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GRDC GROWNOTES™

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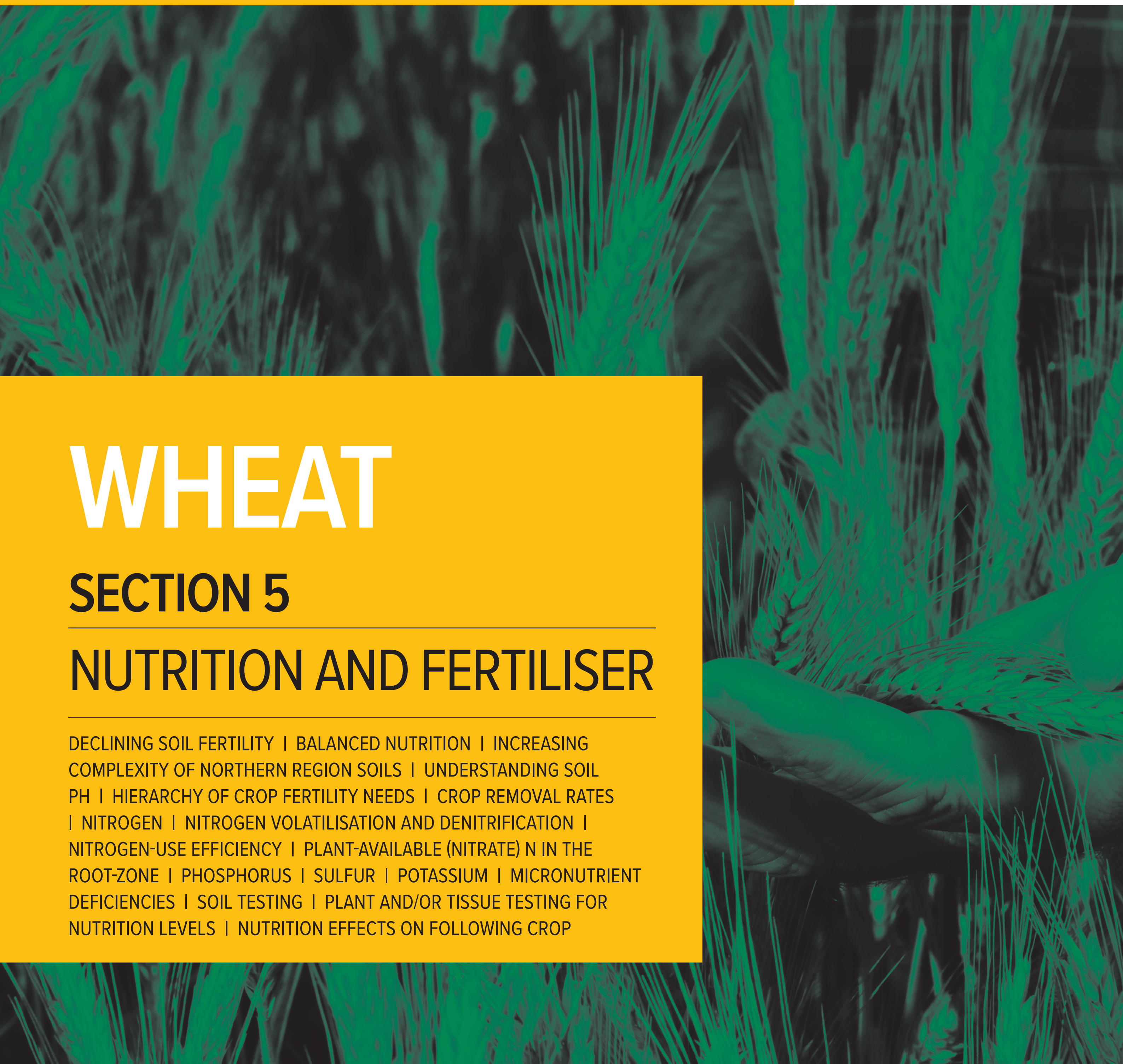

WHEAT

SECTION 5

NUTRITION AND FERTILISER

DECLINING SOIL FERTILITY | BALANCED NUTRITION | INCREASING COMPLEXITY OF NORTHERN REGION SOILS | UNDERSTANDING SOIL PH | HIERARCHY OF CROP FERTILITY NEEDS | CROP REMOVAL RATES | NITROGEN | NITROGEN VOLATILISATION AND DENITRIFICATION | NITROGEN-USE EFFICIENCY | PLANT-AVAILABLE (NITRATE) N IN THE ROOT-ZONE | PHOSPHORUS | SULFUR | POTASSIUM | MICRONUTRIENT DEFICIENCIES | SOIL TESTING | PLANT AND/OR TISSUE TESTING FOR NUTRITION LEVELS | NUTRITION EFFECTS ON FOLLOWING CROP

SECTION 5

Nutrition and fertiliser

With more frequent use of opportunity cropping, improved farming techniques, and higher yielding varieties, nutrition programs should be reviewed regularly.

Common nutrient deficiencies in the northern region´s broadacre grain areas are nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn), while sulfur (S), copper (Cu) and molybdenum (Mo) may be also be lacking in some soil types and growing areas. [1] Deficiencies of boron (B) and Cu have also been recorded in southern Queensland and central-west New South Wales (NSW). Molybdenum deficiency and manganese (Mn) toxicity can occur in more acidic soils. [2]

When fertiliser prices peaked in 2008, questions were raised about the cost-effectiveness of these inputs. New information was sought on best practice for yield and profitability. The result was the Grains Research and Development Corporation's (GRDC) More Profit from Crop Nutrition initiative. [3]

To read about progress made under the program, download: http://www.grdc.com.au/Media-Centre/Ground-Cover-Supplements/Ground-Cover-issue-97-MarApr-2012-Supplement-More-profit-from-nutrition

5.1 Declining soil fertility

The natural fertility of cropped agricultural soils is declining over time. Grain growers must continually review their management programs to ensure the long-term sustainability of high-quality grain production. Pasture leys, legume rotations and fertilisers all play an important role in maintaining the chemical, biological and physical fertility of soils.

Paddock records, including yield and protein levels, fertiliser test strips, crop monitoring, and soil and plant tissue tests all assist in the formulation of an efficient cropping program.

Although crop rotations with grain legumes and ley pastures play an important role in maintaining and improving soil fertility, fertilisers remain the major source of nutrients to replace those removed by grain production. Fertiliser programs must supply a balance of the required nutrients in amounts needed to achieve a crop's yield potential. The higher yielding the crop, the greater the amount of nutrient removed.

The yield potential of a crop will be limited by any nutrient the soil cannot adequately supply. Poor crop response to one nutrient is often linked to a deficiency in another

1 DAFF (2012) Wheat—nutrition. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

2 DAFF (2010) Nutrition management. Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

3 M Blumenthal, I Fillery (2012) More profit from crop nutrition. GRDC Ground Cover Supplement Issue 97, March–April 2012, http://www.grdc.com.au/Media-Centre/Ground-Cover-Supplements/Ground-Cover-issue-97-MarApr-2012-Supplement-More-profit-from-nutrition/More-profit-from-crop-nutrition

nutrient. Sometimes, poor crop response can also be linked to acidity, sodicity or salinity, pathogens or a lack of beneficial soil microorganisms. [4]

Figure 1: The natural fertility of cropped agricultural soils is declining over time.

5.1.1 Organic matter

Organic matter has a fundamental and necessary place in soils. It helps to ameliorate or buffer the harmful effects of plant pathogens and chemical toxicities. It enhances surface and deeper soil structure, with positive effects for infiltration and exchange of water and gases, and for keeping the soil in place, i.e. reducing erosion. It improves soil water-holding capacity and, through its high cation-exchange capacity, prevents the leaching of essential cations such as calcium (Ca), magnesium (Mg), K and sodium (Na). Most importantly, it is a major repository for the cycling of nutrients and their delivery to crops and pastures.

Researchers reported that the effects of land clearing and cropping in reducing soil organic matter (SOM) levels resulted from changes in soil temperatures, moisture fluxes and aeration, increased soil loss through erosion, reduced inputs of organic materials, increased export of nutrients in harvested product and exposure of protected organic matter with cultivation (Figure 2).

Declining levels of SOM have implications for soil structure, soil moisture retention, nutrient delivery and microbial activity. However, probably the single most important effect is the decline in the soil's capacity to mineralise organic N to plant-available N. In the original 83-paddock study, N mineralisation capacity was reduced by 39–57%, with an overall average decline of 52%. This translated into reduced wheat yields when crops were grown without fertiliser N. A healthy soil with good levels of organic matter and moisture can mineralise up to 1 kg N/day in warm or summer conditions.

4 DAFF (2010) Nutrition management. Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

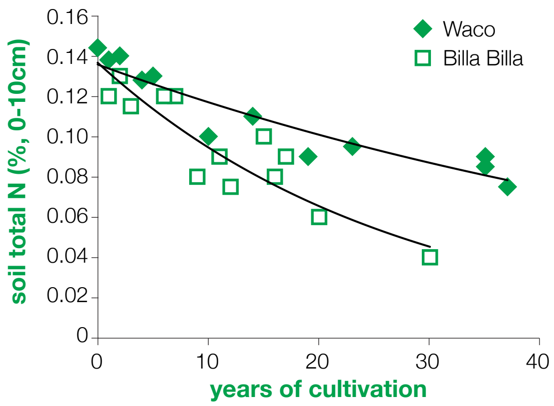

Figure 2: Graph of decline in soil total N with years of cropping. The decline was greater for the Billa Billa soil (clay content 34%) than the Waco soil (clay content 74%) .

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

Soil organic matter is an under-valued capital resource that needs informed management. Traditional cropping practices have dramatically reduced SOM levels, and its nutrients are of far more value than soil carbon (C) itself (Figure 3).

Modern farming practices that maximise water-use-efficiency for extra dry matter production are key to protecting SOM. Greater cropping frequency, crops with higher yields and associated higher stubble loads, pasture rotations and avoiding burning or baling will all help growers in the northern region to maintain SOM. [5]

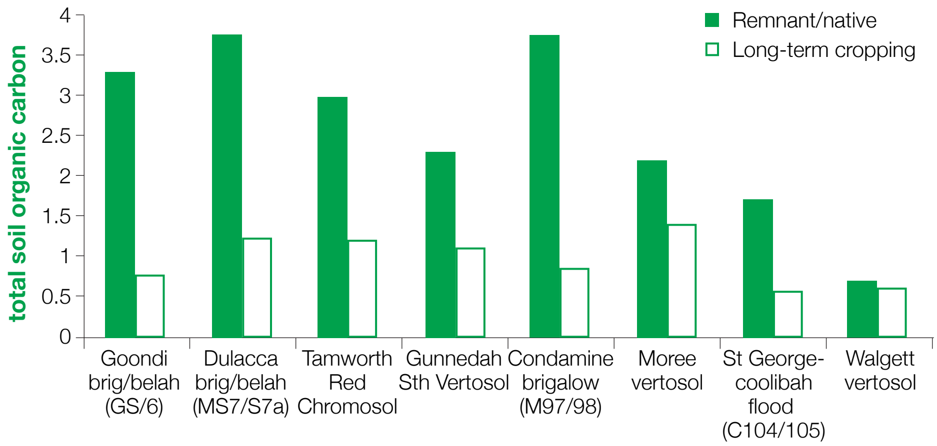

Figure 3: The decline of soil organic carbon with long-term cropping systems.

More information

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Soil-organic-matter-what-is-it-worth-to-grain-production-and-what-practices-encourage-it

5.1.2 Current situation

Current organic C and N levels in northern grains cropping soils reflect previous land use and management, as well as other factors such as rainfall, ambient temperature and soil type. There will be substantial within-paddock and between-paddock variation at a specific location, as well as variation across the whole northern region. In fact, differences between the extremely low and high values for particular localities can be as much as 4-fold. As a result, it may be near impossible to categorically state benchmark values for localities and/or soil types without examining masses of archived soil testing

5 D Lawrence, S Argent, R O'Connor, G Schwenke, S Muir, M McLeod (2013) Soil organic matter what is it worth to grain production and what practices encourage it, GRDC Update Papers 16 July 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Soil-organic-matter-what-is-it-worth-to-grain-production-and-what-practices-encourage-it

A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

data, with the inherent problems of which technique was used for measurement, or embarking on a new, comprehensive testing program. [6]

5.1.3 Options for reversing the decline in soil organic matter

Reversing the decline in SOM can be achieved by increasing organic inputs while reducing losses (Table 1).

Table 1: Practices to increase soil organic matter (SOM)

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

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

Arguably the most direct, effective means of increasing SOM levels is through the use of legume-based pastures. The rotation experiments of I Holford and colleagues at Tamworth, NSW and R Dalal and colleagues in south-eastern Queensland provide good evidence of this. An example is given in Table 2.

The greatest gains in soil C and N, relative to the wheat monoculture, were made in the 4-year grass–legume ley, with increases of 550 kg total N/ha and 4.2 t organic C/ha. The chickpea–wheat rotation fared no better than the continuous wheat system. The shorter (1–2-year) lucerne and annual medic leys resulted in marginal increases in soil organic C and N (Table 2).

Clearly, time and good sources of both C and N are required to build up SOM, which is exactly what the 4-year grass–legume ley provided. Nitrogen was supplied via N_2 fixation by the lucerne and annual medic in the pasture, with most of the C supplied by the grasses, purple pigeon grass and Rhodes grass. There were no inputs of fertiliser N in any of the treatments in Table 2. [7]

Table 2: Effects of different rotations on soil total N and organic C (t/ha) to 30 cm and as gain relative to continuous wheat

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

Source: Hossain *et al.* 1996a.

Impact of fertiliser N inputs on soil

If the rates of fertiliser N are sufficiently high, the effects can be positive. In the Warra experiments, both soil organic C and total N increased marginally (3–4%) over an 8-year

6 D Herridge (2011) Managing legume and fertiliser N for northern grains cropping. Revised 2013. GRDC, http://www.grdc.com.au/GRDC-Booklet-ManagingFertiliserN

7 D Herridge (2011) Managing legume and fertiliser N for northern grains cropping. Revised 2013. GRDC, http://www.grdc.com.au/GRDC-Booklet-ManagingFertiliserN

period when no-till, continuous wheat, fertilised at a rate of 75 kg N/ha, was grown. This is contrasts with decreases of 10–12% in soil organic C and N in the non-fertilised, continuous wheat and chickpea–wheat plots. The result was much the same in NSW Department of Primary Industries (DPI) experiments in northern NSW. At the Warialda site, for example, SOM increased during 5 years of cropping but only where fertiliser N had been applied to the cereals.

