potential for using contemporary SOM fractionation to better predict mineralization rates in response to soil type, climate and management**
* **Develop extension material/training courses to upskill advisors on current DSS and the assumptions inherent in them, as well as updating those tools for modern farming systems**
 | * **Investigate the ability of popular decision support models to predict soil N mineralisation rates and assess the value to growers of improved estimates**
* **Explore potential for using contemporary SOM fractionation to better predict mineralization rates in response to soil type, climate and management**
* **Explore the impact of changing climate (decreasing in crop and increasing fallow rainfall) and cropping systems (less legume pastures ; greater stubble retention) on balance between fallow and in-crop mineralization, and the implications for fertilizer application strategies**
* **Develop extension material/training courses to upskill advisors on current DSS and the assumptions inherent in them, as well as updating those tools for modern farming systems**
 | * **Investigate the ability of popular decision support models to predict soil N mineralisation rates and assess the value to growers of improved estimates**
* **Explore potential for using contemporary SOM fractionation to better predict mineralization rates in response to soil type, climate and management**
* **Develop extension material/training courses to upskill advisors on current DSS and the assumptions inherent in them, as well as updating those tools for modern farming systems**
 |
| **N losses** | * **Strategic research effort to confirm applicability of a recently developed model to predict soil NH3 losses, including risk events and the extent of N losses. Focus on fallow/early season, and management strategies to reduce risks.**
* **Targeted research effort to determine the extent and risk of N2 losses.**
* **Develop simple tools or rules of thumb that allow industry to estimate potential N losses in response to seasonal conditions.**
 | * **Strategic research effort to confirm applicability of a recently developed model to predict soil NH3 losses, including risk events and the extent of N losses. Focus on fallow/early season, and management strategies to reduce risks.**
* **Targeted research effort to determine the extent and risk of losses through leaching and as N2.**
* **Develop simple tools or rules of thumb that allow industry to estimate potential N losses in response to seasonal conditions.**
 | * **Strategic research effort to confirm applicability of a recently developed model to predict soil NH3 losses, including risk events and the extent of N losses. Focus on fallow/early season, and management strategies to reduce risks.**
* **Develop simple tools or rules of thumb that allow industry to estimate potential N losses in response to seasonal conditions.**
 |
| **S supply** | * **Develop better guidelines for defining an S-deficient site**
* **Better understand the fate of S fertilizers applied in banded as well as broadcast applications**
* **Develop simple models to integrate understanding of S cycling and release – preferably linked to SOC fractions/N mineralization**
 | * **Develop better guidelines for defining an S-deficient site**
* **Better understand the fate of S fertilizers applied in banded as well as broadcast applications**
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 | * **Develop better guidelines for defining an S-deficient site**
* **Better understand the fate of S fertilizers applied in banded as well as broadcast applications**
* **Develop simple models to integrate understanding of S cycling and release – preferably linked to SOC fractions/N mineralization**
 |
| **S losses** | * **Collect knowledge to enable development of simple models to predict S leaching rates and implications for crop recovery**
 | * **Collect knowledge to enable development of simple models to predict S leaching rates and implications for crop recovery**
 | * **Collect knowledge to enable development of simple models to predict S leaching rates and implications for crop recovery**
 |
| **N and S management in cropping systems**  | * **Conduct integrated studies that unequivocally quantify the fate of applied fertilizers for key climate and soil combinations. This will include residual value of unused nutrient in subsequent crop seasons.**
* **Investigate the role of soil organic matter depletion in the apparent contradiction between N balance assessments in long-term trials and the 15N results suggesting consistent large losses of applied N fertilizer.**
* **Quantify the trade-offs and risks (productivity as well as use efficiency) of fallow, at planting and in crop fertilizer applications to provide industry with better nutrient management guidelines.**
 | * **Conduct integrated studies that unequivocally quantify the fate of applied fertilizers for key climate and soil combinations. This will include residual value of unused nutrient in subsequent crop seasons.**
* **Investigate the role of soil organic matter depletion in the apparent contradiction between N balance assessments in long-term trials and the 15N results suggesting consistent large losses of applied N fertilizer (and soil N).**
* **Quantify the trade-offs and risks (productivity as well as use efficiency) of at planting and in crop fertilizer applications to provide industry with better nutrient management guidelines.**
 | * **Conduct integrated studies that unequivocally quantify the fate of applied fertilizers for key climate and soil combinations. This will include residual value of unused nutrient in subsequent crop seasons.**
* **Quantify the trade-offs and risks (productivity as well as use efficiency) of at planting and in crop fertilizer applications to provide industry with better nutrient management guidelines.**
 |

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1. Appendix 1: Consultant and grower survey findings – Western region

In the Western Region, interviews with consultants (six) were conducted by Wayne Pluske (EQUII), while Grower Groups facilitated surveys with growers. The Liebe Group conducted a ‘Keepdad Interactive’ survey with their members, with seven questions provided by this project (mean of 94 respondents per question). The Mingenew-Irwin Group included two of the seven questions provided by this project in a paper-based survey (mean number of 32 respondents per question).

The growers surveyed mainly sought nitrogen fertilizer advice from private consultants (52% of respondents). The second highest ranking main source of advice was a fertilizer company representative (25%). While 12% responded that they didn’t seek advice and made their own decisions, 7% used a research organisation as their main source of advice on nitrogen fertilizer and 4% used other sources for their advice.

