NUTRI*pak*

A practical guide to cotton nutrition

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NUTRIpak: A practical guide to cotton nutrition

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The 2018 edition of NUTRIpak is based on a previous version, created by the Australian Cotton Cooperative Research Centre, with support from CRDC, in 2001.

NUTRIpak

A practical guide to cotton nutrition

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RUTH REDFERN

Foreword

Welcome to NUTRIpak – a key manual for the Australian cotton industry designed to provide growers and consultants with the latest science in the field of cotton nutrition.

Much has changed since the previous edition of NUTRIpak was published in 2001, when 10 bales per hectare was generally considered the upper limit on yield. Farm averages of 15 bales, and field averages of over 16 bales, per hectare are now being achieved. This new version of NUTRIpak takes into account the higher average yields now being achieved by Australian cotton growers, and the corresponding increases in plant nutritional requirements and nutrient exports.

It reflects the significant nutrition research and development that the Cotton Research & Development Corporation (CRDC) continues to support, particularly in the areas of nitrogen and phosphorous management. While the nitrogen cycle is complex, and nitrogen-use efficiency is affected by a diverse range of factors, we now have a better understanding of the uptake by the cotton crop of nitrogen, including the importance of soil mineralisation and of the interactions between nitrogen management and irrigation management. As a result, a new section has been added focused on soil organic matter, and there is specific information on managing the risk of denitrification in irrigated cotton.

Much has been learned about phosphorous management, and the previous advice that phosphorous should be banded has been revised in light of new research that suggests that cotton roots are not very good at exploiting banded applications of phosphorous. Rather, the updated advice is to treat the largest volume of soil as possible to maximise the fertiliser that can be intercepted by plant roots.

Good and efficient management of soil fertility and fertilisers remains a vitally important area of research, development and extension (RD&E) for cotton growers and for CRDC.

This edition of NUTRIpak is brought to you by the organisations responsible for cotton industry RD&E: CRDC, and the industry's joint extension program, CottonInfo. We trust that you will find NUTRIpak a valuable and informative reference, and we thank the team of authors, reviewers and contributors from across the cotton research community for their assistance with this publication.

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Introduction

NUTRIpak is a cotton nutrition manual produced to inform the cotton industry about the importance of crop nutrient management and soil health. It has been developed to help advisers and growers identify crop nutritional problems and develop management plans to meet crop demand and long-term sustainability.

NUTRIpak is a distillation of research material relating to the nutrition of cotton in Australia. It is complementary to SOILpak, MACHINEpak and the Symptoms Guide. Issues that are covered in greater detail by these publications are noted within NUTRIpak.

The aim of this manual is to:

- explain the role of each nutrient in cotton nutrition
- examine the nutrient requirements of the cotton crop
- provide an understanding of the processes that affect nutrient availability in the soil and uptake by the plant
- indicate the amounts of each nutrient removed in seed cotton
- describe soil and plant testing procedures that can identify where nutritional deficiencies or imbalances may occur
- provide a means of interpreting the chemical analyses of soil and plant material by indicating the critical levels for each nutrient
- suggest remedial action to alleviate nutritional disorders with appropriate fertilisers. Options for fertiliser management (timing, placement, rates) are given.

It is important for growers to realise that most of the nutrients taken up by cotton from the soil are derived from the soluble and sparingly soluble minerals, decomposition of previous crop residues, soil mineralogy, fertiliser residues, and soil organic matter. Nutrients are being continually cycled between the crop and soil, as occurs in all biological systems. However, because of the high rates of nutrient removal in seed cotton, our natively fertile cotton-growing soils are gradually becoming depleted of nutrients.

Because the removal of nutrients without replacement at an equivalent rate depletes soil fertility, the application of nutrients from off-farm sources is needed to increase the supply of these nutrients to subsequent cotton crops. Farmers can replace these nutrients as they are removed, or wait until they reach a predetermined soil test level to begin replacement, or wait until each nutrient successively becomes limiting to cotton production, then start a fertiliser program to overcome nutrient deficiency. Therefore, it is important to assess nutrient status of the soil and plants from time to time to assess potential for yield limitation. Often, nutrient deficiencies are not identified until well after first symptoms appear, by which time some yield reduction may have already occurred, and remedial fertiliser application may not recover full yield potential.

Inappropriate or excessive use of fertilisers can affect profitability through higher fertiliser costs, excessive vegetative growth of crops and related insect, disease and harvest problems, and the environment via contamination of water and atmospheric greenhouse gas loading.

Soils used for cotton production in Australia

The soils on which cotton is grown in Australia are inherently fertile relative to the majority of rangeland soils used for grazing. They are dominated by cracking clays (vertosols), which are naturally fertile, alkaline, with high clay content (>35%) and, initially, where the soils that supported brigalow/belah vegetation associations with relatively high organic matter content. These soils were formed from fertile alluvium and wind-blown dust under conditions of relatively low rainfall.

Other cotton-growing soils include chromosols (in the Macquarie, Namoi, Gwydir, Lachlan and Murrumbidgee valleys), and in many of the Queensland districts, sodosols form a part of the soil spectrum. These soils supported natural vegetation of woodland and grassland. Before cotton cropping, the previous land use was generally grazing and dryland cereal cropping. Figure 1.1 shows an Atlas of Australian Soils with Australian Soil Classification mapping: http://www.asris.csiro.au/themes/Atlas.html#Atlas_Digital

Go to 'Download the Digital Atlas of Australian Soils'.

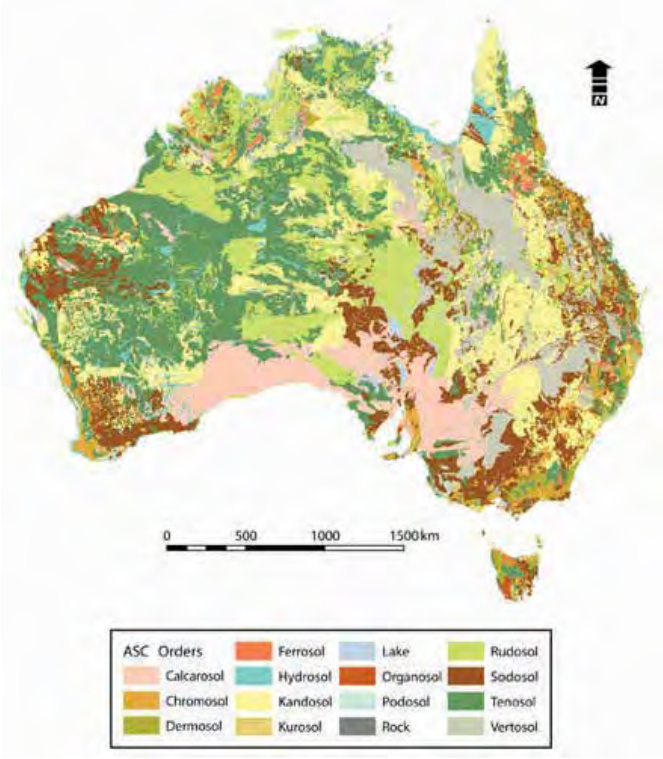

Figure 1.1: Atlas of Australian soils with Australian Soil Classification.

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BASIC COTTON NUTRITION

1. Essential plant nutrients

There are 18 basic elements that are essential for plant growth. They can be divided into non-mineral nutrients (carbon, hydrogen and oxygen) and mineral nutrients derived from the soil. Non-mineral nutrients are supplied from water (H_2O) and the atmosphere (carbon dioxide CO_2), and are the principal building blocks associated with photosynthesis.

Mineral elements can be divided into two groups: **major nutrients**, those needed in greatest quantities; and **micro-nutrients**, equally as important for normal plant growth but needed in only small or trace quantities (Table 1.1).

Table 1.1: Major nutrients and micro-nutrients taken up by plants. Source: Stewart (2010).

Major nutrients	Micro-nutrients
Nitrogen (N)	Boron (B)
Phosphorous (P)	Chloride (Cl)
Potassium (K)	Copper (Cu)
Calcium (Ca)	Iron (Fe)
Magnesium (Mg)	Manganese (Mn)
Sulphur (S)	Molybdenum (Mo)
	Zinc (Zn)
	Nickel (Ni)
	Cobalt (Co)


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2. Nutrient uptake by cotton

Throughout the growing season, nutrients are taken up by cotton plants in proportion with the demand of the increasing vegetative growth and boll load. This uptake is, in turn, regulated by the supply of nutrients from the soil (Rochester et al., 2012). Uptake and accumulation tends to follow the same pattern as growth and dry matter production, with the most rapid rate of increase occurring from flowering through boll fill, and slowing as the crop matures (Oosterhuis, 1990, Stewart, 2010) (Figure 1.2).

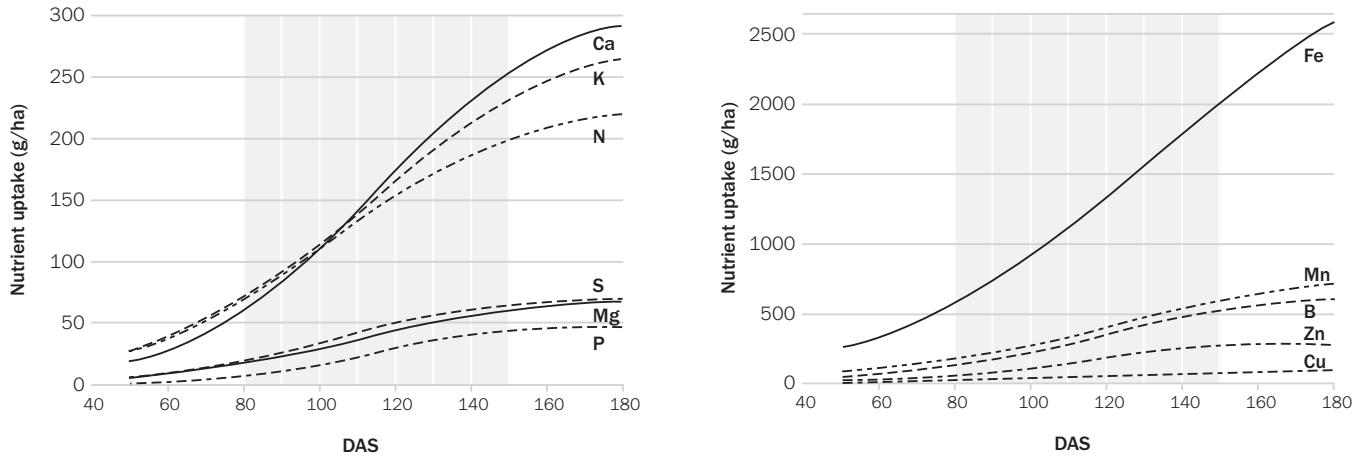

Figure 1.2: The pattern of nutrient uptake during the growth of an irrigated cotton crop that yielded 2250 kg lint/ha in Narrabri, Australia (DAS=Days After Sowing). Source: Cotton Australia (2017) Rochester et al., (2012).

Table 1.2: Maximum nutrient uptake, rates and timing uptake of nutrients in whole crop (kg for N, P, K, Ca, Mg and S; g for Fe, Zn, B, Cu and Mn). Source: Rochester et al. (2012).