It is clear from the above examples that building of SOM requires N. It works in two ways. First, the fertiliser or legume N produces higher crop/pasture yields and creates more residues that are returned to the soil. Then, these residues are decomposed by the soil microbes, with some eventually becoming stable organic matter or humus. The humus has a C/N ratio of about 10 : 1, i.e. 10 atoms of C to 1 atom of N. If there are good amounts of mineral N in the soil where the residues are decomposing, the C is efficiently locked into microbial biomass and then into humus.

If, on the other hand, the soil is deficient in mineral N, then more of the C is respired by the soil microbes and less is locked into the stable organic matter. [8]

More information

GRDC Nitrogen booklet: http://www.grdc.com.au/GRDC-Booklet-ManagingFertiliserN

Figure 4: Where large premiums are paid for protein, EGA Gregory and Suntop may need specific N-management targeting protein. (Photo: Penny Heuston)

5.2 Balanced nutrition

To obtain the maximum benefit from investment, fertiliser programs must provide a balance of required nutrients. There is little point in applying enough N if P or Zn deficiency is limiting yield. To make better crop nutrition decisions, growers need to consider the use of paddock records, soil tests and test strips. This helps build an understanding of which nutrients the crop removes at a range of yield and protein levels.

The use of paddock grain protein to detect N deficiency is well established for wheat (11.5–12.5%), barley (11–11.5%) and sorghum (9.5–10.5%) (Figure 4). Grain protein lower than these levels is likely to indicate loss of yield due to inadequate N supply. Wheat with a protein level >14% has had its yield limited by lack of moisture.

[8] D Herridge (2011) Managing legume and fertiliser N for northern grains cropping. Revised 2013. GRDC, http://www.grdc.com.au/GRDC-Booklet-ManagingFertiliserN

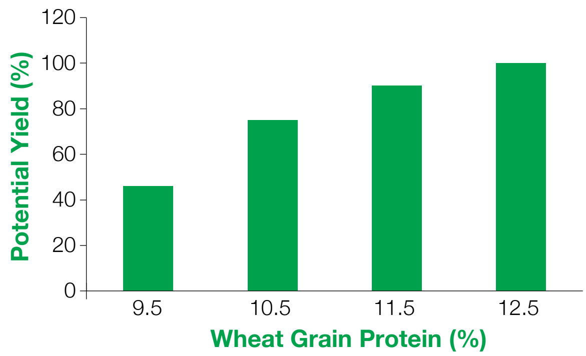

Figure 5: Wheat grain protein and potential yield.

Source: A Verrell, Wheat CRC, and AD Doyle, NSW DPI.

Monitoring of crop growth during the season can assist in identifying factors such as water stress, P or Zn deficiency, disease or other management practices responsible for reducing yield. [9]

Exploiting genotypic variation for use of banded fertiliser might be an important strategy for improving fertiliser use efficiency. There is variation in response to bands of P fertiliser between at least two wheat cultivars and scope to screen the major cultivars grown in the north. Root proliferation in response to S fertiliser is questionable and requires more research.[10]

More information

http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Selecting-cultivars-for-better-use-of-banded-fertilizer

Optimum inputs may be lower inputs for wheat

5.2.1 Paddock records

Paddock records help to:

- establish realistic target grain yield/protein levels prior to planting;
- modify target yield/protein levels based on previous crop performance (yield and protein), planting soil moisture, planting time, fallow conditions, expected in-crop seasonal conditions and grain quality requirements;
- determine appropriate fertiliser type, rate and application method; and
- compare expected with actual performance per paddock and modify fertiliser strategies to optimise future yield/protein levels.

The longer paddock records are kept, the more valuable they become in assessing future requirements. [11]

5.3 Increasing complexity of northern region soils

More information

http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Varieties-and-agronomy-for-maximising-irrigated-wheat-yields-in-the-northern-region

The northern grains region occupies more than 4 million ha across NSW, and southern and central Queensland. The cropping system is dominated by winter and summer cereals (wheat, barley and sorghum) with a relatively low frequency of grain legumes (chickpeas and, to a lesser extent, mungbeans, field peas and lupins).

The main cropping soils are Vertosols, Chromosols and Sodosols. Intrinsic soil fertility was high, especially on the Vertosols, but this has declined over time such that a significant proportion of the crop's nutrient requirement is now supplied by fertilisers.

9 DAFF (2010) Nutrition management. Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

10 GRDC (2014), Selecting cultivars for better use of banded fertiliser http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Selecting-cultivars-for-better-use-of-banded-fertilizer65kWoH2L.dpuf

11 DAFF (2010) Nutrition management. Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

The Riverina and south west slopes of NSW typically receive most of their annual rainfall in winter and the dominant soils types are Chromosols and Dermosols. There are some deep cracking Vertosols but they are not widespread.

In North West NSW, most of the rainfall is in the summer and there is a greater variety of soil types. The main soil types are Vertosols, Chromosols and Ferrosols.

There is widespread use of starter P, N and Zn fertiliser, and continued nutrient removal in grain is expected to increase incidence of deficiencies of other nutrients such as K and S. Indeed, negative nutrient budgets continue to be recorded across the region.

An assessment of the decline in reserves across the Queensland cropping belt showed that, compared with adjacent uncropped reference sites, cropped soils across all regions contained only 60% (+5%) of the organic C, 48% (+6%) of total organic N, 36% (+5%) of the particulate organic N, 68% (+14%) of the total inorganic P and 55% (+5%) of the exchangeable K reserves.

This depletion is resulting in increasingly complex nutrient management decisions for growers, with a recent survey of grain nutrient concentrations in wheat suggesting significant proportions of the commercial grain crop showed low–marginal status of one or more of N, P, K and S.

Until recently, fertiliser use in parts of the northern grains region was dominated by N inputs, with P and possibly Zn applied as starter fertilisers at planting—often with P rates still much less than rates of crop removal. There is increasing evidence of yield constraints due to concurrent deficiencies of P, K and S, with soil tests indicating the most severe depletion of reserves of P and K occurring in the layers immediately below the top 10 cm of the soil profile (i.e.10–30 cm). These layers are important for nutrient supply when topsoil root activity is limited by dry conditions but crop growth continues, utilising subsoil moisture (and nutrient) reserves.

Uncertainty remains about the ability of soil tests to accurately predict responsiveness to P, K and S fertilisers. [12]

More information

Australian Agronomy Conference Paper: http://www.regional.org.au/au/asa/2012/nutrition/8045_bellm.htm

5.4 Understanding soil pH

A soil pH in calcium chloride ($CaCl_2$) of 5.2–8.0 provides optimum conditions for most agricultural plants. All plants are affected by extremes of pH but there is wide variation in their tolerance of acidity and alkalinity. Some plants grow well over a wide pH range, whereas others are very sensitive to small variations in acidity or alkalinity. [13]

Microbial activity in the soil is also affected by soil pH, with most activity occurring in soils of pH 5.0–7.0. Where extremities of acidity or alkalinity occur, various species of earthworms and nitrifying bacteria disappear.

Soil pH affects the availability of nutrients and how the nutrients react with each other. [14]

At a low pH, beneficial elements such as Mo, P, Mg, S, K, Ca, N and other elements may become toxic (Figure 6). Maintain soil pH($CaCl_2$) between 5.5 and 6.5 to achieve maximum P availability for wheat.

[12] M Bell, D Lester, L Smith, P Want (2012) Increasing complexity in nutrient management on clay soils in the northern grain belt—nutrient stratification and multiple nutrient limitations. Australian Agronomy Conference. Australian Society of Agronomy/The Regional Institute, http://www.regional.org.au/au/asa/2012/nutrition/8045_bellm.htm

[13] B Lake (2000) Understanding soil pH. NSW Agriculture, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf

[14] B Lake (2000) Understanding soil pH. NSW Agriculture, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf.

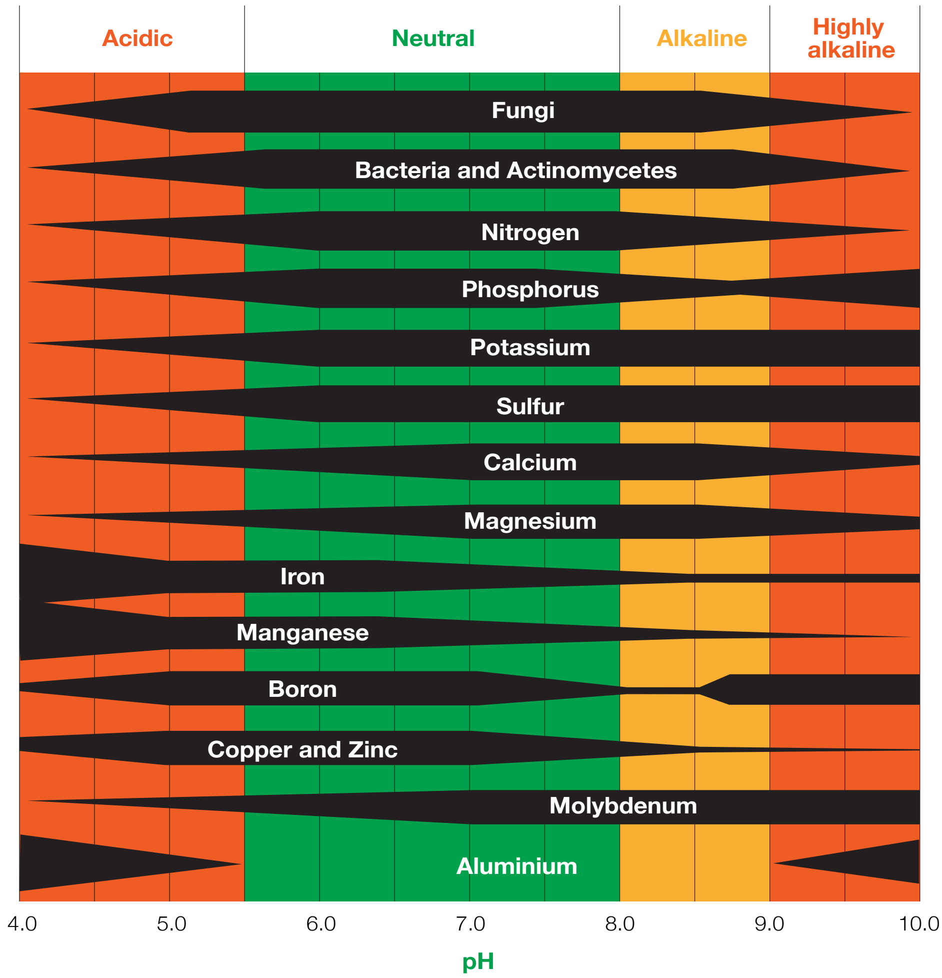

Figure 6: Effect of pH($CaCl_2$) on the availability of soil nutrients.
Source: After Trough.

The two main laboratory methods employed in Australia to determine pH use either $CaCl_2$ or water.

Soil pH in calcium chloride

This is the standard method of measuring soil pH in all states other than Queensland. An air-dry soil sample is mixed with five times its weight of a dilute concentration (0.01 m) of $CaCl_2$, shaken for 1 h, and the pH is measured using an electrode. The results are usually expressed as pH($CaCl_2$).

Soil pH in water

Distilled water is used in place of 0.01 M $CaCl_2$, and results are expressed as pH(w). The pH($CaCl_2$) test is the more accurate of the two tests, as it reflects what the plant experiences in the soil. The values of pH($CaCl_2$) are normally lower than pH(w) by 0.5–0.9. A useful, but not consistently accurate, conversion is to subtract 0.8 from the pH(w) to obtain a pH($CaCl_2$) value. The difference between the methods can be significant when interpreting results and it is important to know which method has been used, especially if pH values derived some years apart are being compared to assess fluctuations. [15]

For more information on crop-specific reactions to soil pH levels, download http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf.

15 B Lake (2000) Understanding soil pH. NSW Agriculture, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf.

5.5 Hierarchy of crop fertility needs

Current research by Department of Agriculture, Fisheries and Forestry Queensland (DAFF) on the Darling Downs confirms a hierarchy of crop fertility needs. There must be sufficient plant-available N to get a response to P, and there must be sufficient P for S and/or K responses to occur. [16]

Liebig's law of the minimum, often called Liebig's law or the law of the minimum, is a principle developed in agricultural science by Carl Sprengel (1828) and later popularised by Justus von Liebig. It states that growth is controlled not by the total amount of resources available, but by the scarcest resource (i.e. limiting factor) (Figure 7). [17]

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2011/09/Observations-on-a-general-decline-in-fertility-of-multiple-nutrients

Figure 7: Leibigs law, or law of the minimum.

Additive effects of N and P appear to account for most of the above-ground growth and yield response. [18]

5.6 Crop removal rates

Ultimately, nutrients removed from paddocks will need to be replaced to sustain production. Table 3 illustrates the different levels of nutrients extracted in both irrigated and dryland scenarios. Growers need to adopt a strategy of programmed nutrient replacement based on yields and protein taken off paddocks.

Table 3: Average nutrients removed by wheat crops—values are kg/ha

	Yield	N	P	K	Ca	Mg	S	Zn
Irrigated wheat grain	7000	125	24	35	3.5	10	3	200
Dryland wheat grain	2000	40	7	10	1.5	2.8	5.5	60

To attain optimum yields, an adequate supply of each nutrient is necessary. However, only a small proportion of the total amount of an element in the soil may be available for plant uptake at any one time. For nutrients to be readily available to plants, they must be present in the soil solution (the soil water), or easily exchanged from the surface of clay and organic matter particles in the root-zone, and be supplied when and where the plant needs it.

Temperature and soil moisture content affect the availability of nutrients to plants, and the availability of nutrients also depends on soil pH, degree of exploration of root systems and various soil chemical reactions, which vary from soil to soil. Fertiliser may be applied in the top 5–10 cm, but unless the soil remains moist, the plant will not be

16 D Lester, M Bell (2013) Nutritional interactions of N, P, K and S on the Darling Downs. GRDC Update Papers 7 March 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Nutritional-interactions-of-N-P-K-and-S-on-the-Darling-Downs

17 Anon. Liebig's law of the minimum, http://en.wikipedia.org/wiki/Liebig's_law_of_the_minimum

18 D Lester, M Bell (2013) Nutritional interactions of N, P, K and S on the Darling Downs. GRDC Update Papers 7 March 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Nutritional-interactions-of-N-P-K-and-S-on-the-Darling-Downs

able to access it. Movement of nutrients within the soil profile in low-rainfall areas is generally low, except in very sandy soils, and some nutrients, such as P and Zn, are relatively immobile in the soil.