The following section includes extracts from a report (Pluske, 2015) prepared following the consultant interviews, as well as findings from the grower surveys.

* 1. Broad approach to and importance of accurate N fertilizer recommendations

Most growers seek post-sowing N fertilizer advice (Appendix 3). For example, 41% of surveyed growers seek post-sowing N fertilizer advice and 38% of respondents sought advice on sowing and post-sowing nitrogen fertilizer rates equally. By contrast, 7% sought advice on sowing nitrogen fertilizer rates only, and 14% of growers did not seek advice on N fertilizer use.

In terms of factors affecting N fertilizer recommendations, all consultants reported these varied depending on a client’s unique combination of financial, managerial, logistical and aspirational circumstances. Nitrogen fertilizer recommendations are the best compromise between what is agronomically sound and what the client is willing and able to implement, with the latter overriding even the best agronomy.

The consultants’ recommendations are “recipes” for clients to follow and are aimed at achieving acceptable returns at low risk with minimal management hassles. The consultants tend to only make recommendations they know will be implemented. This is why they put such a high value on their knowledge and understanding of each client and why they recommend N within the other agronomic and non-agronomic constraints, unless they can convince the client their recommendations are high return, low risk and easy to implement.

Recommendations that are knowingly likely to result in suboptimal use of N fertilizer could be seen as a waste of good science and agronomy and a contributing factor to inefficient N use by the industry. However the consultants argue that their clients ultimately decide how they apply N fertilizer and their decisions will always be a compromise. By recommending the best, compromised N fertilizer strategy that each client can implement, it could be argued consultants are helping achieve better N fertilizer efficiency than would otherwise occur.

Because there are so many factors and risks to consider, the consultants realise they cannot recommend optimal N for every situation. So they tend to suffice rather than optimise N fertilizer. They are satisfied if most of their recommendations fall on the flat part of the response curve (85 – 95% relative yield) because it means large amounts of profit will not be lost from over or under fertilising. It also seems to give them confidence that profits are buffered against seasonal risks.

While they may not sound significant, many non-agronomic and intangible factors have a large impact on N recommendations. These factors include, but are not limited, to (in no particular order):

• Keeping it simple and easy. Over complicating N applications creates logistical, operational and management hassles

• Machinery capabilities

• Minimising the number of different N rates and fertilizer products to be used

• Preferences for fertilizer product types e.g. liquid, granular, straight, compound, blend

• Labour; quality and when it is employed

• Fertilizer transport and storage

• Ability to cover enough hectares at the right time

• Risk of getting bogged while applying N

• Attitude to risk, especially seasonal risk

• Current and past experiences

• Financial position

• Future goals

• History; many clients are reluctant to change what they have always done- if it’s worked in the past, why change it?

• Non-farming investments and interests

The consultants are aware that against a backdrop of so many other factors affecting N fertilizer use and business profitability, their N fertilizer recommendations are singularly unlikely to change the fortunes of a client, except for in-season N recommendations where they can see a more direct link between N fertilizer and profits. Most fixed and other variable costs have already been expended before in-season N fertilizer is applied so it can appear that all returns from that point forward are due to the one variable cost of N fertilizer. Good use of N can appear to be the cream on the profit cake or, on the flipside, poor N use can severely bite into profits.

Interestingly, N fertilizer top-up rate and timing was ranked moderately important (65%) and most important (35%) compared to other in-season crop management by the growers surveys. No respondents ranked nitrogen top-up as being not important.

The consultants interviewed were keen to improve their N fertilizer recommendations particularly if it is quick and simple for them to do (or if someone else does it for them) and has high probability of being implemented by clients and increasing profits.

* 1. Types and usefulness of information and tools

All the consultants see soil tests each year, some see more than others. The three consultants who use fertilise decision support models tend to use a client’s soil tests as the starting point for that client’s recommendations. It was hard to know if soil tests are more important as the catalyst to start the decision making process or for improving decisions because, while all the consultants noted test results, they also noted that the results do not have a huge impact on their recommendations.

Soil tests for N are not valued as much for N fertilizer recommendations as they are for other nutrient and lime recommendations. The consultants recognised mineral N concentrations can vary markedly over time and space, and that soil test results are simply a snapshot of the concentration at one point in time. For this reason they are cautious about soil mineral N results, only considering them when they are high enough, and likely to stay high enough, for N fertilizer rates to be safely reduced. The consultants indicated soil organic carbon tests tend to confirm what they already know; that some soil types, rotations and regions have higher organic carbon contents than others. Organic carbon levels are mainly used to gauge the size of what the consultants refer to as the “N buffer”, especially when recommending in-season N. Larger N buffers appear to increase the confidence in N recommendations rather than altering them, possibly because of the safety net a larger buffer provides against lost profit from under fertilising with N in a better than expected season.

DAFWA’s various N decision tools, Yield Prophet and the fertilizer company’s decision tool FCT (for three of the consultants) are the most widely used decision tools. How much and how they are used varies between the consultants. With the possible exception of the FCT for interpreting soil tests, rarely is a tool used to help generate recommendations for an individual situation because of the time and complexity involved.

Decision tools are mainly used by the consultants to:

• Recalibrate themselves and their rules of thumb

• Provide a big picture view of relative N requirements for common situations e.g. to see how legume in rotation changes N requirements

• Provide explanations for what they see, including outliers to their rules of thumb

• Understand the main directional influences on N rate requirements (not necessarily absolute rates)

• Explain, justify and/or educate clients on the main concepts and drivers of N requirements and their recommendations.