	Maximum uptake (per ha)	Maximum uptake rate (per day)	Time of maximum uptake (days from sowing)	Percentage taken up during flowering
Nitrogen	232	2.1	102	55
Phosphorus	49	0.7	110	75
Potassium	312	3.2	115	61
Sulphur	71	0.8	101	63
Calcium	289	2.6	112	55
Magnesium	72	0.7	108	61
Iron	2592	24.0	130	46
Manganese	829	6.5	123	49
Boron	652	6.5	118	60
Copper	77	0.9	119	61
Zinc	272	3.7	109	73

Although the amount of each nutrient taken up and accumulated by plants varies widely, the patterns of accumulation are similar for most nutrients. The timing of peak uptake ranges from about 101 days after sowing (DAS) to 130 DAS, depending on the nutrient (Table 1.2).

Cotton absorbs nutrients as cations (positively charged nutrient elements) and anions (negatively charged nutrient elements) from the soil solution and from desorbed and exchangeable ions held on clay and humus colloids.

Nutrients are normally in much greater concentration in the plant tissue than in the soil solution. As a result, the plant must expend considerable energy to take up nutrients. Only a small fraction of the total nutrient content of the soil available to plants is found in the soil solution. Most soil nutrients are locked up in unavailable mineral or organic forms. As nutrients are removed from the soil solution, they are replaced from labile (changeable) forms held within the soil, which include:

- organic matter
- nutrients absorbed to mineral and organic matter surfaces
- soluble minerals
- cation and anion exchange sites on clay particles and organic matter.

Most processes that release nutrients into the soil solution are reversible. Where high concentrations of a nutrient exist in the soil solution (especially around fertiliser application zones), a proportion of that nutrient may be precipitated as less soluble minerals, making it less available to the crop until the soil solution becomes depleted. NUTRIpak will outline the processes that apply to individual nutrients in following sections.

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3. Nutrient removal

High-yielding cotton crops impose a high demand on mineral nutrients from the soil over a relatively short period of time. Nutrients are removed and exported from fields principally in the cotton seed and gin trash. Very little nutrient is removed within the fibre itself. Crop nutrient uptake and nutrient removal are related to lint yield, however the amount and proportion of each nutrient removed differs.

These differences are due to differences in redistribution of nutrients from vegetative parts to the boll and seed. Table 1.3 shows the total amount of each nutrient exported as a percentage of nutrient uptake for three different crop yields, while Table 1.4 shows the approximate quantity of nutrient removed in lint and seed in one-bale increments.

Table 1.3: The ranges of each nutrient taken up and the predicted proportion of each nutrient exported relative to that taken up by the crop at two yield levels. Source: Rochester (2007).

	Uptake	Export	% Exported	
			1800 kg lint/ha	2400 kg lint/ha
Nitrogen (kg/ha)	64–403	39–168	52	46
Phosphorus (kg/ha)	18–43	14–28	69	60
Potassium (kg/ha)	43–264	17–88	17	15
Sulphur (kg/ha)	24–66	5.8–11.8	21	18
Calcium (kg/ha)	71–266	2.7–6.5	3	2
Magnesium (kg/ha)	13.9–73.3	8.7–17.9	34	25
Sodium (kg/ha)	1.1–22.2	0.16–0.17	2	1
Iron (g/ha)	350–2022	102–161	17	11
Manganese (g/ha)	127–729	6–22	3	2
Boron (g/ha)	168–682	26–65	13	11
Copper (g/ha)	26–89	14–28	38	31
Zinc (g/ha)	66–214	59–109	73	61

Table 1.4: The total amount of each nutrient removed per hectare for a range of crop yields.

Yield b/ha	N	P	K	S	Ca	Mg	Na	B	Cu	Zn	Fe	Mn
	kg/ha							g/ha				
4	33	11	12	4	2	7	0.13	8	11	56	91	18
5	50	13	17	5	3	8	0.14	18	13	64	99	24
6	65	15	22	6	3	9	0.15	28	15	73	109	30
7	81	17	26	7	4	11	0.15	36	18	85	122	36
8	95	19	30	8	5	12	0.16	43	20	97	138	42
9	109	21	33	9	5	13	0.17	49	22	112	156	48
10	123	23	36	10	6	14	0.18	55	24	128	176	54
11	136	25	39	11	6	15	0.18	59	26	145	199	60
12	148	27	41	12	6	16	0.19	62	28	164	224	66
13	160	29	43	13	7	18	0.2	65	30	185	252	72
14	171	31	45	14	7	19	0.2	66	32	207	283	78
15	182	33	46	15	7	20	0.21	67	34	231	316	84
16	192	35	47	17	7	21	0.22	66	36	257	352	90
17	201	37	48	18	8	22	0.22	65	38	284	390	96
18	210	39	48	19	8	24	0.23	62	41	312	431	101
19	219	41	48	20	8	25	0.24	59	43	343	474	107

Nutrient export from the high-yielding cotton crops can be very significant and can deplete natural soil reserves, leading to deficiencies and crop production limitations. Meeting crop demand is critical in ensuring ongoing high yields. Growers can do this in two ways: (i) in a replacement fertiliser program, replace the nutrients removed and maintain present soil nutritional status; (ii) with a management strategy, wait until a nutrient becomes limiting then implement a fertiliser program to meet the crop's demands. The main problem with the second practice is that crops may be affected by a nutrient limitation, resulting in yield losses before deficiency symptoms are seen and identified ('hidden hunger'). Higher rates may be needed to address the lower soil nutrient status.

4. Nutrient supply to the crop

For nutrients to be absorbed by plant roots, they must come close to the plant root surface. There are three ways by which this occurs:

a. ***Root interception***: As the roots grow through the soil, they intercept new areas of high nutrient concentration, aiding diffusion and mass flow. Actively growing root systems enhance this method of nutrient interception. It is thought to account for only a small percentage of the total nutrients absorbed by plants. It may be more important for the uptake of immobile plant nutrients, such as phosphorus (P), potassium (K) and zinc (Zn), which do not readily move more than a couple of centimetres through the soil in solution and hence are dominantly acquired via diffusion.

b. ***Mass flow***: the movement of water and dissolved nutrient ions (soil solution) through soil pores. It occurs after irrigation or rainfall but also as the result of a water pressure gradient produced when plants transpire (water moving from a wetter to a drier area). Plants absorb water through their root systems from the surrounding soil. Replacement water then moves towards the roots, carrying the dissolved nutrient ions with it. Highly mobile anions and cations, such as nitrate (NO_3^-), calcium (Ca^{2+}) and magnesium (Mg^{2+}), may be carried to the roots in sufficient quantities to satisfy the crop's needs. In contrast, the P concentration in soil solution is very low, so mass flow contributes only a minimal amount of the total crop P requirement.

c. ***Diffusion:*** As a plant root absorbs nutrients from the surrounding soil solution, a diffusion or concentration gradient is set up. Nutrients from areas with higher concentration (around a fertiliser granule) diffuse to the areas of low concentration (where roots have removed nutrient) around the root surface. This process is very important for the uptake of immobile nutrients, such as P and K.

Understanding how plants source nutrients can play a critical role in how we manage crop nutrient programs and fertiliser applications. For example, nitrogen, in the form of urea or anhydrous ammonia, can be applied in bands into the soil, with the understanding that after rain or irrigation, and nitrification, N will move throughout the soil profile in the soil solution as nitrate by mass flow. It can also be dissolved in irrigation water and applied in-crop. However, N is very mobile in soil solution, so that if it is not managed carefully, it can be leached through the soil profile, out of the rooting zone, and is lost to the plant.

In comparison, phosphorus does not readily move through the soil. If applied as a band, it does not move very far from the area of application. By spreading and incorporating P fertilisers in non-P-fixing soils, a far greater volume of soil is enriched, making it more accessible to the plant.

5. Soil health/soil quality

Defining the terms 'soil health' and 'soil quality' has always presented challenges. Although they are often used synonymously, they can have different meanings and can be applied differently. Soil quality tends to have a broader meaning, encompassing chemical, physical and biological properties, while soil health is determined primarily by ecological characteristics. Soil health portrays a soil as a living, dynamic organism that functions holistically, while soil quality uses quantifiable characteristics. Soil health is a component of soil quality. Together, the quality and health of a soil will determine the productivity and sustainability of the soil in an agricultural system.

More specifically, soil health is used to describe the soil's capacity to respond and react to the environment, and function as a living system to sustain productivity. 'A healthy soil is a stable soil, with resilience to stress, has high biological diversity and high levels of internal cycling of nutrients' (Elliott and Lynch, 1994). It is the soil's ability to grow and produce crops sustainably.

Soil quality is generally used to refer to a soil's 'fitness for a specific use'. It includes the inherent physical, chemical and biological properties of the soil as well as its response to management and land-use decisions.

6. Nutrient cycling

Nutrient cycling is the process by which nature recycles nutrients, both organic and inorganic matter, back through the production system. There are many interconnected nutrient cycles (i.e. nitrogen cycle, sulphur cycle, carbon cycle etc.) within the farming ecosystem, many regulated by the diversity and activity of the soil biota (soil microbes and invertebrates). Modern agricultural systems can have a significant impact on soil biota diversity and activity. These impacts are the result of the large reduction of biomass inputs, farming practices, such as cultivation, and with greater fluctuations and extremes in soil temperature and moisture. Matson (1997) states that the 'reduction in diversity of soil biota under agricultural practices may profoundly alter the biological regulator of decomposition and nutrient availability in the soil. The deterioration of biological functions has been largely substituted in intensive agriculture by the use of fertilisers and mechanised tillage.'

7. Retention of nutrients in soil

Soil colloids (mineral and organic) are extremely small particles, formed through natural weathering and decomposition process that are mainly responsible for the chemical reactivity of soils. Although each colloid has a net negative charge, both negative and positive charges can be found on their surface. This feature enables them to attract and retain positive ions (cations or metallic ions) and negative ions (anions or non-metallic ions). Common soil cations taken up by plants include calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), sodium (Na^{+}). Acid soils may contain hydrogen (H^{+}) and aluminium (Al^{3+}). Other cations include ammonium (NH_4^{+}), manganese (Mn^{2+}), iron (Fe^{2+}), copper (Cu^{2+}) and zinc (Zn^{2+}). Common soil anions and ionic forms taken up by plants include nitrate (NO_3^{-}), phosphate ($H_2PO_4^{-}$, HPO_4^{2-}), chloride (Cl^{-}), and sulphate (SO_4^{2-}).

The net negatively charged colloids tend to attract and hold more cations. This process explains why some anions, such as NO_3^{-}, are not readily held in the soil. They remain in soil solution and can be easily leached through the soil profile. On the other hand, ammonium (NH_4^{+}) is held on the soil colloids and is retained in the soil.

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Cation Exchange Capacity (CEC)

The cation exchange capacity of a soil is a measure of a soil's capacity to attract, retain and exchange cations. The CEC of a soil depends on the amount and type of clay and organic matter it contains. A soil with a high clay and organic matter content will have a high CEC, while a soil high in sand and low organic matter will have a low CEC.

The CEC of a soil can be used as a guide to its nutrient retention ability. The relationship between cations can also provide information about its structural stability and resilience in some cases (such as its ability to buffer against soil acidification).

The CEC is calculated by measuring and summing the exchangeable cations Ca^{2+}, K^{+}, Mg^{2+}, Na^{+} (and Al^{3+} in strongly acid soils). Because several methods are used to measure the CEC, the method used must be identified when interpreting the results, so as to ensure consistent interpretation.