Lack of movement of nutrients, combined with current farming methods (e.g. no-till), is resulting in stratification of these nutrients, with concentrations building up in the surface of the soil where they are not always available to plants. Often, on Queensland's Western Downs and in central Queensland, wheat is deep-sown into moisture that is below the layer where nutrients have been placed or are stratified, and this has implications for management and fertiliser practices. [19]

More information

Model your nitrogen to account for in-crop

Nitrogen management in wheat 2014

Understanding causes of poor grain yield response of wheat to phosphorus and nitrogen fertilisers

5.7 Nitrogen

5.7.1 Nitrogen supply and grain protein content

Nitrogen is a primary constituent of protein, so adequate soil N supply is essential for producing wheat with a high protein content. Supply of N is shaped by a number of factors in the farming system (Figure 8).

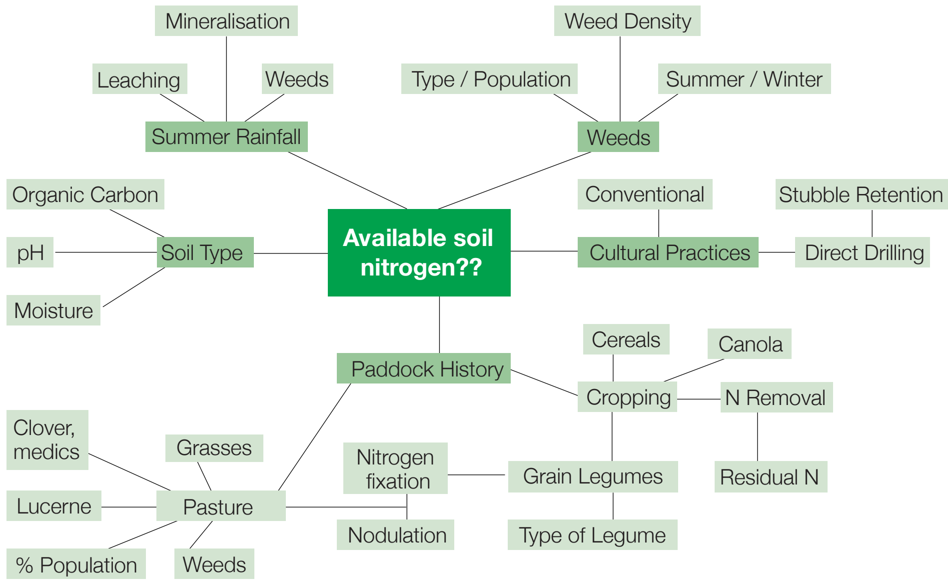

Figure 8: Factors influencing available soil nitrogen. (Source: Incitec Pivot Ltd.)

Grain protein is modified by the grain yield of the crop—increasing grain yield has a diluting effect on grain protein, i.e. yield and protein are inversely proportional (Figure 9).

19 DAFF (2012) Wheat—nutrition. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

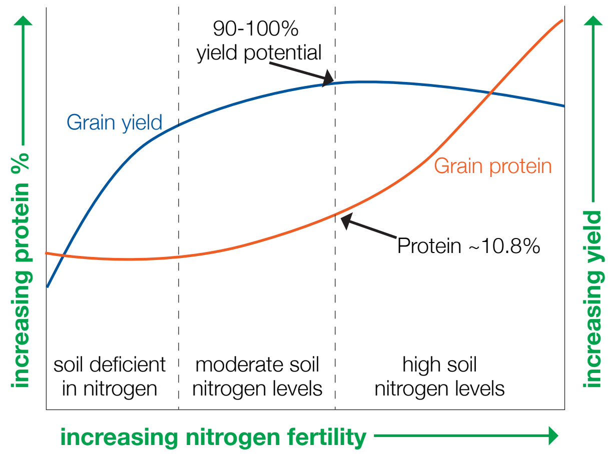

Figure 9: The relationship between yield and protein. (Source: Incitec Pivot Ltd.)

This explains why a larger proportion of the crop is of a high protein in drier seasons or seasons of low grain yield, whereas high yields can be produced but may be at a lower protein level in wetter years. Nitrogen fertility can be extremely variable from one year to the next.

Low grain protein, the signal of nitrogen deficiency

Grain protein can be used to indicate whether current N fertiliser or rotation practices are meeting the crop's demands at given soil moisture levels Without adequate N, profits may also suffer due to lost yield, and potential downgrading to a lower classification (Table 4).

Table 4: Using grain protein to signal nitrogen deficiency

Wheat grain protein	Indicated nitrogen supply
<11.5%	Acutely N-deficient this season. Grain yield would almost certainly have been increased had more N fertiliser been applied; grain protein will increase if sufficient N is applied to achieve season yield
11.5–12.5%	Probably N-deficient this season. Nitrogen adequate to achieve season grain yield. Grain protein will most certainly increase with higher rates of N. High protein premiums for specialty classifications of wheat may justify higher rates of N to produce higher grain protein levels
>12.5%	Nitrogen not deficient this season. Water supply probably limited grain yield. Applying additional N fertiliser will not increase yield but may increase protein. Applying N fertiliser to produce higher protein (13%) is only economical if high protein premiums exist for Australian prime hard wheat or other specialised markets

Nitrogen management should ensure that wheat crops consistently produce a grain protein content of 11.5–12.5% to achieve season yield potential. However, applying N fertiliser to produce grain protein content >12.5% may not be economical unless high premiums are available for high protein Australian Prime Hard (APH) wheat. Table 5 indicates the approximate amount of available N needed at planting for a particular yield and protein.

Table 5: Available soil nitrogen (kg) needed for particular yield and protein

Yield (t/ha)	Grain protein (%):							
	7	8	9	10	11	12	13	14
1.0	25	28	32	35	39	42	46	49
1.5	37	42	47	53	58	63	68	74
2.0	49	56	63	70	77	84	91	98
2.5	61	70	79	88	96	105	114	123
3.0	74	84	95	103	116	126	137	147
3.5	86	98	110	121	135	147	159	172
4.0	98	112	126	140	154	168	182	196
4.5	110	126	142	158	173	189	205	221
5.0	123	140	158	176	193	210	228	245

Factors affecting level of N required:

- Yield and protein levels. If the expected yield is exceeded due to good climatic conditions, grain protein may fall below the protein targeted. If the yield is not achieved, for example due to moisture stress, then grain protein may be above the protein targeted.
- Planting date, variety and soil moisture. These must be considered in establishing seasonal target yield and protein levels. Early planting and good stored moisture at planting should indicate higher target yields. Using a tool like HowWet is a good approach to estimating plant-available water.
- Southern Oscillation Index and seasonal rainfall prospects. With higher rainfall prospects, consider increasing N rates. Using a cropping simulation tool such as Whopper Cropper can provide further information on yield and protein potentials.
- Level of soil fertility. Soil-test paddocks every year, both shallow and deep, and calculate a N budget from these values.
- Summer rainfall. High summer rainfall will result in higher mineralisation of N in the soil. This will be higher in a no-till situation and with higher organic C soils.
- Cropping history. Double-cropping will normally require higher N rates.
- No-tillage. Stubble retention combined with no-till and reduced tillage has increased the yields and cropping frequency of northern farming systems by storing more soil water. Higher N rates may be required to make efficient use of this extra stored soil water.
- Variety to be grown. Some varieties are more efficient at extracting N from the soil than others, e.g. Spitfire⟨D.
- Protein premiums. High premiums for APH high protein wheat may have warranted an increase in N rates. [20]

Contributing factors to widespread low grain protein in the 2012 winter crop included:

- long term loss of soil N supply elasticity as a result of organic matter decline
- general lack of legumes in rotations
- high starting moisture and hence high potential yield conditions
- high yields in crop preceding 2012 winter crop
- summer 2011–12 denitrification events due to high rainfall events
- fertiliser N management strategies—quantity and timing

[20] DAFF (2012) Wheat—nutrition. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

GRDC Video

http://www.grdc.com.au/Media-Centre/GRDC-Gallery/Video/3jDrtfg95Po

More information

GRDC Update Papers:

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Have-we-got-the-foundation-of-N-nutrition-right#sthash.kGrs8NES.dpuf

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/02/Will-low-protein-become-the-new-norm

GRDC Booklet:

http://www.grdc.com.au/Resources/Bookshop/2013/05/Managing-Legume-and-Fertiliser-N-for-Northern-Grains-Cropping

Nitrogen volatilisation: Factors affecting how much N is lost and how much is left over time

- few N topdressing opportunities in-crop
- dry spring subsoil finish—moisture and available N dislocation

Does the 2012 outcome mean that we have the foundations of N nutrition wrong? No, the soil N-cycle (Figure 10) is still the same, but growers need to heed the low-protein warnings, as they have implications for all non-leguminous crop. With increasing impact of factors such as declining reserves of soil N, increased genetic yield potential, and an apparent increasing varietal difference in N partitioning in wheat, N management especially for high grain protein in wheat may need more consideration with regard to in-season management and different N management options for the future. [21]

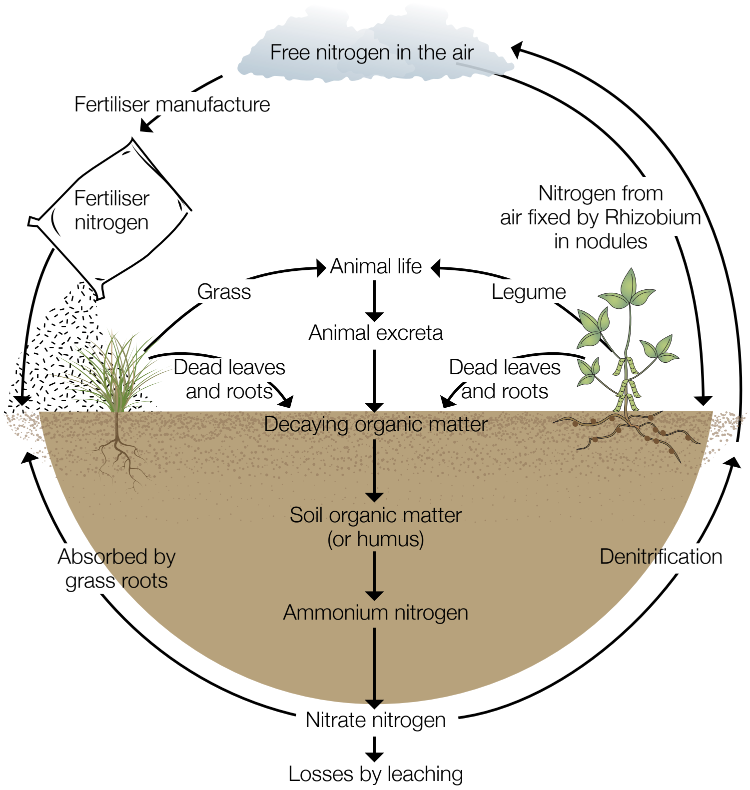

Figure 10: The soil nitrogen cycle.

5.8 Nitrogen volatilisation and denitrification

Ammonia volatilisation (Figure 11) occurs when urea is surface-applied without incorporation. After application, urea dissolves in water and, in the presence of urease, forms ammonium ions (NH_4^+). If there are insufficient adsorption sites at the soil surface for the ammonium ions, ammonia (NH_3) gas can form as the soil dries out, e.g. in the heat of the day following overnight dew. Such losses are greatest in alkaline (high-pH) soils, in which hydroxyl (OH^-) ions are present in high concentrations. [22]

It is known to be safer to incorporate than to rely on surface spreading, but many farmers in the northern region practice pre-season broadcasting and in-season topdressing of wheat crops. Splitting N application between sowing and in-crop allows growers to lower their financial risk on fertiliser application by allowing seasonal conditions to drive decisions on how much to spend on N, but this can come at a cost of additional yield.

[21] C Dowling (2013) Have we got the foundation of N nutrition right? GRDC Update Papers 16 July 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Have-we-got-the-foundation-of-N-nutrition-right

[22] Source: Incitec Pivot Limited, http://www.incitecpivot.com.au/

Most farmers try to apply fertiliser ahead of predicted rain, but what happens if rain does not fall as predicted? Is the N really all lost to the air in 1 or 2 days? International research literature lists the range of measured losses from 0 to almost 100%, but there are very few instances of losses greater than ~40% of that applied, with most studies finding only ~10% loss.

In the 2008 and 2009 GRDC Adviser Updates, researchers detailed the factors that drive the process of N volatilisation from fertiliser, along with the results of some laboratory incubation experiments.

The following is a brief summary of the many factors involved:

1. Soil pH. There is more loss at higher pH. Dissolving urea granule creates a high pH zone.
2. Temperature. The hotter it is, the greater the potential for ammonia loss.
3. Soil moisture. Wet soil dissolves fertiliser but does not move N into the soil.
4. Calcium carbonate ($CaCO_3$). Lime in the soil reacts directly with ammonium sulfate, increasing loss.
5. Soil clay content. Clay in soils adsorbs ammonium-N, decreasing potential for loss.
6. Soil buffer capacity. Clays in soil absorb changes in soil pH.
7. Biological activity. Ammonium is converted to nitrate, which is safe from volatilisation.
8. Wind. Windy conditions at the soil surface lead to greater loss.
9. Rain. Rain moves dissolved fertiliser into contact with soil clays, away from wind.
10. Depth of fertiliser. Ammonia must be at the surface to volatilise. Incorporation reduces loss.
11. Crop canopy. Some ammonia in air can be re-absorbed by a growing crop canopy and the canopy also reduces the wind intensity at the soil surface.
12. Residues/litter. Residues can strand the fertiliser at the surface. Urease enzyme is present in residues.
13. Fertiliser type. Only the ammonium form is lost; urea converts to ammonium and nitrate forms are not volatilised.

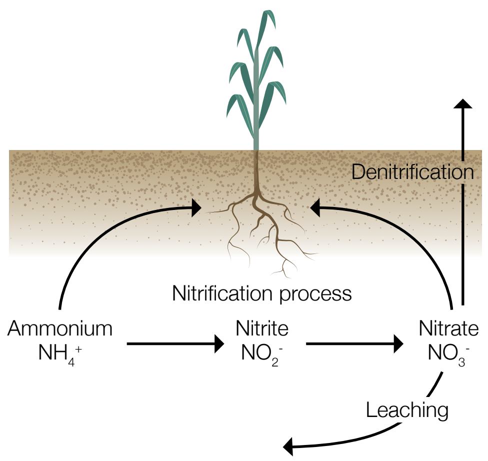

Figure 11: The nitrification process.

In cracking clay soils of the northern grains region, saturated soil conditions between fertiliser application and crop growth can lead to significant N losses from the soil through denitrification. The gases lost in this case are nitric oxide (NO), nitrous oxide (N_2O) and di-nitrogen (N_2) (Figure 12). Isotope studies in the northern region have found that these losses can be >30% of the N applied. Direct measurements of nitrous oxide highlight the rapidity of loss in this process.