Information and tools are combined with the consultants’ own generate rules of thumb were considered sufficient for N fertilizer recommendations. The consultants interviewed believed these rules of thumb are used to apply the principles of N requirements much wider and quicker than would occur if the information and tools were used in every situation.

The consultants have confidence in the information and tools they commonly use because they know there is good science behind them. In most cases they also have some “buy in” to the tools because they have helped or know the researchers and modellers involved in the development of the decision tool.

The consultants clearly know and understand the input parameters that drive the tools they and others use. While they are aware of the major concepts that influence tool outputs, most want more information on the science behind the tools and how outputs are generated. Such information is important for building confidence in the rules of thumb they derive from a tool. However, their confidence in information and tools (as well as their own rules of thumb) has been dented somewhat by the 2013 and 2014 seasons because previous, apparently robust relationships between N supply and harvest results (yield and protein) did not hold up. The consultants would have liked some explanations from researchers why this was the case in order to recalibrate their thinking to be better prepared in the future.

One consultant interviewed, who is familiar with much information and many fertilizer decision tools, has no interest in using them, preferring that someone else uses them to deliver him a simple output that he in turn can deliver to his clients.

All the consultants are sceptical, if not dismissive, of recommendations generated by advisers connected to fertilizer sales, even when the recommendations are purportedly based on what the consultants themselves regard as very credible decision tools. At best they use the recommendations to look at relativities rather than the actual rates e.g. how N rate may vary with yield.

They are unconvinced of agribusiness recommendations because they think they have been generated by advisers who lack agronomic, farming systems and farm business knowledge, are inexperienced users of the tools, are unaware of the client’s situation and/or are biased towards sale of product. In many cases the consultants believe the recommendations are so expensive, impractical or different to previous practices that the client will not implement them anyway.

* 1. Accounting for N mineralisation, losses and uptake

Gut feel and rules of thumb are the main things used to account for soil N mineralisation. Some of the consultants showed some interest in better measuring or estimating mineralisation if it was quick and easy. Otherwise they were comfortable with their current approach because they think more accurate estimates of soil N mineralisation will not markedly improve their recommendations given all the other agronomic and non-agronomic factors that influence their recommendations. They also use gut feel and rules of thumb to “gamble” on the season (and therefore on likely yield and N demand), and to consider N losses and efficiency of uptake so they see little point going to the ‘nth degree’ on soil N mineralisation.

Pre-season mineralisation is measured in soil tests if collected at an ideal time (after all summer/autumn rain and close to seeding) and is estimated in most cases. Pre-season mineralisation is only of interest if it is high and starter N (which can also be total N where all N is applied up front) can be reduced from the usual rate.

During the season most of the consultants base their top up recommendations more on the moving target of N demand (likely yield) than on N supply from mineralisation and other processes. This is because:

• They think yield is the main driver of N requirements.

• In-season N mineralisation has already been estimated before seeding, mainly on the basis of organic carbon and paddock rotation.

• They do not have any quantification of soil N mineralisation that is occurring, and/or

• They don’t know how to modify their recommendations when they do have quantification of soil N mineralisation.

The consultants think they know what happened with mineralisation and immobilisation in the contrasting seasons of 2013 and 2014 and why these seasons failed to conform to established information and decision tools. But they don’t know if their theories are correct because they have not seen any data on mineralisation and immobilisation in those two seasons, and if they did they may struggle to make sense of it without data from other seasons to compare it to.

There is a dearth of knowledge on soil N mineralisation processes and rates amongst the consultants.

Perhaps if there was more information, consultants would consider mineralisation more in their recommendations than they currently do. There is an opportunity for more interaction between consultants and researchers during and after the season to improve knowledge. For instance the consultants are currently unsure whether they should be suggesting in-season soil testing to measure soil mineral N.

Most of the consultants do not consider volatilisation losses when making N recommendations for two reasons. Firstly they believe losses do not occur or, if there are losses, they are so small they are not worth considering. Secondly disrupting or delaying N applications just to minimise any volatilisation losses is likely to cost more (in management hassles and because N is applied too late) than it saves. Timing of N applications (e.g. before rainfall) are done for reasons other than to minimise volatilisation losses. Any reduction in volatilisation that may occur is considered an added bonus.

Leaching losses are considered more important than volatilisation losses, particularly in higher rainfall areas and on lighter soil types. The consultants have little direct proof of N leaching, let alone being able to quantify any losses. Leaching is assumed to have occurred when:

• There has been “substantial” rain

• The soil is light enough for leaching to occur

• Crops look N deficient.

Similarly denitrification losses are assumed from rainfall inundation and crop appearance rather than measured.

Once the risk of leaching or denitrification is assumed to have passed, the common response amongst the consultants is to bring forward the next planned N fertilizer application and to apply extra N. Without much idea of the size of any losses, recommendations for just how much extra N is required are guesstimates.

The efficiency with which plants use soil and fertilizer N is crudely taken into account by some of the consultants but it is doubtful it has much impact on N fertilizer recommendations. Good growing conditions of adequate moisture and temperatures are thought to improve uptake while too much or too little moisture reduces uptake efficiency. The other consultants are oblivious to any affect uptake efficiency may have on N requirements or they assume it is relatively constant across all situations.