The CEC of a soil provides growers, managers and consultants with valuable information about the nutritional retention capacity of the soil, buffering capacity, structural stability, and potential response to amelioration where structure is compromised by the presence of high levels of sodium, magnesium and potassium.

A soil with a high CEC has a greater ability to hold and retain more cations and anions (making them more available to plants) than a soil with a low CEC. Soils with low CEC are prone to nutrient losses through leaching. Understanding this fact plays an important role in the way growers manage crop nutrition and soil health. CEC can be improved in low-CEC sandy soils by increasing the organic matter content, and raising or maintaining the soil pH (1:5 $CaCl_2$) above 6.

8. Base saturation

Base saturation is defined as the total CEC occupied by the cations Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}. The base saturation reflects the extent of weathering and leaching that has occurred in the soil. Base saturation is related to the soil pH and is an indicator of soil fertility. The availability of the nutrient cations Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+} to the crop generally increases with higher base saturation.

9. Anion retention

Anion exchange also takes place on the clay minerals and organic matter (as with CEC), but anions are attracted and retained to the positively charged sites. Anions include nitrate (NO_3^-), chloride (Cl^-), phosphate ($H_2PO_4^-$, HPO_4^{2-}), and sulphate (SO_4^{2-}). Anions with a single charge (e.g. nitrate, chloride) are more prone to leaching down the soil profile, whereas anions with multiple charges or those that react quickly into lower solubility compounds (e.g. phosphate) strongly resist leaching.

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10. Rhizosphere

The rhizosphere is the zone of soil surrounding the root where soil microorganisms flourish in great abundance, relative to the rest of the soil. Microorganisms proliferate here because of the exudation of nutrients, sugars and other materials from the root. The rhizosphere has intense biological activity and cycling of nutrients.

11. Mycorrhizae (vesicular arbuscular mycorrhizae)

Mycorrhizae (VAM) are soil fungi that form symbiotic relationships with roots of the cotton plant. The fungi improve the supply of some nutrients to the plant, which in turn supplies carbohydrate to the fungi. VAM do this by forming extensive networks of fungal hyphae that grow out from the root through the soil to distances of up to 2 cm. This network significantly increases the volume of soil explored. Although there is a benefit in the uptake of all nutrients, VAM plays a critical role in the uptake of P and Zn in cotton, particularly when available soil levels of these nutrients is low.

Long-fallow disorder of cotton is associated with poor mycorrhizal colonisation. Long periods of bare, weed-free fallows or growth of non-mycorrhizal crops reduce the amount of VAM in the soil. The decline in VAM fungi has serious implications for rain-grown cotton production, where it is important for fallow fields to store moisture. Inoculation with VAM does not restore population to a significant nutrient uptake quantity. The best means of keeping VAM active in the soil is to keep crops growing in a rotation system with shorter fallows.

12. Factors influencing nutrient uptake by cotton

Nutrient uptake may be restricted when:

- poor physical soil structure (e.g. compaction) or soil chemical toxicities (e.g. salinity, sodicity, pH) limit root growth, reducing nutrient uptake, even where sufficient nutrients are available
- a deficiency of one nutrient limits crop growth, reducing the capacity of the plant to take up or metabolise other nutrients
- as the crop matures, nutrients and sugars within the plant are diverted from vegetative (including roots) to reproductive organs
- oxygen supply, needed by roots to maintain metabolic processes, including nutrient uptake, is restricted, i.e. through waterlogging.

13. Nutrient distribution within the plant

Nutrients vary in their mobility within a plant, which the expressed deficiency symptoms often reflect. As a general rule, the deficiency symptoms of nutrients with very low in-plant mobility are expressed in the new growth. Deficiency symptoms of highly mobile nutrients within the plant are observed in the older growth (Table 1.5). There are variations. For example, potassium deficiencies early in the plant's life will appear in the older leaves. However, if the deficiency develops at boll fill, deficiency symptoms will appear in the younger growth.

It is therefore imperative to sample the youngest mature leaf (fully expanded leaf, normally 5th leaf from the terminal) when assessing crop nutrient status (see section 'Leaf and petiole analysis' in this manual).

The cotton plant can take up nutrients quickly, as demand requires. The highest demand period for most nutrients occurs from flowering to boll fill (i.e. during the period of fastest growth). Nutrients are stored in leaf tissue and other organs until needed by the developing bolls. Storage is important to provide nutrients to the crop in periods when crop uptake is reduced (e.g. cloudy weather, and periods of waterlogging). This is especially significant for N, P and K when the supply of these nutrients from the soil through the roots may not meet the demand.

Table 1.5: Nutrient mobility in the plant defines where plant tissues express deficiency symptoms.

Mineral nutrient	Nutrient mobility within plant	Plant organ where deficiency symptoms usually appear
N, P, K, Mg	high	old leaves
S	low	young leaves
Fe, Zn, Cu, Mo	very low	young leaves
B, Ca	extremely low	young leaves and terminal

Further reading

Cotton Australia. 2017. *my*BMP [Online]. www.mybmp.com.au: Cotton Australia. Available: www.mybmp.com.au [Accessed 2017].

Elliott, LF & Lynch, JM 1994. Biodiversity and soil resilience. In Soil Resilience and Sustainable Land Use. Eds. DJ Greenland & I Szabolcs. pp 353–364. CAB International, Wallingford, UK.

Matson, P. 1997. NOx emission from soils and its consequences for the atmosphere and biosphere: critical gaps and research directions for the future. *Nutrient Cycling in Agroecosystems*, 48, 1–6.

Oosterhuis, D. M. 1990. Growth and Development of a Cotton Plant. *American Society of Agronomy*, pp. 1–24.

Rochester, I. 2007. Nutrient uptake and export from an Australian cotton field. *Nutrient Cycling in Agroecosystems.*

Rochester, I. J., CONSTABLE, G. A., OOSTERHUIS, D. M. & ERRINGTON, M. 2012. *Nutritional requirements of cotton during flowering and fruiting.*

Stewart, J. M. 2010. *Physiology of cotton*, Dordrecht; London: Springer.

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2. Nitrogen (N)

Australian cotton is grown on fertile clay soils that have become depleted in nitrogen (N) and organic matter over time. They are no longer able to supply the cotton crop's need for N from mineralisation of native organic matter sources. Because of the direct effects of N on crop development, it is generally imperative to apply adequate N fertiliser. To achieve maximum yield, cotton growers may need to supply N fertiliser to each crop at rates up to 300 kg N/ha, considering factors such as paddock history, yield expectation, potential losses, soil N supply, and seasonal conditions. Oversupply of N will encourage rank growth and fruit shedding, reduce lint yield, hamper defoliation, encourage insects and diseases, delay maturity, and increase adverse environmental impacts.

Role of nitrogen in the plant

Nitrogen is an integral component of plant proteins and amino acids that are essential for healthy crop growth and physiological development. Nitrogen is also needed to synthesise the chlorophyll required for photosynthesis. New leaves may contain up to 6% N. It is a very mobile nutrient within the plant and moves from older to newer leaves and developing bolls as the plant ages. Nitrogen is taken up throughout the growing season and is transported and stored in the leaves. The N requirements for boll development are partially met from N stored in the leaf canopy, more so during periods when root uptake activity is limited, e.g. waterlogged soil.

Uptake and removal of nitrogen

To achieve high cotton yields, an uptake of about 250 kg N/ha is needed. In irrigated crops, most N taken up by the crop comes from the surface (0 to 50 cm) soil from where organic matter, mineralised N and fertiliser N are commonly located. In dryland crops, N uptake may extend deeper (120 to 150 cm) as crops forage for stored soil moisture.

Cotton prefers to take up nitrate-N (rather than ammonium-N) and does so in phase with crop growth rates; as the crop matures, N uptake slows. Most of the N is transported to the leaves (hence the use of petiole-nitrate testing). A young cotton plant can take up more N than it needs, and excess N is remobilised from the leaf canopy later if uptake does not meet the crop's requirements. The production of new leaves and squares slows at cut out, which should coincide with the exhaustion of the soil N supply. Thus, low soil N can hasten cut out and limit yield. Most N is taken up between 50 and 110 days after sowing (700 to 1400 day degrees), as shown in Figure 2.1. About 50 to 60% of the N is removed in the cotton seed.

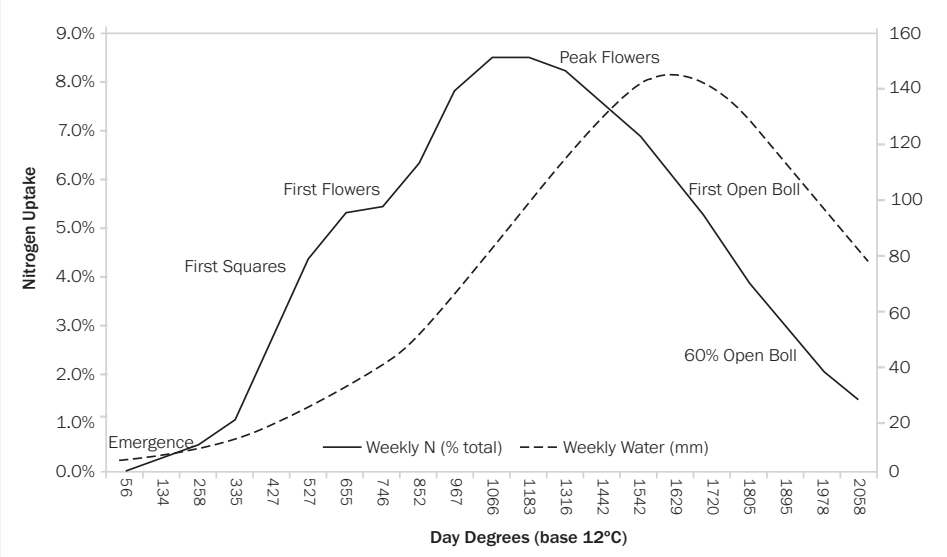


Figure 2.1: N uptake pattern and water use.

Recent introduction of high-yielding low-density seeded varieties has changed N economy of cotton crops only marginally. Although the new low-density seed varieties are thought to have optimised N at a higher N% in whole seed (3.9% vs 3.5%), N removal per bale is generally slightly lower as a result of the higher gin turnout (Table 2.2).

Nitrogen deficiency symptoms

Deficiency symptoms include small, pale yellow leaves. Nitrogen-deficient plants are stunted, and produce fewer nodes through a combination of fewer vegetative branches and fruiting branches that will also be reduced and shorter. As N deficiency progresses, older leaves become yellow, as N is remobilised to new growth. Leaves with severe N deficiency turn various shades of autumn colours as tannins in the leaves are expressed (Figure 2.2).

Crops that are adequately fertilised will exhaust the pool of available N in the soil as bolls start to open, when the lower leaves begin turning yellow. This is a good indication that the crop has received adequate N fertiliser. Mobilisation of N from older leaves, stems and roots is a feature of normal growth. Crops that are over-fertilised with N will remain green throughout the growing season, which delays crop maturity, defoliation and picking.

KIERAN O'KEEFFE

Figure 2.2: nil-N strips in the on-farm field trials.

Nitrogen fertilisers

The major N fertilisers used in cotton production are anhydrous ammonia (82% N) and urea (46% N). The N released from both fertilisers becomes available to plants quickly. Urea and anhydrous ammonia perform similarly in an agronomic sense and are normally equally recovered by cotton.