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2009/09/NITROGEN-VOLATILISATION-FROM-NORTHERN-CROPPING-SOILS

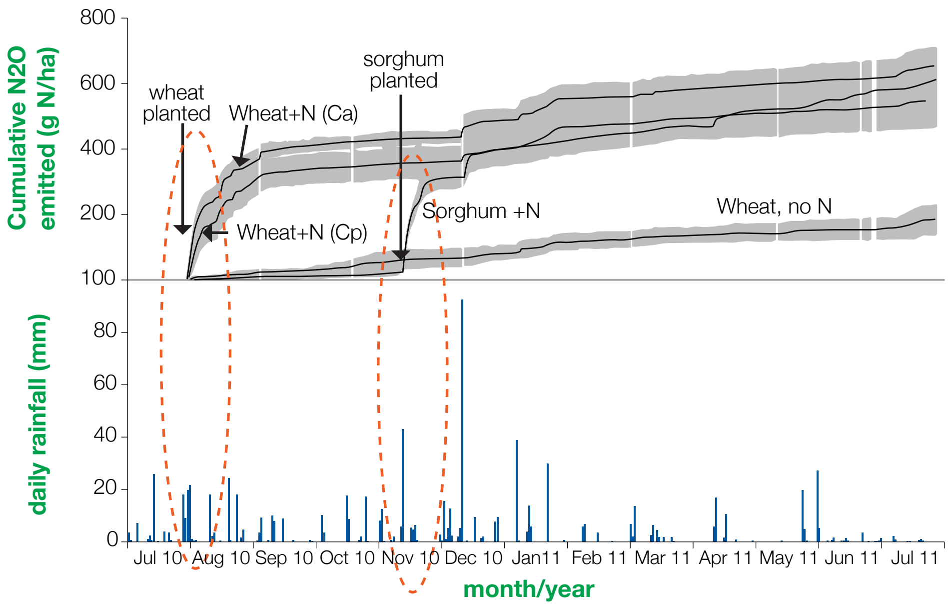

Figure 12: Cumulative nitrous oxide emissions from three wheat crops and one sorghum crop grown in 2010, and daily rainfall. Two of the wheat crops had 80 kg N/ha applied at sowing, the other had nil N. The sorghum crop had 40 kg N/ha applied at sowing. The grey zone around the lines is the standard error about the mean cumulative emissions.

Nitrogen losses from ammonium sulfate applications were less than from urea in both bare fallows and grass-based perennial pastures. However, ammonium sulfate should be avoided on soils with naturally occurring lime in the surface. [23]

Research funded by GRDC and NSW Department of Primary Industries through a Northern Grower Alliance project (NGA0002) showed that delayed N reliably improved grain protein and maintained grain yield with applications up to early stem elongation, irrespective of the N fertiliser used.

Initial trials of summer-fallow broadcast applications have shown that some losses are to be expected but are mostly minor (<10%), unless the soil surface has naturally occurring lime, where losses can be much higher. However, researchers report that naturally occurring lime in the surface soil is quite rare. If in doubt, request a $CaCO_3$ test during soil testing. Once will generally be sufficient, as lime content does not change with seasons. However, cultivation can bring lime up from lower in the soil profile. In general, current research results so far fit well with the research literature, where an average of 10% of applied N is lost from urea added to arable systems. [24]

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Nitrogen-use-efficiency

More information

Australian Grain Consultant Corner: http://www.nga.org.au/results-and-publications/download/31/australian-grain-articles/general-1/canopy-management-tactical-nitrogen-in-winter-cereals-july-2009-.pdf

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/03/Nitrogen-volatilisation-losses-how-much-N-is-lost-when-applied-in-different-formulations-at-different-times

23 G Schwenke (2013) Nitrogen use efficiency. GRDC Update Papers 16 July 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/07/Nitrogen-use-efficiency

24 G Schwenke, A Perfrement, W Manning, G McMullen (2012) Nitrogen volatilisation losses how much N is lost when applied in different formulations at different times. GRDC Update Papers 23 March 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/03/Nitrogen-volatilisation-losses-how-much-N-is-lost-when-applied-in-different-formulations-at-different-times

5.9 Nitrogen-use efficiency

Efficient use of nitrogen (N) is crucial to economic production of wheat. Excessive application of N may increase susceptibility of the crop to disease and increase water use early in the growing season, creating excessive early growth, causing crops to 'hay off'. Insufficient N may limit grain yield, grain protein and subsequent profitability. Within a given season in a cereal crop, fertiliser rate and timing are the major tactical tools used for N management. Applications of N at sowing or up to the start of stem elongation drive greater crop biomass and grain yield response than late applications (around anthesis or GS61), which have little influence on grain yield but can drive a significant protein response. [25]

Nitrogen nutrition represents a significant cost for grain growers. With declining soil fertility in the northern grains region, it is important to select varieties that convert soil N and fertiliser N into grain yield and protein. In the northern grains region there is typically limited opportunity to apply N within the growing season due to unreliable in-season rainfall; therefore, most N is applied at or before sowing. The Variety Specific Agronomy Packages (VSAP) trial investigated grain yield, protein and quality response of commonly grown wheat varieties to N fertiliser application.

Trial results can be summarised as follows:

- Increasing the rate of applied N resulted in a significant yield increase for LongReach Impala⫚ only. EGA Gregory⫚ and Caparoi⫚ had a significant reduction in yield with increasing N application rate.
- There was no significant increase in grain protein (averaged across all varieties) at the 25 kg N/ha compared with nil N. Grain protein increased significantly at the 50 kg N/ha compared with nil N and increased further at the 100 kg N/ha.
- LongReach Spitfire⫚ had the highest grain protein concentration at all rates of applied N.
- Averaged across all varieties, grain yield was maximised at a grain protein concentration of 9%.
- Screenings (% of grain below 2-mm screen) of LongReach Spitfire⫚ and Sunguard ⫚ remained relatively stable at all N rates (average 5%). With increasing N rate from nil to 100 kg/ha, screenings of Caparoi⫚ increased from 7 to 18%.

There was only small recovery of applied fertiliser N in grain in this trial. Increasing the rate of N applied significantly decreased the yield of EGA Gregory⫚ and Caparoi ⫚. The reasons for the yield loss from increasing N are unclear; however, it may have been due to increased vegetative growth or to interactions with crown rot. Suntop⫚ and Sunguard⫚ had relatively high grain yields at all N rates and are potential options for north-western NSW due to their good levels of resistance to crown rot and tolerance of the root lesion nematode *Pratylenchus thornei*. Suntop⫚ and Sunguard⫚ have APH and Australian Hard (AH) classifications, respectively. Over several trials, Suntop⫚ has shown grain protein levels similar to EGA Gregory⫚.

Leguminous crops and pastures appear the most sustainable option to increase N availability in the soil (especially in the subsoil). Increasing N concentration in the subsoil will allow access to that N later in the growing season.

Protein levels

Grain protein levels in the northern region continue to gain attention (Figure 14). The 2012 season could be considered the third, consecutive, low-protein season for much of the northern grains region. Receivals in part of the region were dominated (60% in some areas) by low-protein wheat (<10.5% protein) in 2012. There are generally considered only minor differences among commercial varieties for grain protein

25 R Brill, M Gardner, G McMullen (2012) Comparison of grain yield and grain protein concentration of commercial wheat varieties. GRDC Papers 10 April 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/04/Comparison-of-grain-yield-and-grain-protein-concentration-of-commercial-wheat-varieties

More information

http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Managing-nitrogen-for-yield-and-protein-2013-update

http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Nitrogen-management-in-wheat

Where does fertiliser nitrogen finish up?

Durum wheat variety response to nitrogen management – Tamarang 2014, Rick Graham, Guy McMullen Gururaj Kadkol. p159

Nitrogen response of six wheat varieties – Merriwa 2014, Greg Brooke, Peter Matthews, Guy McMullen. p174

Nitrogen and sowing time response of six wheat varieties – Wongarbon 2014, Greg Brooke, Peter Matthews, Guy McMullen. p177

Wheat variety response to nitrogen management – Tamarang 2014, Rick Graham, Guy McMullen. p184

Getting nitrogen (N) into the crop efficiently and effectively

accumulation. Results from the 2011 GRDC-funded VSAP trials indicated that most varieties conform to the yield–protein trend, where with increasing yield there is a decline in grain protein levels. One variety that appears not to conform to this trend is LongReach Spitfire⦶, which tends to achieve a higher protein level for a given yield than other varieties.

Trials by NSW DPI showed that EGA Gregory⦶ and Suntop⦶ were among the highest yielding varieties at both Moree and Spring Ridge, which supports the results of National Variety Trials (NVT) and other VSAP trials conducted in the central-west in 2012 (Figure 14*a*, *b*). Furthermore, EGA Gregory⦶ had lower grain protein in all trials than LongReach Spitfire⦶, Livingston⦶ and Sunvale⦶. Suntop⦶ appears to behave similarly to EGA Gregory⦶ in terms of both yield and grain protein accumulation, which means that the N removal on a per hectare basis is comparable to other varieties. LongReach Spitfire⦶ appears unique in that, unlike EGA Gregory⦶, even when it achieves higher yields it is still able to maintain protein concentration, giving it the potential for higher protein levels.

Where large premiums are paid for protein, EGA Gregory⦶ and Suntop⦶ may need specific N-management targeting protein. However, the limited responses from in-crop N applications reported here highlight the risk associated with reliance on in-crop rainfall to make use of these applications in the northern region, and poses the challenge of how to reliably supply N throughout the season to adjust for changes in seasonal potential. LongReach Spitfire⦶, on the other hand, may need N management with a greater emphasis on maximising yield. [26]

In 2013 variety choice played a significant role in final grain yield and grain protein concentration, which influenced the capacity to achieve APH. Profitable production is driven not only by yield but is also influenced by quality targets and the cost to achieve them. Growers and advisors need to consider the economic cost:return and risks of targeting/achieving APH. The recovery of applied N in grain can be low with residual soil mineral N levels only accounting for a portion of the unrecovered N.[27]

For more information about variety selection, see *Section 2. Pre-planting*, and visit www.nvtonline.com.au

Figure 13: Where large premiums are paid for protein, EGA Gregory and Suntop may need specific N-management targeting protein.

[26] M Gardner, S Morphett, P Mortell (2012) Response of six wheat varieties to varying N nutrition—Spring Ridge and Moree 2012. Northern grains region trial results, autumn 2013, pp. 199–202. NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/468328/Northern-grains-region-trial-results-autumn-2013.pdf

[27] GRDC (2014), Managing nitrogen for yield and protein 2013 update http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Managing-nitrogen-for-yield-and-protein-2013-update

More information

NSW DPI Northern Grains Region Trial Results: http://www.dpi.nsw.gov.au/agriculture/broadacre/guides/ngrt-results

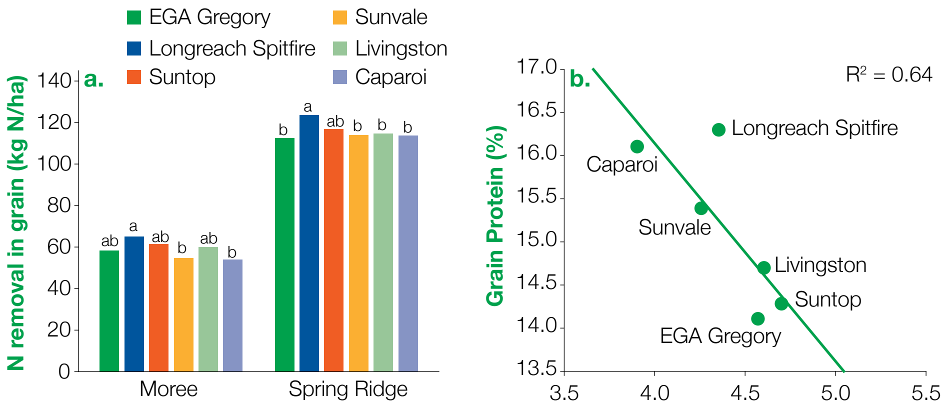

Figure 14: (a) Grain N removal of six wheat varieties at Moree and Spring Ridge when averaged across six N treatments; and (b) the linear relationship between grain yield and grain protein at Spring Ridge for six wheat varieties in 2012.

With the application of N, yield will generally increase to a maximum level, whereas protein may continue to increase beyond this level with further N application. This was shown in a trial at Parkes in 2011, in which yield of wheat increased at a reducing rate where N was applied at 30 kg/ha increments. Yield was maximised with N application of 90 kg/ha. Protein increased linearly for each 30 kg/ha increment up to 120 kg/ha. Yield appeared to be maximised at a grain protein concentration of 11.2% (Figure 15). [28]

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/04/Comparison-of-grain-yield-and-grain-protein-concentration-of-commercial-wheat-varieties

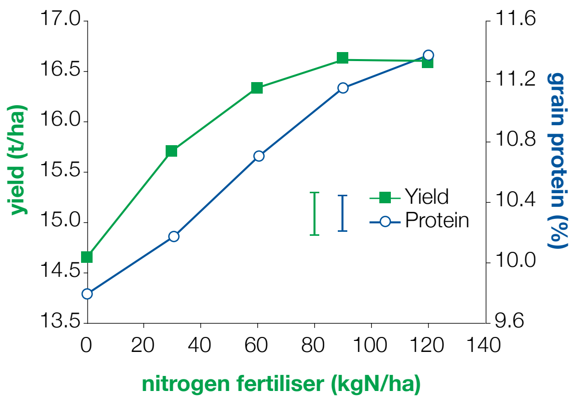

Figure 15: Grain yield (t/ha) and protein concentration (%) from 10 wheat varieties with nitrogen applied at 0, 30, 60, 90 and 120 kg/ha in a trial at Parkes in 2011.

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

Nitrogen in the plant-available, mineral form is a major driver of crop production. In the northern grains region, almost all the N taken up by crops is in the form of nitrate. The other mineral form, ammonium, is present in most soils at low levels and very little, if any, is used directly by crops.

Nitrate levels in the root-zones (top 1.2 m) of soils across the northern region vary substantially in both space (that is, amongst paddocks) and time (from season to season).

In some soils, subsoil constraints will limit the root-zone to less than 1 m. In other soils that are particularly well structured, the root-zones of long-season or particularly vigorous crops such as cotton and sorghum can be as deep as 1.8 m.

28 R Brill, M Gardner, G McMullen (2012) Comparison of grain yield and grain protein concentration of commercial wheat varieties. GRDC Update Papers 10 April 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/04/Comparison-of-grain-yield-and-grain-protein-concentration-of-commercial-wheat-varieties

5.10.1 Nitrate variations with cropping and fallowing

Knowing how much nitrate is in the top 1.2 m of the soil in a particular paddock is critical for the farmer to then make a decision about how much N to add. Soil nitrate concentrations vary greatly amongst paddocks, even though they may have then been used to grow identical crops.