* 1. Additional information and tools to improve N recommendations

Growers ranked the extension of knowledge on nitrogen application to consultants, growers, as hard- copy guides or electronic products as an approach to improve their decisions relatively evenly. Delivery to consultants ranked highest (29%), followed by hard copy guides (24%) and electronic products (24%) delivered to growers and consultants and delivery to growers at field days (22%).

Most of the consultants would like more information to help them with their N recommendations.

The exceptions were where they want someone else to combine all the information and feed it to them in an easy-to-understand manner, or where they think additional information will complicate and slow their processes for little improvement.

The consultants were especially keen to better understand what influences soil N immobilisation and mineralisation in the previous season, pre-seeding and in-season. They feel that factors like N carryover, stubble load, stubble type and stubble management affect N requirements, largely by affecting N transformations, but they have not seen sufficient data to support their hunches. Again, the 2013 and 2014 seasons worried some of them moving forward because those seasons shattered their previous thinking and rules of thumb.

Rough assumptions on the amount of soil N mineralisable are made before the season, but are not tested during the season nor reviewed after the season. If there was better understanding of what the assumptions were based on and more quantification of mineralisation each season, it is likely consultants’ knowledge of and interest in soil N mineralisation would increase markedly.

The pipedream for N information is real-time, spatial quantification of N transformations and losses.

As unlikely as they know this is, in even mentioning it the consultants are asking for more quantification and more timely delivery of it at any scale (e.g. shire level) because currently they are devoid of such data.

Some consultants are keen to access research information directly, rather than through various media or incorporated into decisions tools. They want earlier access to results and to understand where and why results occurred so they can determine if it is worth trying to replicate research findings with clients.

Better explanations (e.g. at workshops) of existing information and of how decision tools work would be beneficial. The consultants believe there is a lot of underutilised information and expertise that their recommendations could benefit from. The best examples of this are the processes, influences and quantification of N losses through volatilisation, leaching and denitrification. In the case of volatilisation, many of the consultants need to be convinced, by data and facts, if volatilisation is worth considering. More formal and informal discussions with developers of decision tools are the preferred way to increase confidence in the tools.

The biggest gap in the consultants’ N recommendations is poor predictions of yields, especially for their in-season recommendations which are easier to assess and are seen as having a marked effect on profits. Gambling on how the season will unfold is something consultants and their clients would like to minimise. Currently N recommendations and investments vary widely depending on essentially gut feel.

Interestingly the growers surveyed ranked a better estimate of yield potential highest (53%) for improving confidence in decisions about N fertilizer. A better estimate of N supply from the soil was ranked second highest (21%). While 10% of growers responded that they were confident they were making the right decision and did not need a better estimate of yield potential, soil N supply or losses. A better estimate of nitrogen supply from leaching, volatilisation and nitrogen supply from residues was ranked highest by 7, 4 and 1% of respondents respectively.

Until the widely fluctuating demand side of the ‘N equation’ can be narrowed, consultants will be slow to invest more of their time and effort into fine-tuning other aspects of soil N, like mineralisation and losses. Their pipedream bridge for this gap is a better yield predictor, perhaps one based on soil moisture measurements and/or historical relationships between rainfall and yields which are site and management specific. Ideally this would be linked to a decision tool that calculates optimal N rates.

Again for in-season recommendations, the consultants would like a more dynamic decision tool than they currently have, one that is updated frequently (e.g. weekly) with seasonal conditions so N rates can better target likely yields. Presently most consultants are using assumptions on what occurs during the season that are made at one point in time well before the season commences.

1. Appendix 2: Consultant and grower survey findings – Southern region

**Survey of decisions used by industry advisers in Southern Region (Victoria and South Australia) for determining N fertilizer management recommendations**

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* 1. Introduction

There is a widespread concern that despite the vast range of different decision tools available to growers and advisers for guiding their decisions about N management; these decisions however often miss the mark. Potential contributing factors to this uncertainty include changing rainfall patterns, declining soil organic matter, use of no tillage and a lower legume frequency in farming systems. This project aims to assist Australian grain growers and their advisers to reduce the uncertainty and financial risk associated with N management.

To achieve this aim, a series of studies are being undertaken throughout all of the Australian Grains Regions to better understand current practices, the assumptions underpinning these practices and general perceptions of grain industry advisers when making decisions about N management. This information will then be compared to that collected from a comprehensive review of the current knowledge of the relative importance of key processes underpinning assumptions about the supply of N (from both the soil mineral pool, organic matter mineralisation and fertilizer inputs) and its subsequent use by crops. This review (led by A/ Prof. Louise Barton, UWA) will use information derived from both the published and grey literature. Ultimately this process will allow an assessment of the consistency (or otherwise) of the various approaches between adviser practice and the formal technical understanding of the underlying processes. This preliminary assessment will then allow the identification of knowledge gaps and development of a research plan to overcome these gaps for the key grain growing regions across Australia.

This report presents the findings of a questionnaire survey of grains industry advisers in the Southern Region (Victoria and South Australia) and subsequent focus interviews on a selection of these respondents to further examine these responses. The survey aimed to understand the perceptions of N fertilizer management held by leading advisors and how they currently formulate their nitrogen management recommendations.