- **Anhydrous ammonia (NH_3)** is a popular option for cotton, especially where high rates of N are needed. It is as effective as and generally no more expensive than other N fertilisers. Loss of ammonia is negligible when anhydrous ammonia is applied deeper than 15 cm. However, the soil-water content is important: gaseous ammonia fertiliser applied to very dry soil may allow ammonia to escape through the voids between large clods, or in very wet soils, ammonia may escape through the disturbed area made by the shank of the fertiliser application tine if not firmed or covered over with fine loose soil.

  Side-dressing anhydrous ammonia can be effective, but there is a narrow range of crop and soil conditions where ammonia losses and risk of crop damage are minimised.

  Effectiveness of water-run anhydrous ammonia is restricted because ammonia distribution down the field can be poor, and volatilisation losses from irrigation water can be high where application restrictions are not followed. General guidelines for effective application:

  - apply only where run length is less than 600 metres
  - application rate is less than 100 kg NH_3/ML
  - water temperatures are less than 20°C
  - water pH is less than 7.5.

  Water temperature is affected by the water source, rate of water application, time of day, the depth of water in the furrows, and shading provided by the crop canopy.

- **Urea ($CO[NH_2]_2$)** is normally hydrolysed to ammonium within days of application. It is then nitrified in the soil and taken up by the crop. Urea can be dissolved in the irrigation water (water-run urea), side-dressed or aerially applied (in which case it must be quickly incorporated or watered in). Urea should not be applied to the surface of wet or moist soil where volatilisation losses can reach 75% of N applied. Urea can be applied to a dry soil surface but it should be incorporated as soon as possible by rainfall, cultivation or irrigation to be effective and to minimise volatilisation losses.

  Water-run urea can work efficiently as the N is distributed throughout the soil volume from which the crop extracts water. The N does not volatilise from the water, and is delivered evenly to the length of the field. However, some N will be unavoidably wasted as supply channels and tail drains are fertilised, hence, irrigation management should aim to minimise the amount of tail-water or it should at least be recirculated.

  The three methods for applying urea with irrigations are:

  1. applied to dry soil surface by either spreader or aircraft then irrigated in as soon as possible. Avoid applying to moist soil and/or allowing a delay before irrigation because shallow incorporation in moist soil can lead to losses with ammonia volatilisation.
     Note: Be cautious with this method when the crop canopy is damp at the time of application because urea may stick to leaves and burn leaf surfaces.
  2. supply of urea solutions is possible in some regions that allow metering of the solution via a constant head tank and float valve. Application rates can be altered by adjusting the flow of the irrigation water or the flow of the fertiliser solution.
  3. solid urea can be applied via N buggy-type equipment that meters and dispenses urea directly to the water flowing through the irrigation channel.

Urea is best added to the water at a drop structure or culvert of a water channel to improve the mixing process. The efficiencies of the three methods are similar.

- **Ammonium sulphate ($[NH_4]_2SO_4$)** is sometimes used where product sources are competitively priced or where sulphur is also required. Due to the crystalline characteristic of byproduct sources, it is commonly surface spread. In calcareous soils, the lack of incorporation of ammonium sulphate significantly increases ammonia volatilisation loss.

- **Starter fertilisers**, such as mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP), supply only a small amount of N to cotton seedlings.

- Use of **recycled bio-solids** can affect the crop N availability. The duration of release and quantity of N contributed depends on the rate of material applied and its soluble carbon–soluble nitrogen ratio. In dryland crops, N availability from these materials is highly dependent on the amount and timing of rainfall.

Determining nitrogen fertiliser requirements of cotton

Most growers use rates based on their experience from previous cotton crops but also consider soil condition and previous rotation crops. The N fertiliser required by cotton can be predicted with greater precision by using pre-sowing soil nitrate analyses (Figure 2.3). Nitrogen fertiliser rates can be modified, as indicated by petiole nitrate analyses and N content of the youngest expanded leaf blade.

RUTH REDFERN

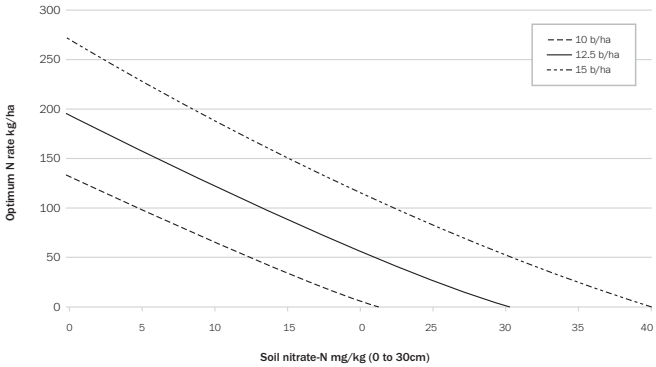
Soil testing

SOIL NITRATE ANALYSIS

NutriLOGIC is an online web tool (www.cottassist.com.au) that includes tools to interpret soil and plant tissue tests for N. Nitrogen recommendations using similar principles to NutriLOGIC are also provided by some commercial soil test decision support system providers.

These decision support systems (DSS) allow the user to enter soil nitrate-N to estimate the N fertiliser required for a target yield of irrigated cotton based on this data, the cotton-growing region, the month the sample was taken, cropping sequences, and soil conditions. Sampling depth for irrigated cotton in NutriLOGIC is 0 to 30 cm, while other DSS provide for deeper sampling for both irrigated and dryland crops. Dryland cotton should be sampled to the depth of effective root activity that, for the majority of cotton soils, is at least 90 cm. Figure 2.3 shows the base N fertiliser requirement of cotton as suggested by NutriLOGIC for ACRI Narrabri. The N fertiliser application rate declines as soil nitrate-N increases for each yield target.

Figure 2.3: The relationship between N fertiliser requirement and soil nitrate-N concentration in an unfertilised clay loam soil, sampled in September, one month before sowing cotton.

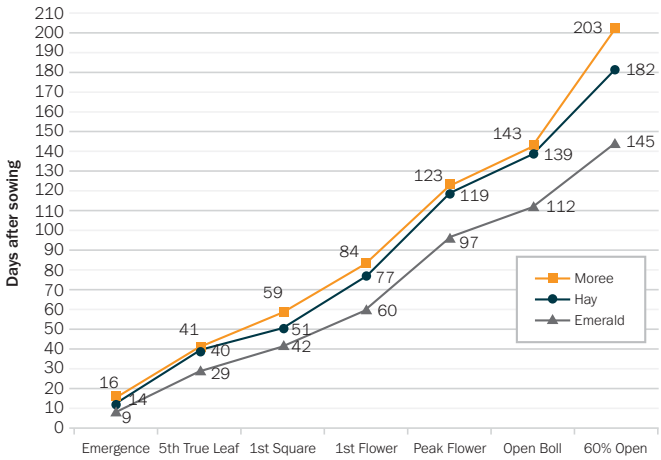


This base rate is subsequently modified for location, soil characteristic, and rotation parameters.

- **Effect of location**

Hotter areas require slightly more N to produce the same lint yield as cooler areas. The higher requirement is driven by the need to maintain a higher soil N concentration to supply the faster phenological development and, therefore, peak N demand in hotter climates (Figure 2.4).

Figure 2.4: Diagram of the phenological development, recorded in days, to 60% open boll comparing Hay, Moree and Emerald.



- **Effect of soil type and compaction**

  The N fertiliser rate indicated by NutriLOGIC and other DSS allows for an average loss of N through denitrification and leaching during the crop-growing season based on soil type and compaction rating. Soil texture impacts the potential for N fertiliser losses, which are lower in lighter clays than in heavy clays. Greater losses occur from poorly structured or poorly drained soils compared to well-structured and well-drained soils.

- **Effect of sampling date**

  Pre-sowing (September) soil nitrate content is closely related to crop N uptake and, ultimately, yield. Nitrogen fertiliser requirements can be estimated from soil nitrate-N. High levels of soil nitrate indicate a high level of N fertility. If fertiliser has been applied before sampling in September, nitrate test values will be extremely high and variable, and are not suitable for estimating further N fertiliser requirements. NutriLOGIC does not contain a calibration for soil sampled earlier than July. Some other DSS cater for earlier sampling by estimating net N mineralisation from sampling till sowing from local soil and climatic data.

- **Effect of previous crops**

  Rotation with other crops and fallowing between cotton crops frequently improves soil structure. Where legumes are used in rotation, they improve the nitrogen supply dynamics. The combination of these two factors generally leads to improved nitrogen-use efficiency (NUE). Rates of N suggested by NutriLOGIC are calculated using N uptake efficiencies adjusted for the rotations crops/fallows in the two years before the planned cotton crop.

MELANIE JENSON

PLANT TISSUE TESTING

- **Leaf blade total N analysis**

  Total N% of the youngest mature blade (minus petiole) can be used as an in-crop N management guide where measured between the crop development stages pin-head square and mid-flowering. Across this period, the adequate N content declines from about 5.4% to 3% (Figure 2.5). This reduction in N is a naturally occurring process because N from these leaves is translocated to the developing bolls of the maturing crop.

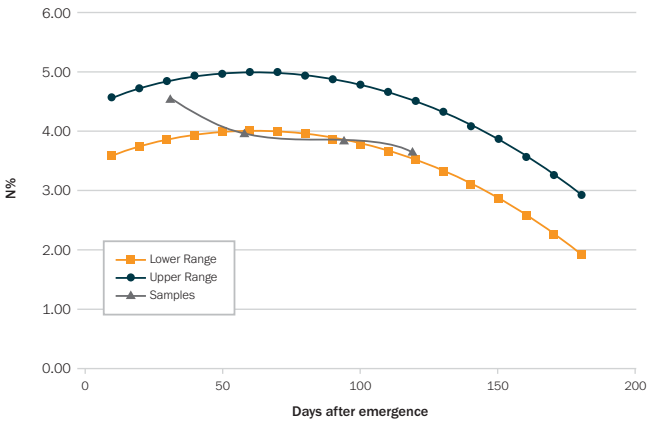


Figure 2.5: Change in youngest expanded leaf blade N% with crop age.

- **Petiole nitrate analysis**

  Petiole nitrate analysis allows growers to determine whether a crop is receiving sufficient soil-derived nitrate-N to produce its optimum yield. Monitor N status early in the growing season (squaring till mid-flowering) so that any N deficiency can be rectified before growth is severely affected. Nitrate-N in the petiole is reflective of the current supply of N from the soil only, and is favoured for irrigated crops where crop stresses that impede root activity are minimised.

  The critical value for petiole nitrate at first flower (750 day degrees from sowing) is about 20,000 mg/kg. Below this value, nitrogen applications may be necessary. Greater certainty of N requirement can be gained from determining the slope of decline of two to three samples in the first couple of weeks of flowering. Sampling procedures are detailed in cotton soil and plant tissue sampling guidelines available at: http://www.cottoninfo.com.au/sites/default/files/documents/Soil%20nutrient%20sampling%20guidelines%20for%20cotton.pdf

- **Proximal and remote techniques**

  Spectral sensors measuring peaks in the red, near infra-red, red-edge, and green and blue wavelengths in the crop canopy appear to have some prospect of being other tools to manage N during early flowering. The benefit of sensing techniques is the rapid non-destructive measurement of plant N, and the ability to scale sampling and subsequent management decisions to the paddock level, exposing variability in crop N.