Data from two surveys of soil nitrate at sowing are shown in Figure 16. The first involved 70 paddocks sown with wheat, the second 51 paddocks sown with either chickpea or faba bean. There were large ranges of nitrate levels in both surveys: 17–315 kg nitrate-N/ha in the wheat paddocks and 13–192 kg nitrate-N/ha with the winter pulses. Such large variations clearly provide challenges for farmers, such as how much additional N to add as fertiliser in the wheat paddocks and how to deal with the suppressive effects of the high-nitrate soils on nodulation and N_2 fixation of the pulses.

In normal cropping cycles of the northern grains region, nitrate accumulates during crop-free fallows, to be used for crop growth during the cropping phase. The accumulation of soil nitrate-N is called 'net mineralisation' because it is really the balance of N released into the soil (mineralisation) during a particular period minus the N immobilised and lost through gaseous emissions.

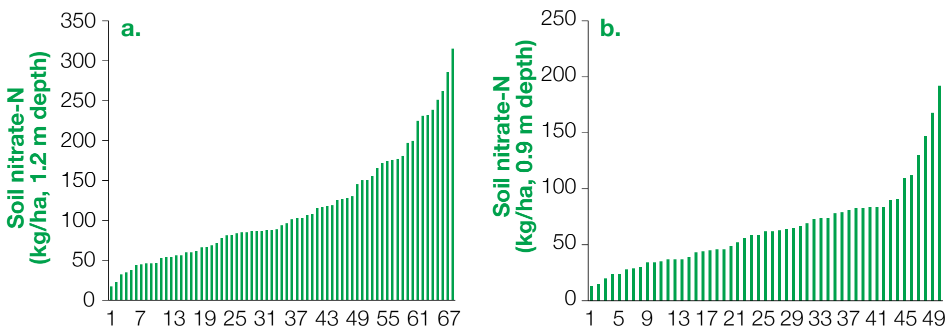

Figure 16: Variations in soil nitrate levels in (a) 70 commercial paddocks in northern NSW 2–3 months prior to wheat sowing in 1996; and (b) 51 commercial paddocks in northern NSW just prior to sowing chickpeas or faba beans in 1994 and 1995.

5.10.2 The effectiveness of nitrogen application for protein 2012 and 2013

An extensive set of Northern Grower Alliance trials was hampered by the low rainfall experienced during the springs of 2012 and 2013, however it clearly showed that:

1. Significant increases in protein can be gained by late nitrogen application
2. The level of increase however was not sufficient to deliver economic benefits
3. Foliar was clearly the most effective method of application
4. Timing differences were less clear but generally supported application between late head emergence and early milk stages when targeting protein accumulation
5. Although late application of spread urea was, as expected, the least effective method, the results from soil coring at two trials indicated a high level of recovery in the 0-30cm samples. This supported recent results from Graeme Schwenke, NSW DPI, indicating nitrogen volatilisation from urea application in-crop may not be as high as previously considered.

These results suggest that trying to increase wheat protein with late nitrogen application is unlikely to be a very effective management tool in areas where spring rainfall is highly erratic. Unless nitrogen in grain recovery levels can be increased dramatically, grain price differentials of ~$20-40/t are probably necessary before even considering this type of approach. Supply of nitrogen requirements either prior to or at planting, or as a top up during early crop growth stages would appear a much more reliable and effective strategy. Economic benefits from nitrogen application targeting yield potential are likely to be far easier to achieve than when targeting protein increases.[29]

5.11 Phosphorus

Australian soils are characteristically low in P in their native state, with the exception of a few soils of basaltic origin and some alluvial soils. Agriculture can further deplete soil fertility, even in soils that are initially high in P.

Most of the P in soils is associated with organic matter. Even in mineral soils, 20–80% of the total P will be present in organic forms.

More information

Understanding causes of poor grain yield response of wheat to phosphorus and nitrogen fertilisers

Topping up wheat with foliar phosphorus – does it work?

5.11.1 Phosphorus deficiency

Phosphorus deficiency is one of the most widespread of nutrient deficiencies. Phosphorus is an important component of many molecules in plant cells; therefore, it is important for growing tissue where cells are actively dividing (e.g. development of seedling roots, flowering and the formation of seed). Phosphorus-deficient plants are stunted, dark green plants with short, erect leaves and stout stems that often develop orange, red or purplish discoloration. Many soils in wheat-growing areas will respond to the application of phosphate fertilisers.

Approximately 3.2 kg of P is removed in every tonne of wheat harvested. Phosphorus deficiency is more likely to occur after a long fallow due to low numbers of arbuscular mycorrhizal fungi (AM, also previously known as VAM) in the soil. These AM are the beneficial soil fungi that help plant roots take up both P and Zn. [30]

5.11.2 Crop demand for P

Crop demand for P can be considered in two distinct phases: during early development (from emergence to the end of tillering, but before stem elongation), and then during the subsequent growth and grain-filling period.

During early development, the requirement for P is small (perhaps 1 kg P/ha), but the root system is small and inefficient, so the crop responds to a concentrated P source close to the seed and developing roots. Ensuring that these young plants have adequate P is essential to determination of grain number (i.e. yield potential) and ensuring vigorous seedling development. Hence, it is important to apply ‘starter fertilisers’ with the seed, so that the seed has a ready source of P for its development.

Subsequent P requirement is much larger, and largely mirrors the accumulation of crop biomass. As a rule, crops require ~5 kg P accumulated to produce 1 t of grain yield, so a typical crop of 3 t/ha will take up ~15 kg/ha of P. Only 1–2 kg will be taken up from the banded P fertiliser applied at planting (either in or below and beside the seeding row). The rest comes from the soil profile, with about half coming from the top 10–15 cm and the rest from the next 15–30 cm. These proportions will change with seasonal conditions, as root activity in surface layers will be minimal in dry periods. Having plant-available P in the immediate subsoil (i.e. 10–30 cm preferably) becomes a critical factor for crop performance.

The need for P fertiliser can be determined by using soil tests (0–10 and 10–30 cm) and/or test strips of fertiliser. When interpreting Darling Downs soil tests, the best predictions of P response are obtained by using both the BSES and bicarbonate (or Colwell) P test results as shown in Table 6 below. These guidelines are based only on results from the 0–10 cm layer of the soil profile, but current research is developing

29 GRDC (2014), The effectiveness of nitrogen application for protein 2012 and 2013. http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/The-effectiveness-of-nitrogen-application-for-protein-2012-and-2013

30 DAFF (2010) Other elements of crop nutrition—phosphorus. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/other-nutrition

guidelines to determine the soil P status in the 10–30 cm layer, and any resulting fertiliser requirement. [31]

Table 6: Phosphorus recommendations for the Western Downs

Soil test Bicarb P (mg/kg)	Interpretation	Recommendations
0–10	Low. Response most likely	Apply 8 kg P/ha
11–15	Marginal. Response likely	Apply 6 kg P/ha (leave a test strip untested)
16–20	Adequate. Response possible	Try test strip of 6 kg/ha
>20	Good. Response unlikely	

More information

[Role of legume break crops in mobilising soil phosphorus (P) for wheat]

5.11.3 Phosphorus availability

A key consideration for growers with regard to fertiliser management is how much P the stubble will supply, and when this P will be available to plants during the growing season. Many studies suggest that the timing and quantities of P release vary and that they are not well explained by the total amount of P or the C/P ratio in the residues.

Stubble type, size and placement, moisture supply and the rate all can significantly influence the timing and amount of P released from stubbles to the soil. Recent research aims to better identify P forms in crop stubble, understand how these forms influence P release and breakdown from stubble, and thereby provide a better estimation of the contribution of stubble P to subsequent crop P uptake.

Phosphorus within the stubble can be released directly to soil as soluble P (where it can be used immediately by the crop or chemically fixed onto the soil) or be absorbed by microorganisms and subsequently be released back into the soil in the future.

The chemical composition of crop stubble plays an important role in the rate of nutrient release. Currently, the quality of crop stubble is usually assessed using the C : N : P ratio of the stubble, as this ratio influences the proportion of P that follows pathways of immediate release or incorporation by microorganisms and subsequent release back to the soil.

This occurs because the microbial population requires a C source for energy, which is provided by the stubble, as well as certain amounts of nutrients such as N and P to continue to grow. How crop stubble affects soil P availability will therefore depend on the balance between direct release of P (and C and N) from stubble and microbial uptake and release. The presence of different chemical P forms in the stubble is likely to influence the proportion of P that undergoes direct release or microbial uptake and decomposition.

Research results indicate that P release is strongly controlled by the size of the stubble pieces, and studies that use ground stubbles are likely to over-predict the rate at which P is released from stubble in the field. [32]

5.11.4 Difficulty in establishing P levels

Grain yield potential is set by water (and nutrient) availability in the pre-anthesis period, although actual yield is determined by post-anthesis water (and nutrient) availability. Under conditions where the crop is reliant on stored subsoil water for growth, P is acquired from subsurface layers (10–30 cm) for much of the growing season. Because the root surface area for P absorption increases as the crop grows, slowly available P

31 DAFF (2010) Other elements of crop nutrition—phosphorus. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/other-nutrition

32 S Noack, M McLaughlin, R Smernik, T McBeath, R Armstrong (2012) The value of phosphorus in crop stubble. GRDC Update Papers 23 February 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/02/The-value-of-phosphorus-in-crop-stubble

sourced from the dissolution of sparingly soluble soil minerals and fertiliser reaction products ('reserve P') becomes increasingly important as the crop matures.

Although these reserve P sources can be quantified using an acid soil P test such as the BSES-P test (0.005 M sulfuric acid extractant), the actual quantity of this P available depends on the ability of the root system (which may be mycorrhizal) to lower the soil solution P concentration below the threshold value where these reserve P sources start to dissolve. This threshold value will vary depending on the chemical composition of the P source and its degree of crystallinity. Therefore, it is a major challenge to develop soil P tests capable of determining how much 'reserve' P is available.

Figure 17 conceptually indicates soil P pools and the relative efficiency of Colwell-P (0.5 M sodium bicarbonate) and BSES-P (0.005 M sulfuric acid) for extracting P from these pools. Reserve P comprises the calcium phosphate minerals and fertiliser reaction products. [33]

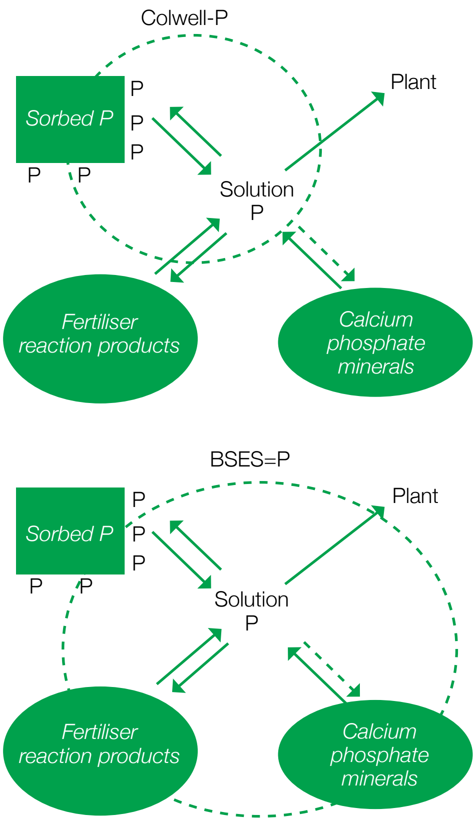

Figure 17: Conceptual diagram of P pools extracted by the Colwell-P method (upper panel), and the BSES-P method (lower panel).

5.11.5 Long fallow disorder

When fallow length exceeds 12 months due to crop rotation or drought, moderate to high rates of P fertiliser are often required to prevent long fallow disorder affecting the crop. A suggested rate is 10 kg P/ha. Wheat following canola may also benefit from higher P rates as canola is not a host of AM fungi.

5.11.6 Reduced tillage

Reduced tillage/no-tillage may accentuate the responsiveness of a soil to phosphate fertiliser due to the immobilisation of phosphate in the soil surface. Phosphorus is immobile in the soil, as unlike nitrate-N, it does not move in soil water. Phosphate

More information

GRDC Update Papers: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/02/The-value-of-phosphorus-in-crop-stubble

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/04/How-much-of-the-soil-P-is-available-for-plant-uptake

Deep phosphorus placement case study integrating research into Darling Downs farming

Improving fertilizer decisions for P on the Western Downs

Alternative phosphorus fertiliser trial

GRDC Fact Sheet: http://www.grdc.com.au/~/media/578CC7FEE649428D9C4C90B7461537D0.pdf

[33] P Moody, G Pu, M. Bell (2012) How much of the soil P is available for plant uptake? GRDC Update Papers 12 April 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/04/How-much-of-the-soil-P-is-available-for-plant-uptake

A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

fertilisers are most effective when applied at planting in direct contact with, or just below, the seed. Table 7 shows the actual rate of fertiliser product required to apply various rates of phosphorus as recommended in Table 6 above.

Table 7: Products used primarily to supply phosphorus

Product trade name	% P in product	Required rate of application of P (kg/ha)				
		4	6	8	10	15
MAP/Starterfos	22	18	27	36	45	68
DAP	20	20	30	40	50	75
CK700	8.2	49	73	98	122	183
Granulock ST-Z	20.5	20	24	39	49	73

5.11.7 Phosphorus budgeting

The traditional practice of banding P below or with the seed seeks to provide a rapid boost to root growth, promoting vigorous root systems that than can then set the plant up for a good season and great yields. How much P is required to achieve vigorous roots? To answer this question, we need to understand what is going on below the surface. How does a root system change the way that it grows in response to a high-concentration patch of P?

Figure 18 is an example of a wheat root responding to a band of P placed between the blue dots in a column about a foot long. The P was evenly distributed between the blue dots, in contrast to the second image, which is the root response to a granule of P placed in a similar depth in a similar pot.

These technologies allow researchers to answer questions about how root architecture changes in response to nutrition. Then the researchers can address the question of how much P is required to create an architecture that allows for extensive exploration of soil volume.