* 1. Methods

A questionnaire (see Appendix 1), based on questions developed by the national project team, was used to gauge the practices of consultants. Questions were based on multiple choice responses. The majority of questionnaires were completed during a workshop held at Longerenong College in mid - August 2015 as part of a tour of the ‘Carbon Farming’ project (led by Mark Stanley). The participants were advisers based in a wide range of grain producing regions from South Australia and Victoria though some came from southern NSW. In addition, 5 questionnaires were completed by members of a private consulting firm (which mainly services grain growers in Western Victoria). A total of 32 questionnaires were used in the analysis (several completed questionnaires were discarded as the respondents indicated that they focused on grazing or indicated that ‘they didn’t give advice on nutrition).

Nine focus interviews, representing over 25% of the questionnaire respondents, were subsequently undertaken in November 2015. The basis for selection was availability and a spread of demographics including experience, type of business, soil type and rainfall region. The survey data set contained highly knowledgeable and well informed advisors.

Phone interviews were conducted for a period of 45 to 60 minutes. Open questions were asked to explore the answers provided in the survey and provide context. Key areas of interest identified by the investigating officer were the response to N losses, the use of soil tests and how N mineralisation was accounted for. The level of understanding of mechanisms and assumptions behind rules of thumb was also discussed at length.

To build on the discussion, interviewees were provided with key themes that were emerging from the interviews conducted previously

List of those interviewed:

|  |  |  |
| --- | --- | --- |
| **Name and years consulting** | **Company** | **Region** |
| Ian Delmenico (> 20) | Croprite | Low rainfall and irrigation, Vic Mallee |
| Simon Severin (> 20) | Agritech Rural | Low and medium rainfall, Vic Wimmera and Mallee |
| Jeff Brauhn (10-15) | Agrilink | Low, medium and high rainfall, SA various |
| John Stuchbery (> 20) | JSA Independent | Low, medium and high rainfall, Western and central Vic. |
| Trevor Howie (> 20) | Agritech rural | Medium rainfall, Vic Wimmera |
| Lou Flohr (<10) | Agrilink | Low-medium rainfall, SA and Vic Mallee |
| Peter Cousins (> 20) | Peter Cousins Consulting | Medium rainfall, SA mid north and EP |
| Josh Hollit (<10) | Hollit Consulting | Low to medium rainfall, upper and central EP |
| Peter Hooper (10-15) | Hooper Consulting | Medium Rainfall Mid North SA |

* 1. Discussion and Conclusions

The sample population used for the questionnaire/survey and subsequent focus group interviewees predominantly contained highly knowledgeable and well informed advisors. As such, we consider that their level of scientific understanding to be far greater than the ‘industry average’.

Farming systems have evolved markedly since the N management ‘rules of thumb’ were developed in the 1990s based on research conducted in the 1980s. There was a perception that ‘Excellent research has been conducted subsequently with localised extension efforts’. Examples given include ‘John Angus, especially with Incitec Pivot’ mainly on the NSW South West Slopes, Pivot/MEY Check, Gupta and Roget in South Australia, Recent GRDC Initiatives including Soil Biology (e.g. changes in microbial populations and relationship to mineralisation by Lori Phillips), Gupta’s recent findings, Deb Turners Ammonia Volatilisation research. However, the focus group participants delivered a strong message requesting the reframing of N management ‘rules of thumb’ and guidelines in the modern farming system context. The focus group was requesting effective science communication and extension.

There was support for simple and practical extension guidelines to remind advisors of the principles behind existing ‘rules of thumb’ and to update these for aspects of N management to account for significant changes that have since occurred to farming system and climatic patterns- specifically:

* Mineralisation: estimates of quantity and availability based on soil type, temperature, rainfall pattern, season length and organic carbon
* Clarification of what situations and scale of different forms of N loss may occur, particularly denitrification and volatilisation.
* Estimates of crop uptake efficiencies based on time, method of N application and seasonal conditions. The ‘feeling’ was that the knowledge exists e.g. Armstrong/Harris/Wallace recent NANORP work, in the most part, but needs packaging up in a consumer friendly manner.
* The view was that much of the information needed for ‘N management guidelines’ exists from current and previous research. An example was given of the need to ‘extrapolate’ data collected from a limited number of seasons/sites to a much broader range of scenarios and more practical contextualising. This is best summarised by the quote *‘I really value the science but that’s only one factor I take into consideration. At the end of the day I need to make a decision’.*

There was a clear desire for guidelines to be simple with a focus on problem solving. Advisors emphasised that the science is important but is only part of the information an advisor weighs up. The challenge for research bodies is to communicate the key science findings in a manner that supports the other decision making tools advisors use, which are primarily experience and intuition. Guidelines must recognise that on farm logistics and scale require estimations not precision, hence the need for simple ‘rules of thumb’.

While seasonal conditions were reported as most important consideration, few advisors appear to be using all the available resources needed to account for potential seasonal outcomes using the information available (e.g. climate models). There is room to increase industry knowledge of how to interpret seasonal outlook information to improve estimation of potential yield and N demand.

The queries raised could all be explained by understanding the context behind the respondents’ answers to the questionnaire. A good example of this was the high proportion of respondents who indicated that leaching was a major source of N loss but the focus interviewees put this in context when they indicated that this was the case for deep sands, not clay.

In summary, there was a perception that ‘a lot of the research has been done’ but needs to be adapted and validated to current farming systems and management practices. This information must be then packaged into a form that is of use to advisers e.g. as ‘rules of thumb’. The question remains however is how well do the advisers perceptions about the current of knowledge generated by researchers (past and present) match that of what has been published (in both the peer-reviewed and grey literature).