GEOFF HUNTER

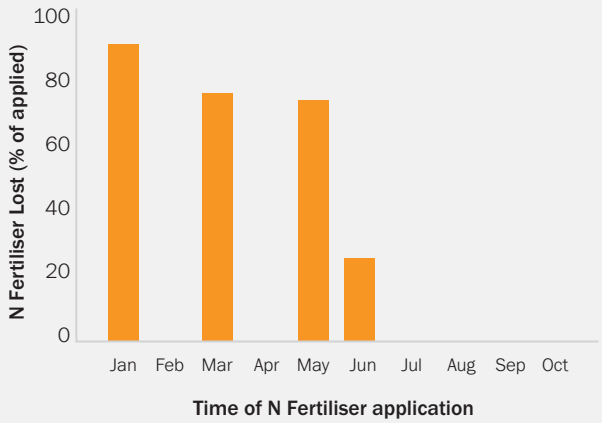
Nitrogen fertiliser application management

TIMING OF APPLICATION

Pre-plant N fertiliser should be applied as close as practical to sowing in order to reduce N losses and maximise the effectiveness of N fertiliser in both irrigated and dryland crops. Often, N losses are substantial when fertiliser is applied in warm/moist soil during the summer/autumn months before the crop is sown. It can be wasteful and costly for the grower. Early application can increase the risk of exposing fertiliser to N loss episodes over many months, when soil conditions favour denitrification.

Severe N losses (primarily through denitrification) can occur between the time of fertiliser application and the crop being sown, particularly during wet winters. The practice of applying N fertiliser in the summer while preparing fields after cereal cropping is not recommended because of the potential for much of this N to be lost (Figure 2.6).

Figure 2.6: Percentage of N lost from early fertiliser applications as determined by fertiliser remaining in October. Almost complete loss of fertiliser N may eventuate from early applications in years of above-average winter rainfall. (Source: Freney, Australian Cotton Conference 1992).



- **Side-dressing N fertilisers**

When side-dressing N fertiliser, growers must take into account the time for fertiliser N to become available to the plant and the risk of being unable to apply in-crop N due to wet soil conditions. Most growers aim to side-dress N prior to flowering, when the crop may take up as much as 5 kg N/ha/day. By applying N early to the crop, the damage caused by fertiliser tines pruning the roots is minimised, which is critical in areas where soil diseases are prevalent because the damaged roots provide ideal infection sites. As the plant ages, its ability to take up N decreases, even if N deficient. However, nitrogen taken up before the flowering period in excess of its needs can be stored within the plant, relocated within the plant, and used efficiently if deficiencies occur later in the crop.

Side-dressing can produce comparable N responses to pre-plant applications, assuming there is sufficient N in the seed bed to allay early N deficiency. Side-dressing can be a problem in wet summers when soil structure can be damaged or there is a chance that access to the field is limited. In these cases, water-run urea is often a better option than applying urea or anhydrous ammonia. A well-planned split application strategy with a reduced pre-sowing N application rate can help reduce surface movement in irrigation water, leaching and denitrification losses associated with pre-watering, and the first couple of in-crop irrigations, which is when the greatest losses of N occur.

- **Timing N fertiliser to avoid crop damage**

Where growers opt to place anhydrous ammonia or urea below the plant line before sowing, they should ensure sufficient time has elapsed for the ammonia to dissipate from the soil and nitrify where the root system will develop. This process may take up to three weeks for high N application rates under good nitrification conditions. In dry, cool soils the mineralisation process is slowed. Damaging concentrations of soil ammonia can exist for many months.

PLACEMENT OF N FERTILISER

Nitrogen fertilisers should be placed a short distance from where seedling roots will grow, especially when N is applied close to sowing. Generally, the best responses and recoveries are achieved from urea or anhydrous ammonia placed either:

- more than 30 cm beneath the seed row if more than one month before sowing, or
- shallower and to the side or both sides of the crop row, if closer to sowing (Figure 2.7).

Depth of N fertiliser application is important. The developing seedlings may become N deficient where they cannot access N fertiliser placed too deeply. Shallow placement of N fertiliser may result in damage to the developing seedlings. Also, substantial N losses can be experienced during shallow application of anhydrous ammonia (or urea). Further, shallow N may be washed down the furrows from the head to the tail of the field during flood irrigation, especially where high nitrate concentrations persist.

Nitrogen fertiliser needs to be placed near the developing cotton roots, but not so close that ammonia toxicity will damage the root system. Ideally, the fertiliser band should be below and to the side of the developing roots, allowing the root system to grow into the band. Roots will proliferate through the fertiliser band as the ammonia is nitrified. Band placement of N fertiliser can reduce N loss. Where 2-metre beds are used, the centre of the bed is the ideal position for N application. Placement of N in the furrow often achieves poor responses to fertiliser.

Urea should not be placed with the seed. Urea is extremely soluble, and if applied near the crop row prior to sowing and watered-up, it may be moved into the seedling root zone. This can damage seedlings, especially where the high N rates generally associated with pre-plant application are used. Water-run urea is unlikely have this effect at commercial application rates.

Dryland crops are mostly grown in climates that rarely provide predictable opportunities for in-crop application, so most N is applied pre-planting. With a varied range of row spacings and configuration used by dryland producers, the guiding principle for N placement is ensuring that roots from crops in each row have unimpeded access to an N band. The N band should be placed at a depth and distance from the plant line that ensures root interception during the late squaring to early flowering period.

- **Foliar application of N fertiliser**

Crops in difficult growing conditions may respond to foliar applications of N, particularly when irrigating poorly drained fields. Poor soil aeration and waterlogging can limit nutrient uptake for some days after irrigation.

Foliar applications of urea have been used to overcome N stress caused by short-term waterlogging from early crop irrigations. As the plant rapidly absorbs foliar urea, such applications can overcome a deficiency faster than soil-applied N.

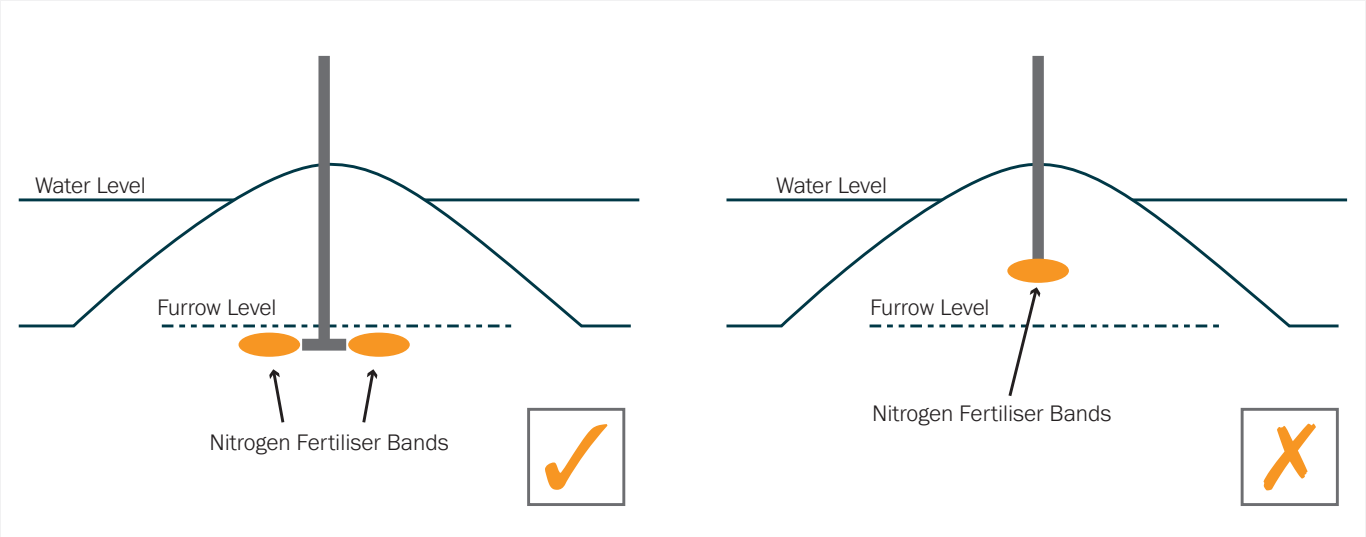


Figure 2.7: Preferred placement of pre-sowing application of nitrogen fertilisers to help avoid seedling root damage (Image courtesy Dr Ben McDonald).

Waterlogging due to irrigation or rainfall often creates a short-term deficiency as roots lose their ability to absorb N when the soil is saturated. In these conditions, denitrification loss is also increased. Foliar application is most effective when applied a day before the waterlogging event (irrigation). Applications of 8 to 10 kg N/ha (before first and/or second irrigation) at early squaring and early- to mid-flowering can overcome the effects of waterlogging. Concentrated urea solution used at 20 to 40 litres/ha is generally sufficient to meet plant requirements for the 2 or 4 days until waterlogging passes. Use of urea-ammonium nitrate solution for foliar application increases the risk of leaf burn (Figure 2.8). Application of foliar N under conditions where photosynthesis is restricted (low light, high temperatures, high humidity, low water availability) increases the potential for foliar burn. Foliar N requires plant carbohydrate production to enable its metabolism to functional compounds.

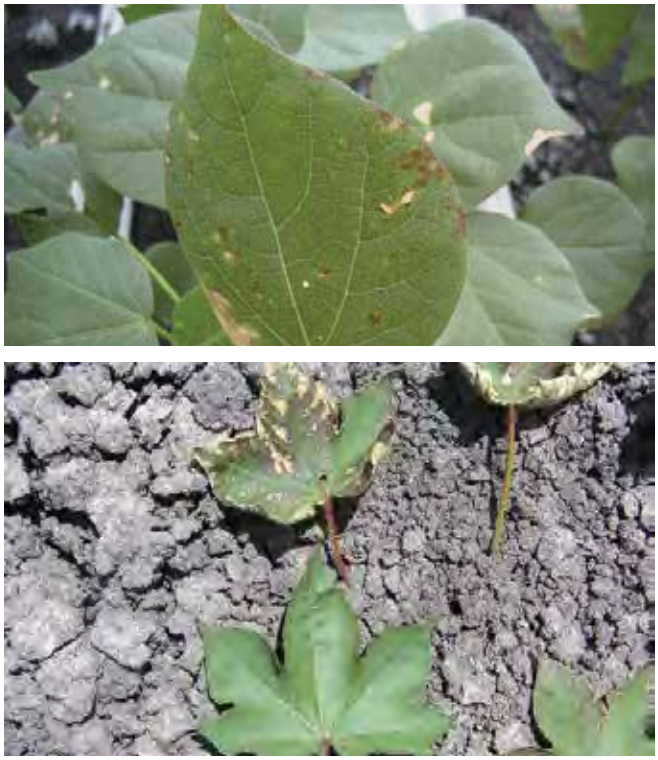
- **Applying N fertiliser at or near sowing**

The most influential factor in fertiliser injury of seedling cotton is the presence of toxic gaseous ammonia near developing roots. When ammonia-producing fertilisers (urea, anhydrous ammonia, MAP, DAP) are applied in alkaline soils, a proportion of the N remains as ammonia in the soil water and air spaces within the soil. The pH of the soil within a band of ammonium-producing fertiliser increases towards the centre of the band, causing the ammonium-ammonia equilibrium favouring a higher toxic ammonia concentration.