The aim is to find the lowest amount of P (and N) required to stimulate an efficient root system, which then frees the P resource to be spread more widely in the surface and subsoil where those newly foraging and stimulated roots are best placed to find and exploit it in moist soil. [34]

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2011/09/Cereals-seeking-phosphorus-How-much-to-spend-on-a-first-date

[34] C Guppy, R Flavel (2011) Cereals seeking phosphorus: How much to spend on a first date? GRDC Update Papers 6 Sept. 2011, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2011/09/Cereals-seeking-phosphorus-How-much-to-spend-on-a-first-date

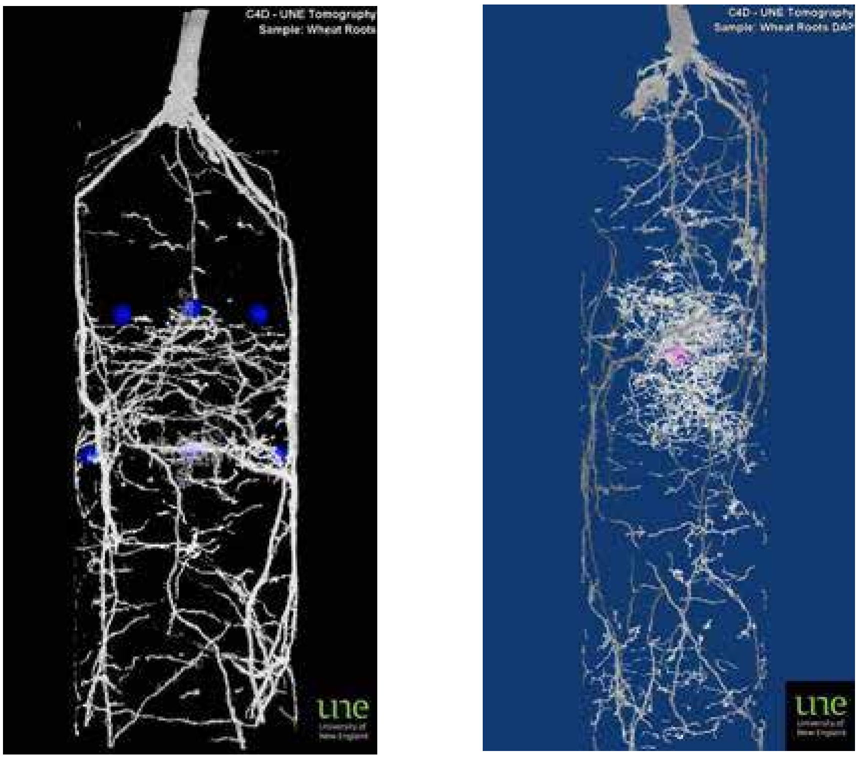

Figure 18: 3D Computer-aided tomographs of cereal root systems supplied with P in a diffuse band (black left panel) or in a granule (blue right panel) after 30 days of growth.

The economics of deep phosphorus use

Immobile nutrients like P need to be placed to meet both seedling and older crop demands, with root system distributions and soil moisture playing a key role in crop demand, yield response and fertiliser recovery.

Residual value of applied P for subsequent crops is generally good, and responses are recorded over multiple crop seasons. This holds the key to profitability of deep P applications, which can be made infrequently to cater for varying seasonal conditions and stubble loads.

Getting P nutrition right can improve productivity and profitability by improving system WUE and returns on other crop inputs (like N), but only if other nutrients are also adequate.

Researchers have examined the responses to P in cropping systems, primarily focusing on deep placement to address infertile subsoils. They have looked at the costs and returns using simulated crop yields (to explore seasonal variability) in combination with trial data from sites in northern NSW and Queensland grain growing areas. The key findings suggest deep P applications are most profitable when the combination of climate and soil characteristics allows higher potential yields. [35]

More information

GRDC Update Paper: http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Changing-nutrient-management-strategies-in-response-to-declining-background-fertility

http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Economics-and-management-of-P-nutrition-and-multiple-nutrient-decline

A calculator to assess the economics of deep placement P over time

35 GRDC (2014), The economics of deep phosphorus use. http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/03/Changing-nutrient-management-strategies-in-response-to-declining-background-fertility

5.11.8 Forms of P

Adequate P is not only an essential component of profitable and sustainable crop production but is also an increasing component of crop gross margins. In recent years, the price of phosphatic fertilisers has increased, leading to interest in ways to improve P-fertiliser use efficiency.

There has been a considerable increase in the use of liquid fertilisers, especially for the supply of N for crop production. Several products are available from a range of suppliers for use as starter fertiliser to provide P and micronutrients. Research in South Australia on highly calcareous soils (20–90% CaCO3) has shown possible benefits in using liquid fertilisers over the traditional granular forms. [36]

Soils in northern NSW have CaCO3 concentrations much less than those found in the calcareous soils of South Australia. Researchers reported on dry matter responses to liquid and granular P fertilisers from soils collected from around Australia. Six soils from the northern grains region were studied with CaCO3 levels ranging from undetectable to 1.3%. Five of these soils had positive dry matter responses to liquids, i.e. greater than when granular products were used.

One of the key conclusions was that grain yield responses to liquid P need to be assessed under field conditions. The aim of these trials was to see whether there is any benefit in using liquid instead of solid P, and to see whether the volume of water used to apply liquid P has an influence on yield by increasing the volume of soil in which the P is distributed at higher volumes of water. Because most P is applied as starter fertiliser containing Zn, treatments plus and minus zinc were also included.

More information

NSW DPI Trial Results 2012: http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0019/430291/Northern-grains-region-trial-results-autumn-2012.pdf

Grain yield responses to fertiliser P were not as clear as was expected from this site. The wet seasonal conditions may have influenced the P response due to increased root growth resulting in a greater capacity of the crop to utilise existing soil P reserves.

There was no difference between the types of fertiliser used with respect to plant growth or grain yield. When deciding whether to use liquid P fertilisers, the additional cost of equipment to use these fertilisers also needs to be taken into account. [37]

On most soils, although liquid P might initially increase dry matter production, it offers no agronomic advantage or yield increase over granular P. If in doubt about the usefulness of any new products, use test strips on-farm and assess economic (as well as agronomic) effectiveness before adopting, or refer to local trial data.

Manures

More information

GRDC Update Paper: https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2010/09/NUTRIENT-SUPPLY-BY-MANURES-IN-BROADACRE-CROPPING-SYSTEMS

Manure might seem cheaper by the tonne, but available nutrients are released very slowly (only 50% of P is available in the first year), so larger quantities are needed to supply enough nutrients for plants to use in the first year. In no-till systems, manures do not have a place because they need to be worked in.

When using manures, always ensure the manure being applied is analysed for available nutrients, because the nutrient content varies greatly depending on source and storage.

The cost of transporting and applying manure may be greater than of traditional fertiliser, so add it to budget comparisons. [38]

[36] B Manning, J Hunt, G McMullen (2012) Phosphorus fertiliser—Does product choice matter? NSW Department of Primary Industries, Northern grains region trial results autumn 2012, pp. 83–86, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0019/430291/Northern-grains-region-trial-results-autumn-2012.pdf

[37] B Manning, J Hunt, G McMullen (2012) Phosphorus fertiliser—Does product choice matter? NSW Department of Primary Industries, Northern grains region trial results autumn 2012, pp. 83–86, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0019/430291/Northern-grains-region-trial-results-autumn-2012.pdf

[38] GRDC (2009) Targeted nutrition at sowing. GRDC Fact Sheet, http://www.grdc.com.au/Resources/Bookshop/2010/10/~/media/27AA21276EE7425FA368BE48A95B5676.pdf

5.12 Sulfur

Because S forms a part of many proteins, S deficiency may depress protein formation and prevent nitrate being converted into protein. This may result in low protein grain with high total N content.

Sulfur responses are widespread on the eastern and southern Darling Downs, more so on the Anchorfield and Haselmere soil types, and in areas of the Jimbour plain. It is prevalent on basaltic black earth soils that have been intensively farmed for more than 20 years, particularly if they have been eroded, waterlogged or irrigated, and especially where double-cropping is practiced or fertilisers containing gypsum and/or S have not been used regularly.

5.12.1 Deficiency symptoms

- Young plants are pale green or yellow with only limited stunting.
- Upper leaves of mature plants are pale green to yellow, with the lower leaves remaining green (unlike N deficiency).
- Tiller production is not affected, although mature tillers will produce small heads.

In severe deficiencies, the upper leaves are yellow to white in colour with the lower leaves turning pale green. Tiller number will also be reduced.

Testing to 60 cm is suggested, with soil test levels <4 mg S/kg indicative of areas where it is necessary to undertake test strips of S application for growth responses. Consider applying ammonium sulfate into the soil at 75–100 kg/ha (15–24 kg S/ha) or broadcasting gypsum (calcium sulfate) at the rate of 500 kg/ha as test strips. [39]

5.12.2 In-crop nutritional levels for S

Evidence of S deficiency in crops following recent wetter seasons has prompted a request for updated information on S cycling in the northern grains region.

Key points to consider include:

- Sulfur deficiency is not yet widespread; however, a history of gypsum application can mask the problem.
- Crop residues are important in recycling S in cropping systems.
- Many soils in the northern region have free lime or gypsum at depth. Deep soil testing should be undertaken, as shallow testing may show up an incorrect reading of low soil S. Advisers and producers are encouraged to measure S to depth at least once every 5 years and in increments that will allow identification of gypsum layers containing subsoil reserves of S. Measurement at 0–10, 10–30, 30–60, 60–90 and 90–120 cm every 5 years, with more frequent monitoring of surface layers (particularly following flooding events), is advised.
- Wet conditions may have led to some leaching of S. Again, deep soil testing is important here.
- Appropriate soil testing strategies are important in future monitoring.

The S cycle has been well characterised for many years (Figure 19). The key processes in northern cropping soils are the reactions between soil solution sulfate and soil organic S, and solution sulfate and adsorbed sulfate, and loss of S by leaching. Two important processes not highlighted in Figure 19 are the movement of S from crop residues into the soil directly rather than through an animal, and the tendency for S to accumulate in the soil profile in the form of gypsum.

Most of the S that the crop acquires early in life is most likely derived from immediate release of S from crop residues that remain in the surface soil, and from mineralisation of S from organic matter over the fallow period. Sulfur behaves in a manner similar to

39 DAFF (2012) Wheat—nutrition, Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

N with respect to fallow build-up as an anion (sulfate and 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 to nitrate.

However, sulfate is not quite as readily leached as nitrate and can remain higher in the soil profile for longer periods. The reason for this is 2-fold. First, sulfate is slightly more reactive with the clay in the soil; second, as soils dry out, water that may have filled large pores and diluted the S to a soluble form susceptible to leaching retreats to smaller pores and the sulfate becomes more concentrated. As the concentration of sulfate increases, it reaches a critical stage where it begins to react with Ca in solution to form gypsum. Once in the form of gypsum it is not as susceptible to leaching and the movement of S down the profile stalls until conditions again become wet enough to dissolve the gypsum into its constituent parts. This is an extra step in the process and slows movement of S relative to movement of nitrate. One consequence of this is banded layers of gypsum in the subsoil, and the depths of these bands may be related to the frequency of periods of inundation.

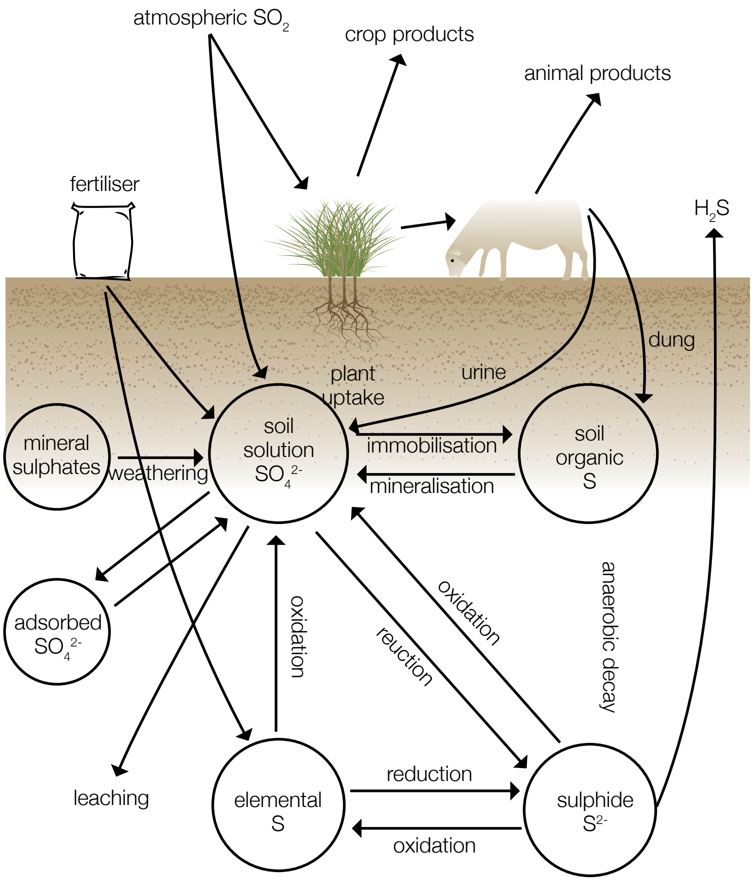

Figure 19: The sulfur cycle (McLaren and Cameron 1996).

If these bands are inadequate because there has been prolonged inundation that has moved sulfate beyond the reach of young root systems, then transient S deficiency may be observed.

5.12.3 Sulfur status of the northern grains region

Responses to S have been observed but are often confused with N responses. Shifting to no-tillage systems though, with less incorporation of residues (or even burning of stubble—a major loss mechanism previously), slowed the loss of S and increased the cycling of crop S through residue return. However, as S is predominantly found in organic matter, particularly in the surface soil, the long-term run-down in organic matter will ultimately result in widespread S deficiency. Unlike coastal areas, where >20 kg S/ha is received in rainfall, the northern grains region receives only 1–2 kg S/ha in rainfall. [40]

5.13 Potassium

Potassium is important in vegetative growth and is essential for a number of metabolic processes, yet its precise functions are poorly understood. It does enhance N uptake and can increase protein content. It can also help prevent lodging in cereals.

Due to the gradual decline in soil K levels with crop removal and historically low fertiliser application rates, some situations (particularly red soils) require K fertiliser applications. However, crops also vary in their response to improved soil K levels. Generally, winter cereal responses are low to moderate unless gross deficiencies occur.

Crops generally take up as much K as they do N, although this may not be reflected in crop removal. In particular, irrigated cotton, grain legumes and hay baling/silage can affect the K reserves in the heavier soil types.

Potassium fertiliser inputs in Australian cropping systems have generally been low relative to other nutrients, with Reuter *et al.* (1997) estimating that, nationally, Australia had a negative K balance, with that balance strongly negative in broadacre cropping regions. The negative K balances recorded for rainfed cropping systems in the Red Ferrosol (Isbell 1996) soils of the inland Burnett are consistent with the widespread evidence of declining and increasingly stratified soil K reserves, leading to K deficiency and yield losses.

5.13.1 Deficiency symptoms

- Young plants grow very slowly and are often stunted.
- In older plants, the lower leaves exhibit a marginal 'scorch', with yellow to brow margins towards the leaf tips.
- Potassium-deficient plants may also lodge more readily.