1. Appendix 3: Consultant and grower survey findings – New South Wales

**A survey of decisions used by industry advisers in New South Wales for determining N fertilizer management recommendations**

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* 1. Introduction

There is concern that grower and adviser decisions about nitrogen (N) management in field crops often miss the mark, despite the range of decision tools available to inform and assist. Factors that potentially contribute to sub-optimal decisions on N management include changing rainfall patterns, declining soil organic matter, use of no tillage and a lower legume frequency in farming systems. This project aims to improve our understanding of how advisers make decisions relating to grain crop N nutrition, and thus to better target assistance to Australian grain growers and their advisers to reduce the uncertainty and financial risk associated with N management.

To achieve this aim, a series of studies are being undertaken across the Australian grains regions to better understand current practices, the assumptions underpinning these practices and general perceptions of grain industry advisers when providing advice on N management. This information will then be compared to that collected from a comprehensive review of the current knowledge of the relative importance of key processes underpinning assumptions about the supply of N (from both the soil mineral pool, organic matter mineralisation and fertilizer inputs) and its subsequent use by crops. The review will use information derived from both the published and grey literature. Ultimately this process will allow an assessment of the consistency (or otherwise) of the various approaches between adviser practice and the formal technical understanding of the underlying processes. This preliminary assessment will then allow the identification of knowledge gaps and development of a research plan to overcome these gaps for the key grain growing regions across Australia.

This report presents the findings of an on-line survey of grains industry advisers in New South Wales and subsequent in-depth interviews with a NSW-wide selection of selected senior respondents to further examine their responses. The survey aimed to understand the knowledge, perceptions and practices used in coming up with N fertilizer recommendations by advisers for clients involved in grain production in NSW.

* 1. Methods

A questionnaire (see Appendix 1), based on questions developed by the national project team, was used to gauge the practices of grains consultants. Questions were based on multiple choice responses. Hardcopy surveys and email requests were sent out to advisers throughout New South Wales from late September to November 2015 using Survey Monkey. In total, 132 advisers responded to this survey by the end of November.

In addition to the Survey Monkey responses, phone interviews were conducted for a period of 45 to 70 minutes with 11 senior advisers grouped by three regions within the state – Northern NSW, Central NSW and Southern NSW. In the interview, the questions used in the survey were used again, with the responses explored further using additional open questions and prompts. Not all supplementary questions were put to each interviewee, as some answers automatically covered some of the extra questions.

This report is sectioned by the Survey Monkey questions, with graphs and tables detailing the responses from the whole survey group across the state. Each section then has a summary blending the results from the on-line survey with more detailed information summarised from the in-depth interviews.

The appendices list first the Survey Monkey questions along with the multiple choice answers posed. A second appendix lists the prompt questions linked to each Survey Monkey question used with the senior adviser interviews. A third appendix provides detailed notes from the senior adviser interviews. For privacy reasons the names and details of the senior advisers interviewed are not included, but instead a code is used for each interviewee that indicates the regional location of their client base in NSW.

The project team gratefully acknowledges the significant input from Susan Orgill in gathering data from southern NSW, and we are also very thankful for support from Fiona Pearson, Helen Squires, Erica McKay, and Georgia Rose in compiling the notes and producing the report document.