Crop root systems are extremely sensitive to ammonia. Symptoms of ammonia toxicity typically appear as rows or patches of wilting, and dead seedlings becoming evident when the rate of soil drying exceeds the rate of downward root growth (Figure 2.9). Close observation of the tap root damaged by ammonia burn generally reveals a blackened withered tip with early development of lateral roots.

DR CHRIS DOWLING

Figure 2.9: Rows of cotton wilting due to fertiliser burn. Seeding rows overlapping fertiliser bands.



DR CHRIS DOWLING

DR CHRIS DOWLING

Figure 2.8: Moderate (top) and severe (bottom) leaf damage resulting from foliar application of nitrogen urea-ammonium nitrate solution.

In winters with above-average rainfall, growers may not be able to apply fertiliser before sowing. In this situation, growers need to explore other options available for N application, including side-dressings of ammonia and urea, and water running high rates of urea. Application of the total N requirement in-crop should be split over 2 to 3 applications from about the four-leaf stage to early flowering time, with each application to be followed by irrigation to incorporate the urea.

Where pre-plant application is not possible prior to crop establishment in a dryland crop, an application before first flower, timed with a rainfall event, is recommended.

Mono-ammonium phosphate (MAP) rates of up to 4 g/m (40 kg/ha with 1-metre rows) can generally be safely applied with seed where seedbed moisture is good in clay soils. Because of the acidifying effect of MAP, the ammonia concentration within the seed-fertiliser band is reduced, lowering the chance of establishment failure from ammonia toxicity. Alkalinity from DAP bands favours the formation of toxic ammonia and should not be substituted for MAP applications with seed.

Cost of over-fertilising with N fertiliser

Too much N and water can cause rank vegetative growth leading to shedding of young squares and bolls. This will delay full fruit load and crop maturity. The fruit will be smaller and the fibre more immature, largely because leaves and bolls lower in the canopy are shaded by the excess vegetative growth. Diseases, such as boll rots and Verticillium wilt, may also be more common.

Minor effects of increased N supply are increased boll size and increased seed/boll numbers. The effect of N on lint quality is variable. A rank crop resulting from too much nitrogen can create problems for insecticide application and defoliation. Over-fertilised cotton may be more attractive to insects, which can be more difficult to control.

The application of growth regulators (such as mepiquat chloride) may reduce the problems associated with rank growth in over-fertilised cotton, however the first priority should be to ensure N management is optimised for the desired yield target.

Efficiency of N fertiliser use by cotton

The most efficient use of N fertiliser is achieved by applying the correct rate at a time when N loss will be minimal, i.e. after June when cooler conditions slow the nitrification and denitrification processes.

Irrigated crops frequently use less than half the fertiliser N applied. Large quantities can be lost from the production system through either leaching (lateral and horizontal) or biological denitrification (the process where soil nitrate-N is converted into gaseous forms of N and returned to the atmosphere) before crop uptake.

Cotton crops recover, on average, about 33% of N applied; about 25% remains in the soil at crop maturity, but in an unavailable (organic) form. The remainder of N applied (i.e. 42%) is assumed lost from the system through denitrification and leaching.

About two-thirds of N taken up by irrigated cotton is derived from the soil organic N pool (i.e. non-fertiliser N). This N is mineralised from soil humic and labile organic matter pools before and during crop growth. The N fertiliser applied meets only about one-third of the crop N requirement, hence increased fertiliser N use efficiency and or increasing organic N supply are key to improving overall NUE (Table 2.1).

In dryland crops, without the more regular denitrification events initiated by irrigation, higher NUE is generally achieved.

RUTH REDFERN

Table 2.1: Example of typical nitrogen budgets in irrigated (fallow cotton) and dryland cotton (long fallow from wheat) for low-density seed type variety.

Crop N Demand	Irrigated		
Target yield	12 bales/ha		
	2724 kg lint/ha		
Gin Turnout	44%		
Seed % of seed cotton	51%		
Weight of seed	3157 kg/ha		
Seed N content (Sicot 74 BFR)	3.9%		
Seed N removal	123 kg/ha	10.7 kg N/bale	
Trash N removal	6 kg/ha		
N removal in seed cotton	129 kg/ha		
% Crop N in seed	55%		
Crop Uptake	234 kg/ha		

N Supply	Available N Pool (kg/ha)	N Pool Use Efficiency	Crop-Available N (kg/ha)
Humic fraction (0.8% OC)	28	80%	22
Labile fraction	124	60%	81
Residual Mineral N (0–50 cm)	60	50%	30
Total effective soil N			133
N deficit (Uptake – Supply)	101 kg/ha		
N fertiliser efficiency	Low 25%	Typical 35%	Target 45%
Required N rate	403 kg/ha	288 kg/ha	224 kg/ha

Crop N Demand	Dryland		
Target yield	5 bales/ha		
	1135 kg lint/ha		
Gin Turnout	42%		
Seed % of seed cotton	53%		
Weight of seed	11,432 kg/ha		
Seed N content (Sicot 74 BFR)	3.9%		
Seed N removal	56 kg/ha		
Trash N removal	2 kg/ha		
N removal seed cotton	58 kg/ha	11.7 kg N/bale	
% Crop N in seed	55%		
Crop Uptake	106 kg/ha		

N Supply	Available N Pool (kg/ha)	N Pool Use Efficiency	Crop-Available N (kg/ha)
Humic fraction (1.3% OC)	35	80%	28
Labile fraction	14	70%	10
Residual Mineral N (0–90 cm)	90	50%	45
Total effective soil N			83
N deficient (uptake – supply)	23 kg/ha		
N fertiliser efficiency	Low 30%	Typical 40%	Target 50%
Required N rate	78 kg/ha	58 kg/ha	47 kg/ha

Nitrogen derived from mineralisation of organic N sources is generally more efficient as a result of sequential small releases when moisture and temperature conditions are suitable. This release pattern lowers the losses of mineral N at any denitrification event compared to a single pre-plant or simple split fertiliser N application.

- **Concept of Nitrogen-Use Efficiency (NUE)**

With nitrogen being one of the higher variable costs in cotton production, achieving high efficiency has potential to improve profitability and lower environmental impacts. Partial factor productivity of nitrogen (PFPN), Nitrogen Fertiliser Use Efficiency has been adopted as the common benchmark N efficiency measure for irrigated cotton. NFUE is simply the lint yield (kg/ha) divided by total rate of N fertiliser (kg/ha) that was applied to the crop. NFUE is a coarse but useful industry target as it is easy to calculate. Research has defined a target range of Australian cotton production. Crops with NFUE in the range 13 to 18 kg lint/kg N are thought to have been produced from optimised seasonal N tactics (combination of products, timings and application methods). NFUE below 13 kg lint/kg N in irrigated cotton suggests higher rates of application for the yield achieved, while figures above 18 kg lint/kg N may indicate under-fertilisation and lost yield, although this is not always the case.

In the absence of frequent denitrification and leaching events associated with irrigation, dryland NUE appears to be higher than that for irrigated production.

Improving NUE requires careful investigation of the causes of the inefficiency before modifying seasonal N fertiliser tactics (Figure 2.10). Improvement of efficiency may be achieved more reliably by modifying soil physical characteristics and irrigation practices without changing seasonal N tactics.

With reducing denitrification being the prime opportunity to improve NUE, the following are areas of management change that should be investigated:

- Identify production areas with soils that have potential for soil structural decline (e.g. sodic, magnesic dispersive) and back-to-back cotton, and manage appropriately.
- Consider the effect of run length, slope and hill shape.
- Reduce duration of anaerobic soil conditions by introducing practices that increase water infiltration rate and internal drainage, e.g. use of gypsum rotation and with cereal.
- Shorten irrigation duration to optimally fill soil profile.
- Adjust seasonal N application tactics to account for limitation not addressed in the points above.

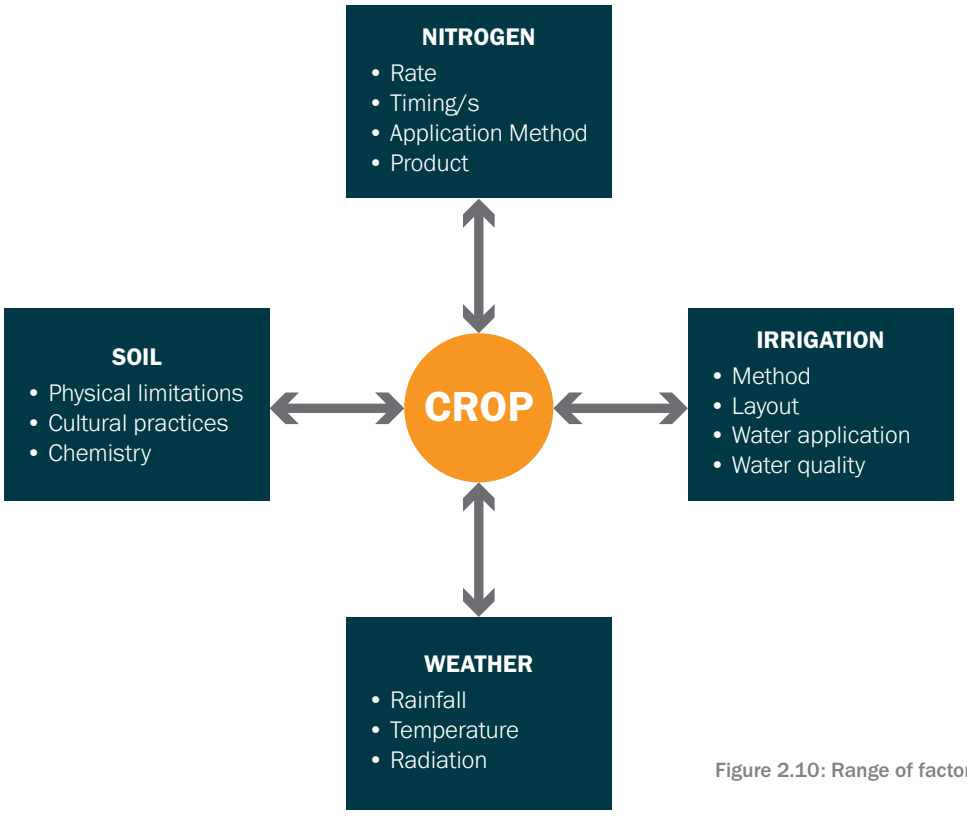


Figure 2.10: Range of factors influencing NUE in irrigated crops.

N cycling in cotton soils

A complex cycle exists in the soil, where N is transformed through numerous pathways, converting nitrogen contained in organic matter (proteins and amino acids) into plant-available forms of N (i.e. nitrate and ammonium). Nitrogen can be added to the system as N fertiliser or by growing legume rotation crops, and can be removed by nitrate leaching, denitrification, volatilisation, crop residue burning, and N in harvested seed cotton. The cycle in Figure 2.11 is not closed, as various processes are constantly adding or removing N.