Potassium soil tests are reported as exchangeable K (meq/100 g or cmol/kg) or, in the case of a Colwell-K test, as mg/kg of available K. Research is under way to better define critical soil-test K levels, but in the interim, exchangeable K <0.3–0.4 cmol/kg or 130–160 mg/kg of Colwell-P would be considered low–marginal, and test strips worth a try.

Remember that, like P, K is effectively immobile in the soil, so profiles are tending to stratify (much higher levels in the top 10 cm, with significant depletion in the 10–30 cm layer). Testing for soil K in both the 0–10 and 10–30 cm layers is advisable, with the deeper K essential when the topsoil is dry.

Potassium fertilisers can be side-banded at planting, drilled in pre-plant, or broadcast and cultivated in fallow or even prior to preceding crop. The residual value of K fertiliser is excellent, so sporadic applications at higher rates can be an effective alternative to lower rates with each crop. However, K banded in the seed row can affect germination. Use the safe rates of the nitrogen table as an application guide.

Once K fertility of the surface layers has been restored, deep application is the best way to apply K fertilisers to maintain soil productivity. A proportion of the deep K taken up by the crop is returned to the soil surface in the litter and crop stubble, which replenishes the K fertility of these layers.

Although soil K reserves are greatest in the heavier alluvial and cracking clay soils, it is important to maintain adequate K soil levels by replacing that removed in harvested

[40] C Guppy (2013) Sulphur in northern Vertosols. GRDC Update Papers 5 March 2013, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Sulphur-in-northern-Vertosols

product as often as possible. Once soil K levels have been depleted in these soils, very heavy fertiliser K applications are required and this becomes prohibitively expensive. [41]

Field studies have examined crop yield–soil test K relationships for a Ferrosol, and glasshouse studies have been used to determine patterns of K accumulation in Ferrosols with different K status.

Crops varied markedly in critical soil-test K for grain yield, but there was no significant response to K placement in either grain or cotton-seed yield. Patterns of K accumulation differed between crop species. Although all crops exhibited faster relative accumulation of K than of biomass, relative K accumulation rates in maize were much greater than in wheat or sorghum. This was related to the more indeterminate growth habit of the last two species resulting from addition of tillers compared with maize. Delayed access to surface-applied K until flowering in all species resulted in significant late-crop K uptake but no significant biomass or grain yield responses, even under conditions of severe K deficiency. [42]

5.14 Micronutrient deficiencies

Micronutrient deficiencies can be difficult to diagnose and treat. However, by knowing your soil type, considering crop requirements and the season, and supporting this knowledge with diagnostic tools and strategies, effective management is possible.

Key points:

- Micronutrient deficiencies are best determined by looking at the overall situation: region, soil type, season, crop and past fertiliser management.
- Soil type is useful in determining the risk of micronutrient deficiencies.
- Soil testing can be a useful indicator.
- Tissue testing is an accurate way to diagnose a suspected micronutrient deficiency.
- When tissue testing, sample the appropriate tissues at the right time. Plant nutrient status varies according to plant age, variety and weather conditions.
- The difference between deficient and adequate (or toxic) levels of some micronutrients can be very small.
- When applying fertiliser to treat a suspected deficiency, leave a strip untreated. Either a visual response or tissue testing can allow you to confirm whether the micronutrient was limiting. [43]

More information

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/02/Trace-Elements-Importance

41 DAFF (2102) Wheat—nutrition, Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

42 RF Brennan, MJ Bell (2013) Soil potassium–crop response calibration relationships and criteria for field crops grown in Australia. *Crop and Pasture Science* 64, 514–522.

43 GRDC (2013) Crop nutrition. Micronutrient and trace elements. GRDC Fact Sheet Nov. 2013, http://www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

5.14.1 Zinc

- Zinc is essential for protein shape and consequently important for enzyme function in many different tissues.
- Deficiency symptoms appear as oily grey- green patches in the centre of leaves. Young leaves are most affected.
- Deficiency is typically associated with alkaline soils over a wide range of textures. Lime and gypsum can reduce Zn availability.
- Critical tissue concentrations in the youngest expanded blade of wheat are 8–10 mg/kg but the response curve is very steep.

Zinc supplements can be applied with fertiliser as zinc oxide, chelated Zn or zinc sulfate. The last two products are soluble and can be used for foliar applications. Product efficacy varies with the time and placement of application.

5.14.2 Copper

Copper is essential for chlorophyll formation and pollen production as well as baking quality. Wheat and barley are more responsive to copper than are lucerne and canola.

Deficiency is common in organic soils and sandy soils that are low in organic matter, as well as where there is high Fe, Mn or Al in the soil. Critical tissue levels have been reported as <1.5 mg/kg at the youngest expanded blade in wheat (Brennan *et al.* 1986). [44]

Copper deficiency occurs in a narrow band stretching from Taroom to Wyaga in the Goondiwindi district, and in a belt of scattered ironbark country stretching from Cecil Plains through to Inglewood and in parts of central-west NSW.

Soils are generally brigalow/belah grey or grey-brown clays adjacent to ridges where the natural vegetation is ironbark, molly box and wattles, i.e. light soils or those prone to leaching. It can also occur in some alkaline soils. Plant tissue testing is most likely the best indicator of Cu adequacy in plants.

Deficiency symptoms in wheat include:

- wilting despite ample water supply
- leaf tip dieback of youngest leaves with leaves becoming tightly twisted
- ear tip dieback, where the top of the head turns white or yellow (the remainder of the head stays green, but may not set grain)
- white heads and delayed maturity, and melanism (blackening) of stems
- ear branching
- upper node tillering

Copper can be applied as an additive to fertilisers, or as foliar spray as copper sulfate, copper oxychloride or chelated Cu. It also has a fungicidal effect

Copper sulfate applied to the soil at 10–20 kg/ha prior to or at planting will last a number of years. One foliar spraying at booting may still be necessary in dry years.

Alternatively, apply two foliar sprays of 1% copper sulfate/ha (1 kg copper sulfate to 100 L water/ha). Apply the first spray 3–5 weeks post-emergence, and the second spray any time from when the ear begins to swell the stem of the plant to when the plant is in the boot stage. Foliar sprays have little residual value and must be applied every year. [45]

[44] R Norton, J Laycock, C Walker (2012) Trace elements—importance. GRDC Update Papers 14 Feb. 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/02/Trace-Elements-Importance

[45] DAFF (2012) Wheat—nutrition, Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

5.14.3 Boron

- Boron is essential for germination and sugar metabolism.
- Lucerne is more susceptible to deficiency than canola and wheat is less susceptible than canola.
- Symptoms of deficiency include stem splitting and poor seed-set.
- Liming can induce boron deficiency.
- Critical tissue levels are <2 mg/kg in the youngest mature leaf blade at mid-late tillering. Leaching can reduce tissue levels.
- Boron sources are borax, boric acid, Solubor®, ulexite, sodium pentaborate.
- Even application is critical.

5.14.4 Iron

- Iron is an essential component of chlorophyll and in respiratory enzymes.
- Legumes are more responsive to iron than are cereals.
- Chlorosis of the youngest part of the plant is the most common symptom of deficiency.
- Deficiency is worst in high pH and low organic matter soils, especially if there is a lot of free bicarbonate (soil or irrigation water origin).
- Soil analysis is not able to provide critical values, and tissue samples can be easily contaminated with iron from soil. Levels of 70 mg/kg or more in tissue seem adequate.
- Foliar sprays are useful as iron sulfate or side dressings with iron chelates.

5.14.5 Manganese

- Manganese is a common enzyme cofactor for chlorophyll and photosynthesis.
- Deficiency symptoms are often preceded by wilting and then chlorosis of younger leaves, often at the base of the leaf.
- Deficiency is mainly a problem on high organic matter soils, and those with free lime present. It may be toxic at low pH (<5).
- For cereals, tissue concentrations of <12 mg Mn/kg in the youngest mature leaf are considered deficient.
- Foliar Mn can be more efficient than soil-applied Mn, as the latter can result in iron or phosphate precipitates. Chelated formulations are also available.

5.14.6 Molybdenum

- Molybdenum is important for nitrate reductase activity in all plants.
- Deficiency symptoms are similar to N deficiency.
- Availability increases with high soil pH, and deficiencies are common on acid soils especially in high rainfall areas.
- Tissue levels of 0.28–0.55 mg Mo/kg in youngest mature leaf are adequate for canola, and <0.1 mg/kg mid–late tillering in wheat is considered deficient.
- Very small quantities (50 g/ha) applied with fertiliser are usually sufficient, usually in the form of molybdenum trioxide. Sodium or ammonium molybdate can be used as sprays. [46]

46 R Norton, J Laycock, C Walker (2012) Trace elements—importance. GRDC Update Papers 14 Feb. 2012, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/02/Trace-Elements-Importance

More information

Soil Analysis Services And Fertcare National Stewardship Program: http://agronomycommunity.incitecpivotfertilisers.com.au/~/media/Files/IPL%20pdfs/Crop%20Soil%20Sampling%20Procedure1.ashx

http://www.backpaddock.com.au

http://www.afsa.net.au/index.php?action=content&page=11

http://www.aspac-australasia.com

5.15 Soil testing

Soil testing and professional interpretation of results should now be an integral part of all management strategies. Soil tests estimate the amount of each nutrient available to the plant rather than the total amount in the soil. Valuable information obtainable from a soil test includes current nutrient status, acidity or alkalinity (pH), soil salinity (electrical conductivity, EC), and sodicity (exchangeable sodium percentage. ESP), which can affect soil structure.

Soil test information should not be used alone to determine nutrient requirements. It should be used in conjunction with test strip results, and previous crop performance to determine nutrients removed by that crop, and previous soil test records, to obtain as much information as possible about the nutrient status of a particular paddock.

Soils must sampled to the correct depth. Sampling depths of 0–10 and 10–30 cm should be used for all nutrients. Additionally, a 30–60 cm sample is required for S, and 30–60, 60–90 and 90–120 cm samples (or to the bottom of the soil's effective rooting depth) are needed for N, pH, EC and chloride.

Care must be taken when interpreting soil test results, as nutrients can become stranded in the dry surface layer of the soil after many years of no-till or reduced tillage, or deep nutrient reserves may be unavailable due to other soil factors, such as EC levels, sodicity or acidity.[47]

5.15.1 Test strips

Test strips allow you to fine-tune the fertiliser program. To gain the maximum benefit:

- Run them over a number of years, as results from any single year can be misleading.
- Obtain accurate strip weights.
- Protein-test a sample of grain from each strip.
- Harvest strips before your main harvest, as the difference between the strips is more important than the moisture content.

When setting up a test strip area:

- Ensure that you can accurately locate the strips—a GPS reading would be valuable.
- Repeat each fertiliser treatment two or three times.
- Change only one product rate at a time.
- Separate each strip of fertiliser by a control or nil-fertiliser strip.
- Ensure the tests are done over a part of the paddock with a uniform soil type.
- Keep clear of shade lines, trees, fences, headlands and any known anomalies in the field.
- Ensure that the test strip area is ~100 m long, with each strip 1–2 header widths.

More information

www.nga.org.au

www.grainorana.com.au

A number of local Grower Solutions Groups, such as the NGA and Grain Orana Alliance (GOA), as well as NSW DPI and DAFF conduct nutrition trials in most years.

Colour photographs of nutrient deficiencies can be found in: Grundon NJ (1987) 'Hungry crops: a guide to nutrient deficiencies in field crops', Department of Primary Industries, Queensland Government, Information series Q187002. [48]

47 DAFF (2010) Nutrition management—Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

48 DAFF (2010) Nutrition management—Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

5.15.2 Rules of thumb

1. Choose the same soil test package each year (including methods), otherwise comparisons between years will be useless. For example, do not use Colwell-P for P one year, then DGT-P the next, the two tests measure different forms of available P in the soil.
2. If you do not use a standard approach to sampling, a comparison of the data between different tests will not be reliable. Aim for data that have the best chance of representing the whole paddock, and mix the sample thoroughly.

For monitoring, sampling needs to cover roughly the same area each time to ensure meaningful comparisons between years. Permanent markers on fence posts to mark a sampling transect, or a handheld GPS or your smartphone, will serve this purpose.

Soil-testing laboratories should be able to provide information on appropriate soil sampling and sample-handling protocols for specific industries and crop types. Refer to the 'Australian Soil Fertility Manual' at www.publish.csiro.au/pid/5338.htm or for more information, download the GRDC Fact Sheet 'Better fertiliser decisions for crop nutrition' at http://www.grdc.com.au/GRDC-FS-BFDCN. [49]

More information

http://www.aspac-australasia.com

Utilise an ASPAC- and NATA-accredited testing service. The results are more likely to be statistically significant and have reduced variation between tests.

5.15.3 Soil testing for N

The approximate amount of N available in the soil can be determined by soil testing. Soil tests should be taken at various places in each paddock to a depth of at least 60 cm, but preferably 90 or 120 cm. Primary wheat roots grow to a depth of 2 m ([50]) and can extract N from this level. Test results are an indication only, so historical grain yield and protein levels from the paddock should also be used to determine N requirements. [51] Environmental conditions, including temperature, time and rainfall events can affect starting soil N; therefore, it is important to test later in the summer fallow or make adjustments to factor in mineralisation amounts as well as denitrification and leaching events.

More information

GRDC Update Paper: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2011/03/Nitrogen-uptake-pathways-and-implications-for-foliar-and-solid-fertiliser

http://www.dpi.nsw.gov.au/agriculture/resources/soils/improvement/n-acidify

Forms of N fertiliser

There are four main forms in which N is available:

1. Nitrate, e.g. ammonium nitrate, sodium nitrate, potassium nitrate
2. Ammonium, e.g. anhydrous ammonia, sulfate of ammonia, ammonium nitrate
3. Amide, e.g. urea
4. Organic, e.g. blood and bone, meat meal

It is important to choose the right product, as the differing compositions are more suited to certain conditions than others.

Calculating N fertiliser application

If N fertiliser is required, the calculation below can be used to obtain the quantity of fertiliser required. For example, if 40 kg N/ha is required, this rate of N can be supplied by applying 87 kg/ha of urea (46% N) (Table 8).