* 1. Executive Summary
* From September to November 2015, 132 grains advisers responded to an on-line survey on decision-making for nitrogen (N) nutrition in NSW field crops. Concurrent with this, in-depth interviews of approximately one hour duration were conducted with 11 senior advisers from across the northern, central and southern NSW grains regions, to further explore agronomists understanding, processes and tools used to make N fertilizer recommendations for their clients.
* Soil moisture at sowing, seasonal conditions, rotation, soil testing, financial risk, in-season crop assessment and previous paddock history were all listed as important factors used by advisers in preparing their N recommendations, but soil moisture at sowing (or at the time of N decision making) was identified as the single most important determinant of N fertilizer requirement by senior agronomists across NSW.
* Decision support tools were used in decision making by advisers interviewed, but usually not for every decision. Several advisers cited their use of decision support tools to help them understand issues and challenge thinking on some jobs, with the learning from this experience then applied elsewhere. The Back Paddock system appeared to be in widespread use by senior advisers in northern NSW, with the N Balance model also used. The Angus N model /spreadsheet was similarly well respected and used by senior advisers in southern NSW. Yield Prophet was used by several senior advisers primarily for assisting development of more accurate yield estimates based on soil water present at the time of decision making. Good soil characterisation was core to this system’s accuracy.
* Senior advisers gained their knowledge from leading experts (GRDC Updates, personal contact and formal training events) and from experience with their own clients. The need for adviser access to expert advice, plus the availability of detailed and well delivered training targeted to the needs of advisers, is ongoing.
* Senior advisers report that a client’s attitude to risk influences their N recommendation, with more conservative growers aiming for a lower input, lower risk system. In some instances the amount of N applied is limited by available funds rather than a cost/benefit estimate. However, in the higher yielding and most reliable cropping zones of the state, advisers recommend and growers generally apply higher rates of N fertilizer to maximize long term profit.
* N contribution from legumes is considerable in southern NSW where long pasture phases dominated by lucerne are often an integral part of the farming system, whereas central west NSW farmers are moving away from pasture ley mixed farming to continuous cropping. Advisers in the center and north of the state highlighted the low contribution of N from crop and pasture legumes in these areas.
* Most advisers believe they have a very good understanding of the mechanisms behind their approach to N recommendations and issues such as mineralization rates, yield, N and protein budgeting. As a result, most felt their recommendations were generally good with the occasional failure when seasonal conditions were contrary to predictions, such as in 2015.
* Most advisers felt that their N fertilizer recommendation needed to be within 10-15% of yield potential, and that their prediction of yield potential needed to be between 10-25% of actual yield. Greater accuracy is not possible due to the many variables affecting yield and the inherent variability in parameters measured or estimated through rules of thumb.
* Soil tests were considered moderately to very important with testing often used as a tool to help determine recommendations. Senior advisers said it was uneconomic to test as rigorously as science required and moreover a significant number of growers had confidence issues with soil testing, with high perceived variability in soil nitrate results reported in the lead up to sowing. Northern region advisers mentioned that they stratified soil tests by depth. Soil testing is carried out much earlier pre-season in the north, where N fertilizer is likely to be pre-applied. In the south testing is conducted nearer to sowing as N is mostly applied post-sowing.
* Most advisers (80%) always account for pre-sowing mineralization in their recommendations, and 70% always account for in-crop mineralization as well. The estimates were usually based on rules of thumb coming out of years of research and practical on-farm experience.
* Most advisers (86%) account for how efficiently plants absorb N in their recommendations, with interviewed advisers commonly using 50% efficiency from N fertilizer to grain N.
* N losses (leaching or gaseous) were accounted for by 40% of advisers. The understanding of gaseous N losses was better in northern NSW, where research over the past few years had been well publicized, than in southern NSW where no recent field work had been done.
* In the online survey, denitrification as nitrogen gas (N2) was considered the major source of N loss by 40% of advisers, with 31% choosing leaching and 23% choosing ammonia volatilisation. Greater emphasis than this was placed on denitrification as the key loss pathway in interviews with senior advisers. However, as denitrification losses were generally associated with significant waterlogging events that were difficult to predict and sporadic in most regions, losses due to these pathways were generally not considered in N budgeting.
	1. Recommendations
* Senior advisers highlighted the importance of quality training in N decision-making, understanding the background soil and plant science involved, and soil test interpretation for the next generation of agronomists, with training courses including representation from highly experienced local agronomists.
* The understanding of gaseous N losses requires further research, development and extension to the grains industry. Recent field research in the north was limited in scope and produced challenging outcomes that can potentially lead to large practice changes in when and how N fertilizer is applied. Further research and development work is warranted to answer more of the practical questions growers and advisers are asking in regards to losses associated with various alternative practices.
* The northern results on N loss pathways are less relevant to advisers in the central and southern regions where N application timing, soil type and climatic differences are generally quite different from the dominant medium-heavy clays of the north. New N loss research is recommended for the lighter textured soils in regards to the potential for N volatilization losses from surface N application of various products. Economic outcomes from the various strategies being practiced are also needed. Nitrogen loss research should focus less on expensive slow-release products and more on optimizing results from urea, the cheapest N source.
* Research into better soil water measurement was seen as a priority area, especially given the importance all advisers place on knowing this when making expensive N-fertilizer decisions for a coming cropping season. Zonal management within paddocks is not possible with single site characterisations, so atypical areas of paddocks are over or under-fertilised.
* The very early application of N fertilizer ahead of a winter cropping season is well established, but what is not known is how well the subsoil N may be protected or at risk from denitrification in flooding events. Also, better knowledge on specific N use within the profile during the cropping season will help growers to know when late-applied N is likely to be inaccessible to crop use.
* Nitrogen mineralisation was highlighted by agronomists from all three regions as an area for greater understanding with regards to the differences caused by climatic conditions, especially rainfall. They also require better understanding of the N produced from both native organic matter and recent legume pasture residues.
* There are a number of good decision support tools available currently, with several advisers suggesting that combining the best points of each into one package, even one available as an app, would be highly useful, particularly one with good grower-friendly reports.
* Many farmers have low confidence in soil testing. This may be related to a range of factors from poor sampling strategies, to poor sample handling, to poor service from laboratory analysts, to insufficient sample numbers or poor interpretation of the results. It is seen as an expensive option for many, with some advisers looking for quicker and cheaper means of estimating soil mineral N.
* Variety-specific N management packages were seen by some senior advisers as key areas for continued research funding, as results from some new varieties have been quite different in terms of N uptake and protein outcomes.
1. Appendix 4: Consultant and grower survey findings – Queensland

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Summary and integration of survey responses

* 1. Introduction

An online survey tool was used to gather responses from agronomists in Central and Southern Queensland grain production areas on what are the considerations, processes and mechanisms they use when developing a nitrogen recommendation for their clients. Sixty seven invitations were sent, and twenty seven responded to complete the survey.

Most respondents (20) indicated the 550-650 mm rainfall zone was the annual rainfall their clients received, and almost half (13) also indicated they managed irrigation blocks also. Winter cereals (bread and durum wheats, barley) and summer cereals (sorghum & maize) are the main species for virtually all the responding group, while canola is also identified by a reasonable number of respondents (6). Additional target species where cotton (9), pulse crops (winter and summer 3), forage and pastures crops (5), sunflower (2).

Table 8. Crops for which fertilizer nitrogen recommendations are prepared.



* 1. Results and Discussion
		1. Decision Framework

Nitrogen budgeting (with some variation) forms the main framework for preparing recommendations, with the calculations altered with some adjustment for likely (or perceived) crop demand (yield potential) and soil supply (profile mineral nitrogen, nitrogen losses and mineralisation).