RUTH REDFERN

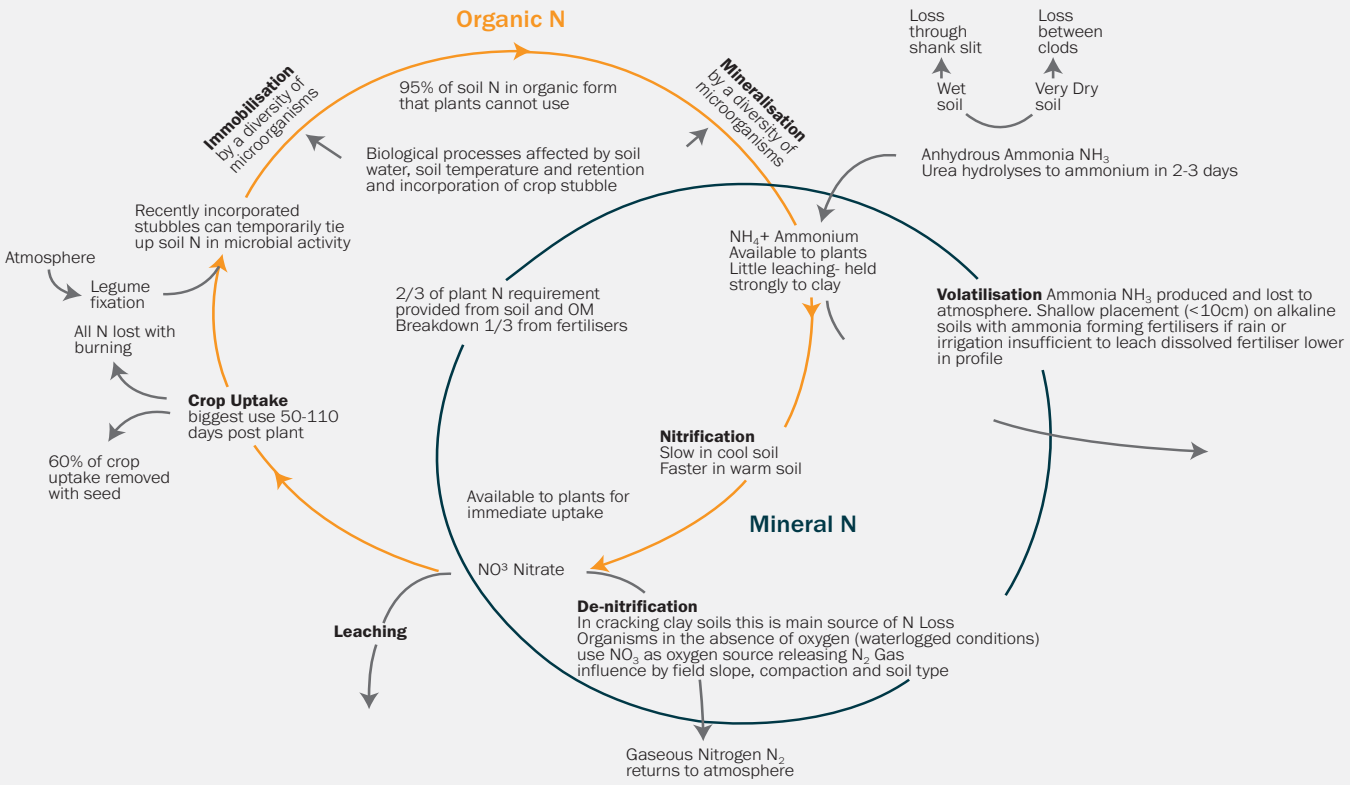


Figure 2.11: The N cycle indicating pools and processes of relevance to cotton production.

ORGANIC N AND MINERAL N

Normally, more than 95% of soil N is in an organic form that plants cannot use. Organic N must first be mineralised before it becomes available to the plant. This is a biological process performed by diverse microorganisms present in the soil. Plant-available (mineral) forms of N – ammonium (NH_4^+) and nitrate (NO_3^-) – are available to the crop for immediate uptake.

organic N ⇨▸mineralisation ⇨▸plant-available (mineral) N

Because soil organisms also require N, they compete for the available mineral N and convert a portion of this N back into organic forms. The process whereby plant-available (mineral) N is converted into an unavailable organic form by the soil's microbial populations is called immobilisation.

mineral N ⇨▸immobilisation ⇨ organic N

These two opposing processes operate continually within the soil, creating a balance between plant available (mineral) N and organic soil N. Mineral N converted into organic N is not lost from the system, but becomes available as other soil organisms recycle the organic N back into a plant-available N.

While some organic N, such as stubbles, is readily decomposed (labile), much organic N is highly resistant to decomposition (associated with the soil humic and recalcitrant carbon fractions). Because these processes are biological, the balance is affected by the soil-water content, soil temperature and, particularly, the retention and incorporation of crop stubbles. The N fertility of soil can be improved by legume cropping as well as N fertiliser application.

The nitrification process involves the conversion of ammonium (whether from organic matter or ammonium fertiliser) to nitrate. This process may take a couple of months after fertiliser is applied to cool dry soil, but only two to three weeks in warm moist soils. Nitrification will proceed more slowly where N is applied at high rates, because of the high pH and ammonia concentration in the soil around the fertiliser band. In unfertilised soils, very little ammonium normally exists because of the dominance of the nitrification process. Nitrate (NO_3^-) is the most common form of mineral N in alkaline soils. Ammonium (NH_4^+) derived from the fertiliser or organic matter is quickly oxidised to nitrate by nitrifying microorganisms. Mineral N levels fluctuate throughout the year (Figure 2.12) with concentrations lowest in August/September in back-to-back irrigated crops. This corresponds to the recommended sampling time for soil nitrate analysis. In dryland and irrigated crops that have been long-fallowed sampling during winter and early spring in the planting year, the soil nitrate is generally at its highest.

LOSSES OF N FROM THE SYSTEM

Nitrogen can be lost from the system in various ways:

- removal of produce (seed cotton)
- denitrification (especially through waterlogging)
- leaching (both lateral and horizontal)
- volatilisation (ammonia lost from soil surface after fertiliser application, especially urea)
- burning stubble.

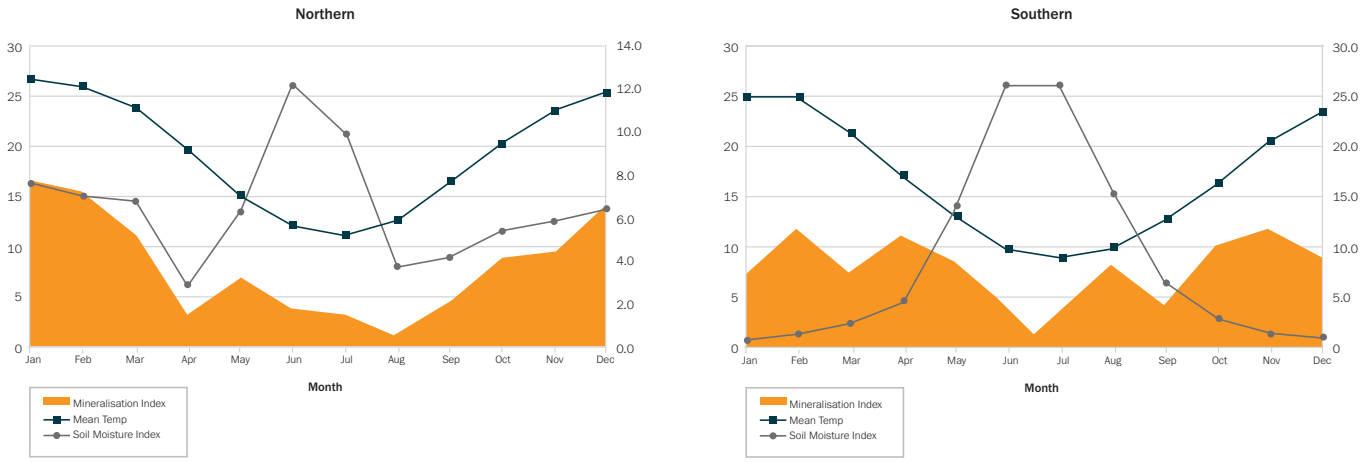


Figure 2.12: Contrasting long-term average N mineralisation pattern in northern summer-dominant and southern winter-dominant rainfall cotton-production regions, based on mean temperature and median rainfall.

REMOVAL IN PRODUCE

Removal of N in cotton differs from the majority of other crops grown in rotation as the highest value part of the harvested crop contains little or no N. The N removal in cotton is dominantly in the seed, with a lesser quantity contained in trash caught in the lint and extracted during ginning.
The key determinants of N removal are the weight and N content of seed and trash, each of which varies to some extent with variety, crop management and growing conditions. Table 2.2 shows change in N removal resulting from recent improvements in ginning % with low-density seed varieties. The apparent 11% increase in seed N% has been more than offset by a 23% reduction in the weight of seed removed, resulting in an overall 10% reduction in N removal per bale.

DENITRIFICATION

Denitrification is a biological process whereby soil nitrate-N is converted to nitrogen gases and is lost to the atmosphere. It is the most significant N loss process in clay soils. High soil temperatures and saturated soil encourage denitrification. Following flood irrigation and/or heavy rainfall, the soil profile may become waterlogged. The pore spaces in the soil become devoid of oxygen as air is forced from the profile. As the soil-water content increases up to Field Capacity, mineralisation of organic N is stimulated, which also consumes oxygen. Under these circumstances, the denitrifying microorganisms start to use nitrate as a source of oxygen. This reduces the amount of mineral N available for the cotton crop.

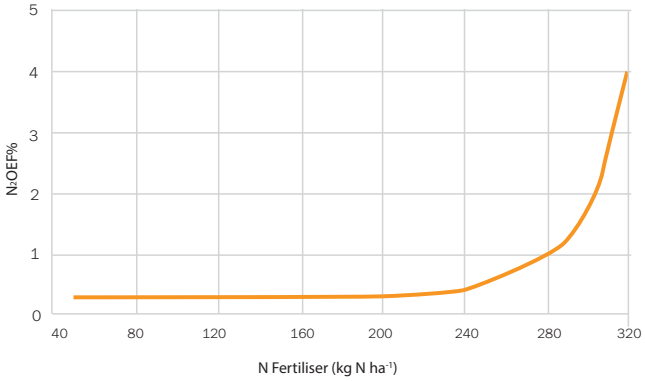
Table 2.2: Variables influencing per bale (227 kg lint) N removal.

Raw cotton composition	44% lint + 51% seed + 5% trash	38% lint + 57% seed + 5% trash
Seed kg/bale	263 kg/bale	340 kg/bale
Seed N%	3.9%	3.5%
Seed N removal	10.3 kg/bale	12 kg/bale
Trash kg/bale	52 kg/bale	30 kg/bale
Trash N%	1.7%	1.7%
Trash N removal	1 kg/bale	0.5 kg/bale
Total removal	11.3 kg/bale	12.5 kg/bale

Nitrous oxide (N_2O) gas, a component of denitrification emissions, is a greenhouse gas (GHG) 298 times as potent as carbon dioxide. It is a major target for Australian agriculture's contribution to GHG emissions reduction. Although the default N20 emission factors of 0.55% and 0.08% for irrigated and dryland cotton production respectively may seem insignificant, actual N loss via N_2 (dinitrogen) gas can be 10 to 50 times these values, thereby averaging a total loss of 5% to 25% of N applied for irrigated, and 1% to 4% in dryland crops.

The degree of loss increases exponentially when soil and fertiliser N exceeds crop uptake (Figure 2.13). The relationship between N rate and N_2O loss in Figure 2.13 is derived from studies where all N was applied pre-planting. This relationship may not be the same for other tactics, such as splitting N application pre- and post-sowing.