49 GRDC (2013) Better fertiliser decisions for crop nutrition. GRDC Fact Sheet Nov. 2013, http://www.grdc.com.au/GRDC-FS-BFDCN

50 NSW DPI Agronomists (2007) Wheat growth and development. PROCROP Series, NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/449367/Procrop-wheat-growth-and-development.pdf

51 DAFF (2010) Nutrition management—Overview. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/nutrition-management/overview

Fertiliser product required (kg/ha) = rate of N required kg N/ha x 100/% N in fertiliser product. [52]

Table 8: Nitrogen fertilisers commonly used in broad-scale farming

Fertiliser	% N	% P	% S
Urea	46		
Ammonium sulfate	21		24
Calcium ammonium nitrate	27		
Di-ammonium phosphate	17.5–18.0	20	
CSBP Agras No. 1®	17.5	7.6	17
CSBP Agyield®	17.5	17.5	4.5
CSBP Agrich®	12.0	11.4	12
CSBP Agstar®	15.5	12.8	11
Summit Easycrop 2®	31	9	4
Summit Canola 2®	33		12
Summit Topyield 3®	27.3	11.5	5
Summit Cereal®	18.5	11.0	14.4
Summit Canola 1 ®	18.5	11.0	14.4
Summit Coprich ®	18	14	11.5
Summit Sustain®	10.8	12	1
Summit Cropyield®	17.1	19.6	3.5
Summit DAPSZC®	17.1	18.3	8

(Source: DAFWA.)

'NBudget' calculator

'NBudget' is an Excel-based calculator for estimating the fertiliser N requirements of cereal and oilseed crops and N_2 fixation by legumes. It contains rule-of-thumb values for soil nitrate based on paddock fertility status and recent paddock history with linked equations for calculating soil nitrate following crop growth and post-crop fallow.

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

Input data to develop NBudget were sourced from published and unpublished experiments conducted principally by the farming systems and plant (N) nutrition programs of the NSW and Queensland agricultural agencies during the past 30 years. The data required to run NBudget include: location and description of the paddock as very low, low–medium, medium, or high fertility; tillage practice; yield and protein level (for cereals) of the previous crop; fertiliser N applied to previous crop; simple assessment of crown rot risk for the winter cereals; and fallow rainfall or depth of wet soil.

For a detailed guide to use of NBudget and N management, download Dr David Herridge's publication, 'Managing legume and fertiliser N for northern grains cropping': http://www.grdc.com.au/GRDC-Booklet-Managing-Fertiliser-N. [53]

52 DAFF (2012) Wheat—nutrition, Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

53 D Herridge (2011) Managing legume and fertiliser N for northern grains cropping. Updated May 2013. GRDC, http://www.grdc.com.au/~/media/6E5659619C7C4063AB3C8E58A4DE39E7.pdf

A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

5.15.4 Soil testing for P

Colwell-P

The Colwell-P test uses a bicarbonate (alkaline) extraction process to assess the level of readily available soil P. It was the original test for P response in wheat in northern NSW. It is used with the P buffering index (PBI) to indicate the sufficiency and accessibility of P in the soil.

BSES-P

The BSES-P test was developed for the sugar industry and is now an important tool in the grains industry. BSES-P uses a dilute acid extraction to assess the size of slow-release soil P reserves. These reserves do not provide enough P within a season to meet yield requirements, but they partially replenish plant-available P.

Because the P measured by BSES-P releases only slowly, changes in the test value of subsoil layers may take years. Therefore, this test needs to be done only every 4–6 years, and is most important in the subsoil layers.

Phosphorus buffering index

The 'buffering capacity' of a soil refers to its ability to maintain P concentration in solution as the plant roots absorb the P. The PBI indicates the availability of soil P. The higher the value, the more difficult it is for a plant to access P from the soil solution. Generally, a PBI value <300 (a range that would include most northern Vertosols) indicates that soil P, as assessed by Colwell-P, is readily available.

Colwell-P and PBI values are needed in both 0–10 and 10–30 cm soil tests.

BSES-P is optional in the 0–10 cm layer but essential in the 10–30 cm layer. [55]

Traditionally when testing to determine crop P requirement, a soil sample from 0–10 or 0–15 cm was taken and analysed for Colwell-P and PBI. According to recent work into depletion and stratification of P, as well as the existence (or otherwise) of additional slow-release P reserves that can be detected using the BSES-P test, Colwell-P alone is unlikely to provide all of the information to make an informed decision. Of particular note is the lack of correlation between the two soil P tests, with this most obvious in samples from below 10 cm.

Although data are still being collected on the rates at which these BSES-P reserves can become available to plants (i.e. over days, weeks or long fallows), current observations suggest that subsoils with quite low BSES-P levels (i.e. <25–30 mg/kg) are still able to

More information

GRDC Fact Sheet: http://www.grdc.com.au/GRDC-FS-PhosphorusManagement

54 DAFF (2012) Wheat—nutrition. Department of Agriculture, Fisheries and Forestry Queensland, http://www.daff.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/wheat/nutrition

55 GRDC (2012) Crop nutrition. Northern region—phosphorus management. GRDC Fact Sheet Nov. 2012, http://www.grdc.com.au/~/media/578CC7FEE649428D9C4C90B7461537D0.pdf

meet the demands of a well-developed root system (i.e. a trickle of P from many roots accessing a large soil volume).

However, there are many subsoils across the region where soil P (both Colwell and BSES) is low. For example, grain P data from wheat, barley and sorghum collected across the region in the GRDC-funded project 'Toward *a Better P Nutrition Package: Diagnosing P Status and Application Strategies to Improve Fertiliser*' (DAQ00084) suggest that 20–25% of all crops were marginal–low in P, while the proportion of marginal–low-P chickpea crops was much higher. Early results suggest that some significant yield gains may be possible on these soils. [56]

5.16 Plant and/or tissue testing for nutrition levels

Tissue testing is the best way to accurately diagnose nutrient deficiencies when a crop is growing, whether this is the macronutrients, or micronutrients such as Zn and Cu (Figure 20).

The successful use of plant tissue analysis depends on sampling the correct plant part, at the appropriate growth stage as demonstrated by Dang (1992; fig. 6 therein) for Zn. Similarly, the critical tissue P concentration changes with the age of wheat plants.

For these reasons, critical tissue concentrations should be associated specifically with defined stages of plant growth or plant part rather than growth periods (i.e. days from sowing). Growers are advised to follow laboratory guides or instructions for sample collection.

Plant nutrient status varies according to plant age, variety and weather conditions. The difference between deficient and adequate (or toxic) levels of some micronutrients can be very small.

When applying fertiliser to treat a suspected deficiency, leave a strip untreated. Either a visual response (where a 20% yield difference cannot be seen) or plot harvesting of the strips can allow you to confirm whether the micronutrient was limiting. [57]

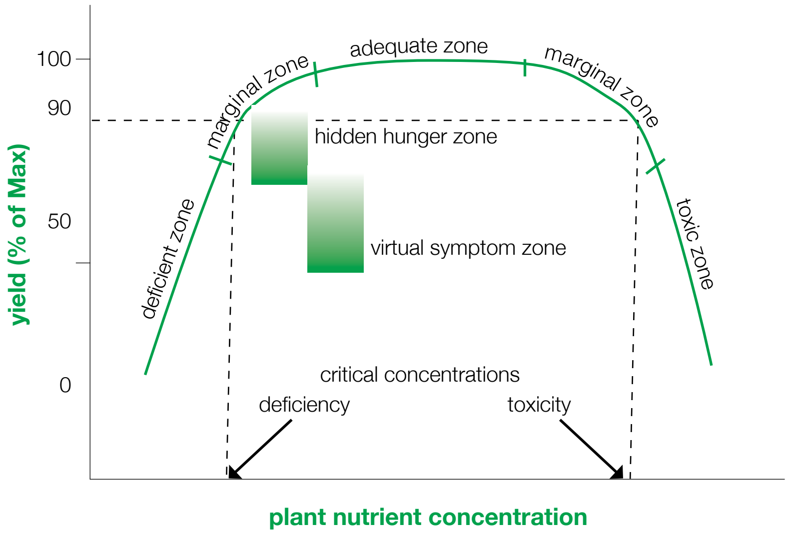

Figure 20: Generalised grain yield response curve.

More information

GRDC Update Papers: http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2010/09/NEW-WAYS-TO-ESTIMATE-CROP-NEEDS-AND-DELIVER-P-TO-IMPROVE-THE-RETURN-ON-FERTILISER-INVESTMENT

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2010/05/Toward-a-Better-P-Nutrition-Package-Diagnosing-P-Status-and-Application-Strategies-to-Improve-Fertiliser-Response

http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/03/Nutritional-interactions-of-N-P-K-and-S-on-the-Darling-Downs

More information

GRDC Podcast: http://www.grdc.com.au/Media-Centre/GRDC-Podcasts/Northern-Weekly-Update/2013/11/21-north

More information

GRDC Podcast: http://www.grdc.com.au/Media-Centre/GRDC-Podcasts/Driving-Agronomy-Podcasts/2010/06/Plant-Tissue-Testing-uncovering-hidden-hunger

56 M Bell, D Lester, P Moody, C Guppy (2010) New ways to estimate crop needs and deliver P to improve the return on fertiliser investment. GRDC Update Papers 17 Sept. 2010, http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2010/09/NEW-WAYS-TO-ESTIMATE-CROP-NEEDS-AND-DELIVER-P-TO-IMPROVE-THE-RETURN-ON-FERTILISER-INVESTMENT

57 GRDC (2013) Crop nutrition—micronutrients. GRDC Fact Sheet Nov. 2013, http://www.grdc.com.au/GRDC-FS-CropNutrition-Micronutrients

5.17 Nutrition effects on following crop

In consultation with regional agronomists and crop consultants, typical five-crop rotation sequences were developed for each of the regional production environments in the northern grains region. The accumulated deficits or surpluses of N, P and K over this crop sequence (the period will depend on rainfall) are shown in Table 9 based on a summation of the individual deficits or surpluses from the crops in the database. While this approach has limitations (especially in regions where most of the crops monitored were drought-affected), it serves to highlight the extent of nutrient depletion that is occurring, not only in risky dryland environments such as the Central Highlands, but also in more reliable, generally higher input systems such as the Eastern Downs and Liverpool Plains. If this depletion continues unchecked, there will be long-term consequences for the sustainability of the soils supporting the northern grains farming systems.

Table 9: Typical rotation sequences in the various production regions and the surpluses or deficits of nitrogen, phosphorus and potassium (kg/ha) over this sequence of five crops Chickpeas assumed to have net N balance of zero (addition = removal)

Region	Crop sequence (5 crops)	N : P : K (kg/ha)
Central Highlands	Sorghum, sorghum, sorghum, wheat, wheat or Sorghum, sorghum, wheat, chickpea, wheat	–262, –3, –41 –202, 1, –47
Dawson Callide	Chickpea, sorghum, wheat, mungbean, wheat	–59, –14, –63
Eastern Downs	Sorghum, sorghum, short fallow, wheat, long fallow, sorghum, sorghum	–245, –48, –91
Goondiwindi-Moonie	Wheat, chickpea, wheat, long fallow, sorghum, sorghum	–115, –5, –61
Liverpool Plains	Wheat, barley, long fallow, sorghum, sorghum, sorghum	–116, –62, –109
Moree-Narrabri[A]	Wheat, fallow, sorghum, wheat, fallow, sorghum, wheat or Wheat, fallow, sorghum, wheat, chickpeas, fallow, sorghum	–60, 7, –34 –40, 10, –23
NorthStar	Wheat, chickpea, wheat, long fallow, sorghum, sorghum or Barley, Chickpea, Wheat, long fallow, sorghum	–115, –5, –61 33, 5,: –6
South Burnett	Peanut, maize, peanut, sorghum, wheat	Insufficient info.
Western Downs	Wheat, wheat, wheat, sorghum, sorghum	–74, –8, –20

[A]Durum wheat is typically grown in Moree–Narrabri crop sequences, but wheat was substituted in these calculations due to no available nutrient removal data for durum wheat.

In order to put a current costing on the depletion of these soil reserves, or alternatively a nutrient replacement cost of meeting these deficits with fertilisers, calculations were made using fertiliser prices in November 2008 to manage macronutrients only (i.e. N, P, K and S). In these calculations (done on the basis of individual crops) it was assumed that where P deficits occurred, that deficit would be met by applying additional mono-ammonium phosphate. This would obviously also supply some N, which would reduce the cost of any additional N inputs (costed as urea). In a similar fashion, S deficits were costed based on applying sulfate of potash fertiliser, with the K applied in this product reducing the amount of K that needed to be applied as muriate of potash (KCl). The cost of each nutrient at that time was as follows: P as MAP (AU$8.80/kg), N as urea ($2.92/kg), S as SOP ($11.12/kg) and K as MOP ($2.55/kg). Where a surplus of nutrient had occurred (e.g. in the case of P in some crops), a credit was generated equivalent to the amount of that nutrient in order to reduce the cost of overall nutrient decline. Data are shown in Figure 21.

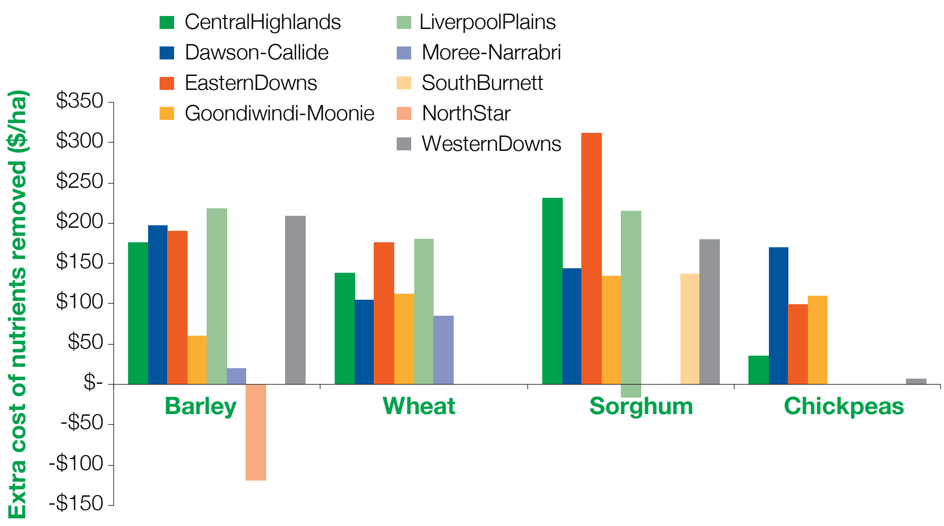

Figure 21: Estimated AU$ value of fertiliser needed to replace nutrients exported from soils across the northern grains region in the study period.

Results clearly show the significant cost of nutrient depletion that will need to be met by future grain-producing systems. The average additional cost per ha of replacing these nutrients was $106/ha for barley, $89/ha for wheat, $153/ha for sorghum and $47 for chickpea, with these costs often doubled in the higher production regions. The anomaly for barley in the North Star area (and probably the low deficits for Moree–Narrabri and Goondiwindi–Moonie in some cases) will be addressed by addition of better production years to the database. If growers are to meet an increasing number of these costs, there will be a clear need to see some combination of higher grain prices, lower fertiliser prices and very efficient nutrient application strategies for these farming systems to continue to be viable and sustainable. [58]

58 M Bell Soil characteristics and nutrient budgeting in northern grains region