It would appear from consolidating the responses over a number of questions that advisers have a common framework in applying nitrogen budgeting, but are very flexible application in using it. Influences on the approach also include a consideration of nitrogen replacement (budgeting of sorts) and having a grain protein target.

85% of respondents indicated that profile soil testing and crop nitrogen budgeting was their main tool (Q3). Soil mineral nitrogen and water at sowing, along with crop rotation/paddock history, seasonal forecast and growing conditions to flowering were recorded as the main factors influencing the fertilizer nitrogen recommendation (Q4). Soil mineral nitrogen was rated as moderately or very important by 23 responders (Q5) reflecting a confidence in using profile soil sampling.

There could be some disconnect between modifying model parameters and actual understanding of the model assumptions. Over 66% of responders indicated by modified the default values (Q15) and accounted for the nitrogen recovery by the crop (either from soil or fertilizer, Q13), yet only 33% indicated they had a good or very good understanding of the assumptions (Q14). If the basic understanding group is included, then it would align with the number of responders that modify the default values.

Just over half (56%) felt that their yield prediction needed to be within 10 to 15% of the final yield target (Q24). The < 10% and 15-25% options each had 5 or few responders. The perceived accuracy of yield potential at the time of nitrogen application (Q25) was more generous with majority of responders (15) suggesting it needed to be between 15-25% of final yield.

* + 1. Mineralisation

Questions on mineralisation where separated into fallow (Q7-9) and in-crop (Q10-12) periods. Fallow mineralisation was considered by most (75%) with estimations from models the predominant method of inclusion (78%) followed by soil sampling (48%) (Q8).

I think it would be difficult to explicitly account for fallow mineralisation by soil sampling unless a post-previous crop sample was taken to give a start of fallow value. The soil sampling approach would therefore incorporate both residual mineral N and nitrogen mineralised to the time of sampling.

Whatever method is used to derive an estimate of fallow mineralisation, most agronomists make some adjustment to the recommendation (presumably starting soil mineral nitrogen). Ten used part of the mineralisation, and another 10 used all of it.

Inclusion of the in-crop mineralisation was split roughly into three between i) no consideration (40%), ii) some consideration (26%) and iii) yes (33%) (Q10). The responses on how it is used are more difficult to assess the intent of (Q11) as 48% of responses said it doesn’t change their recommendation. Is that because they have considered it and it doesn’t change; or they haven’t considered it and hence it’s just ignored. For most winter crops the in-crop mineralisation is not going to be a substantial inclusion to the overall crop nitrogen supply. Summer in-crop mineralisation is going to be more subject to combinations of weather and crop growth.

* + 1. Losses

Only 6 responses (24%) did not include some consideration of nitrogen loss pathways in their recommendation (Q6). The majority of most responders (74%) classify their knowledge as “reasonable understanding but could be improved” (Q16).

Of the loss pathways offered, denitrification as nitrous oxide or as nitrogen gas where the two most selected answers (Q19). A surprising number responded with ammonia volatilisation (10) and leaching (8). Perhaps the concern over volatilisation infers a large adoption of surface spreading of urea. The leaching value may be influenced by the number of irrigated fields managed.

The suggested proportion of nitrogen lost in winter is much smaller than the estimate of that in summer. Most responders for winter (55%) thought less than 10% is lost, but 25% suggested that between 20 and 40% was lost in winter (Q17). The most popular response for amount lost in summer was 10-20 % with 42% of responders selecting that (Q18). 30% suggested the loss is between 20 and 40%, whilst 23% of responders suggested more 40% of soil and fertilizer N is lost in summer.

* + 1. Recommendation Review

A review of the nitrogen recommendation is carried out by all but one agronomist, with the majority of these being conducted with the client at the end of the season (Q20). Parameters included in the review process are the key outputs (yield), inputs (applied N, mineralisation) and growing season conditions (weather and denitrification) (Q21). Recommendations are (self) rated as good (10) or very good (10) (Q22), with various methods used in the assessment mainly being grain yield (92%) followed equally by zero strips, soil testing and post-crop nitrogen budgets (≈ 50%) (Q23).

* 1. Conclusions

Responses to the survey by advisers in Queensland strongly endorse the continued deployment in developing a fertilizer recommendation of profile soil testing and crop nitrogen budgeting. This includes (mostly) a review at the end of the season evaluating the recommendation performance. While most respondents give themselves a positive mark on how well their recommendation was, it is difficult to actually quantify using a self-assessment basis.

Inherently, advisers want to be able to allow growers’ crops to respond if seasonal conditions are better than average. While nitrogen fertilizer is a significant cost, it can also become a significant constraint if limiting. This translates to advisers (probably) including more conservative estimates (in-crop mineralisation, internal nitrogen transfer efficiency and/or fertilizer crop recovery efficiency) and so increasing the crop nitrogen supply to allow an additional pool for exploitation during a good season.

In integrating the different soil biological and crop physiological processes involved with formulating a recommendation, agronomists are coming up with recommendations (plus a factor) to meet the clients’ expectation. Whilst the outcome of the integrated process is (probably) appropriate, the understanding on individual processes can be better developed in the agronomic community.

Communicating the reported amounts of denitrification for winter and summer seasons will help reduce the uncertainty in current estimates for advisers’ recommendations. Use of 15N recovery studies previously undertaken should quantify the losses for various season/crop combinations as an initial position.