Figure 2.13: N_2O emissions increase with N fertiliser rate in irrigated cotton where all N had been applied pre-plant.



RUTH REDFERN

Managing denitrification risk – summary of significant factors in irrigated cotton

SOIL PARAMETERS

- **Soil type** – consider the interaction of chemical and physical characteristics, and irrigation layout that can increase the risk of waterlogging and therefore denitrification potential.
- **Soil water** – assess the risk of applying N, with knowledge of soil-water content and forward risk of waterlogging, from general climate data.
- **Soil N sources** – maximise N available from soil organic matter sources.

IRRIGATION PARAMETERS

- **Slope** – ensure optimal drainage through degree and consistency of slope appropriate for the soil type and length of field where the method of irrigation is via mass water flow (flood/furrow).
- **Bed shape and dimensions** – should be designed around the physical characteristic of the soil to minimise waterlogging and maximise water infiltration rate.
- **Water application rate and method.**
- **Water quality** – should be monitored to ensure it does not cause a decline in the stability of physical soil characteristics.
- **Efficient removal of tail-water** during irrigation and rainfall events that create run-off.
- **Reuse tail-water** containing significant quantities of N immediately to avoid losses while stored in channels and storage.

NITROGEN-SUPPLY PARAMETERS

- **Product** – ammonium forms preferred but with consideration of logistics and cost.
- **Rate** – minimise exposure time as nitrate; the application rate is a compromise between product, logistics, cost, crop requirement and forward denitrification risk.
- **Timing** – as close to crop demand as practical.
- **Placement** – apply in a location that maximises root exploitation and minimises risk of root damage and loss via denitrification and lateral movement.

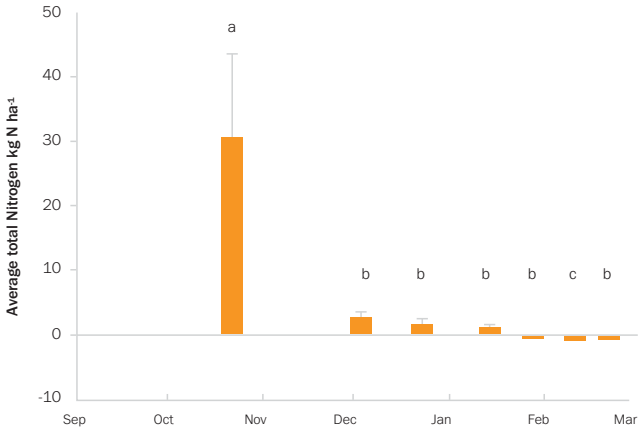
LOSS FROM SOIL

The loss of fertiliser N during crop growth is variable and site dependent. In irrigated cotton experiments at Dalby, Wellcamp, and Narrabri, between 12% and 65% of N applied was lost from the system, as well as some non-fertiliser N. Fields with poor drainage, low slope, poor soil structure, compaction, high organic matter content etc. may be predisposed to severe denitrification losses. Soil clay content (texture) is closely related to denitrification loss. Australian research has shown that inhibitor chemicals applied with the fertiliser can reduce the loss of N fertiliser through denitrification in cotton-growing soils, but increased yield and profitability have been less reliable.

LOSS IN IRRIGATION WATER

Movement of soil nitrate-N by irrigation water is a common feature of flood irrigation systems. The wetting front of irrigation water dissolves soluble N salts in the surface soil, moving them down the length of the field (horizontal leaching), and from watered furrows to non-water furrows (lateral leaching). The majority of N movement is associated with the first two irrigations and will increase further where in-crop N application is shallow (Figure 2.14).

Figure 2.14: Nitrogen contained in irrigation water where urea was surface spread just before the first irrigation (MacDonald 2015).



Another potential N loss during irrigation is N dissolved in the water (water-run) that is allowed to run off the field in tail-water.

Where water is recycled on-farm, there is potential for reuse of water-borne N in tail-water, however, denitrification losses occur from channels and water storage structures with water containing NO_3-N.

NITRATE LEACHING

Because the nitrate ion, NO_3^-, is not strongly held to clay and organic matter, it is subject to movement within the soil profile. Downward movement of ions (leaching) is a problem in coarse-textured soils (loams and sands) and in well-structured clay soils. In clay soils where movement of soil water is slow, nitrate movement is also slow. During flood irrigation, surface soil high in nitrate is washed into cracks with the irrigation water, thereby transporting nitrate (and soil) into the subsoil. Studies at ACRI have demonstrated deep drainage losses of 2 to 18 kg of NO_3^- N/ha, averaging 15 kg of NO_3^- N/ha per year, from 2008 till 2013.

High levels of nitrate at depth are commonly reported in dryland cropping soils where long fallows are used. This nitrate may have accumulated over many years, particularly in the early years of cropping where mineralisation of N from native soil organic matter frequently exceeded removal rates. The use of deep nitrate by cotton in dryland is possible in proportion to the use of water from deeper in the profile. Most N taken up by an irrigated crop is derived from the surface 50 cm of soil.

AMMONIA VOLATILISATION

Ammonia volatilisation can result in significant N loss from ammonium-forming fertilisers (e.g. urea, ammonium sulphate, DAP) applied to the surface of alkaline soils, or at shallow (<10 cm) depths. Where high concentrations of ammonium exist at the soil surface, ammonia gas can escape into the atmosphere. Volatilisation is a purely chemical process driven by environmental parameters, such as soil pH, calcium carbonate content, temperature, ammonium concentration and wind speed. Addition of urease inhibitors to surface-applied urea has been shown to be effective in reducing ammonia loss, but has not been shown to reliably improve profitability.

Improving soil N fertility with legume crops

N FIXATION BY LEGUME CROPS

All effectively inoculated legume crops have the capacity to fix atmospheric nitrogen (N_2) and incorporate this N into their tissues via an association with bacteria (Rhizobium spp.). As a legume seedling's root system comes near live Rhizobia bacteria, the bacteria infect the root hairs. Nodules form on the roots as the bacteria reproduce. The Rhizobia contain an enzyme (nitrogenase) that converts N_2 into a plant-available form of N. The conversion process requires a high input of energy in the form of carbohydrate that is 'donated' by the plant. In turn, the plant is rewarded with a supply of N from the nodules in this symbiotic relationship.

INOCULATE LEGUME SEED BEFORE SOWING

Cotton-growing soils often contain low amounts of these Rhizobia bacteria, hence selected strains of the bacteria should be applied when the legume crop is sown.

As most legumes are quite specific in the strain of Rhizobia that can infect the root, growers should apply the appropriate Rhizobia inoculum strain at the recommended rate. The inoculum can be applied either to the seed just before sowing or diluted and injected into the soil with the seed at sowing. Because the inoculum is a live organism, temperature and moisture conditions during application are critical for effective inoculation.

SOIL NITRATE IN LEGUME SEEDBED

Because soil nitrate-N concentrations are normally low (<4 mg/ha) following a cotton crop, a legume crop sown after cotton will need to derive most of its N requirement from N fixation. Where high levels of plant-available nitrate-N are present in the soil, the crop will use that N in preference to fixing N. If nitrate-N is greater than 20 mg/kg (0 to 120 cm), legumes are unlikely to provide a net N benefit to subsequent crops.

WATER STRESS

Legume crops grown under moisture stress from either waterlogging or drought will not fix as much N as crops grown in good soil moisture conditions. Nutrient deficiencies in the legume crop will also affect N fixation. Similarly, soil salinity drastically reduces N fixation.

SOIL STRUCTURAL IMPROVEMENT

Legume crops offer other beneficial effects, such as improving soil structure (tilth) that makes ploughing and root growth of following crops easier. Green manuring of some legume crops may also reduce the effects of some cotton pathogens. Legume crop stubble should be incorporated into the soil to reduce the incidence of seedling diseases (such as Pythium and Rhizoctonia spp.) that may be encouraged by stubble left on the soil surface.

SLOW-RELEASE NITROGEN

Because legume-N is added to the soil in an organic form, it must go through the mineralisation process before that N is available to the following crop(s). As this may take several years or several crops, the addition of legume-N can be thought of as a slow-release form of organic N fertiliser. Losses of N from legume stubbles are substantially less than that from the equivalent input of chemical fertiliser-N.

COMMERCIAL LEGUME CROPS

Surveys of commercial legume crops grown in rotation with cotton indicate that high levels of N fixation are possible in this system. Although substantial quantities of N can be removed in grain, normally there is a net input of N into the system (Table 2.3).

Table 2.3: Means and ranges of the proportion of crop N fixed, N_2 fixation and residual fixed N (including estimates of below-ground N) in 98 legume crops grown in rotation with cotton. Where no estimates of residual fixed N are provided, no grain was harvested and the crops were green manured (all fixed N was returned to the soil). Data from Rochester et al. (1998).

Species	No. of crops	Prop. crop N fixed (%)	N fixed (kg/ha)	Residual fixed N (kg/ha)
		mean	mean	mean
Summer				
soybean	6	83	371	194
peanut	2	80	273	168
(late sown)	3	40	84	33
(saline)	1	14	37	-20
adzuki bean	4	20	12	5
mung bean	5	51	47	12
pigeon pea	5	14	16	
cowpea	3	74	160	
lablab	9	73	140	
Winter				
faba bean	35	74	177	113
lupin	3	71	176	97
field pea	5	75	161	
lentil	1	61	169	
Winter forage				
clover	9	86	118	
medic	3	84	149	
vetch	4	89	171	

MELANIE JENSON

3. Phosphorus (P)

Role of phosphorus in the plant

Phosphorus (P) plays a central role in the conservation and transfer of energy in cell metabolism. P deficiency reduces seedling vigour, and slows plant establishment and root development. Deficient plants are usually stunted, dark green in appearance, and exhibit delayed flowering, boll set and maturity.

In short or cool wet seasons, good P nutrition is critical to avoid delayed crop maturity and the possibility of reduced yield.

Both phosphorus and potassium (K) are important in late-season crop nutrition because they are implicated in premature senescence syndrome. As the crop matures, phosphorus is translocated from the leaves to the developing bolls. P uptake will be reduced during waterlogging or overcast weather. During these events the plant can draw on plant reserves if sufficient P is stored within the plant, although during periods of high demand if there are insufficient P reserves, this may become one of the causal factors in premature senescence of older foliage.

Uptake and removal of phosphorus

High-yielding cotton crops typically take up 18 to 43 kg/ha P, and remove between 14 and 28 kg/ha P in the seed cotton, equivalent to approximately 1.7 to 2 kg P/bale. On soils with a long history of cotton production, this removal amounts to a substantial reduction in soil P reserves where P has not been replaced. Peak P uptake (0.3 to 0.6 kg/P/ha per day) occurs between mid-flowering and boll filling.

Phosphorus deficiency symptoms

P deficiency symptoms for cotton include stunted plants with dark green foliage, which may later become discoloured (reddish, purple on some plant parts) as shown in Figure 3.2.

Figure 3.2: P deficiency symptoms include stunted plants that later become discoloured.

DR IAN ROCHESTER

MATTHEW HOLDING

Figure 3.1: Pot plant trial of rates of Granulock Z (22% P, 11% N, 4% S and 1% Zn) applied; 0 kg/ha, 200 kg/ha and 400 kg/ha.

When the deficiency is not corrected, fruiting is delayed and restricted (Figure 3.3).

Figure 3.3: The sample on the left-hand side is P deficient. The right-hand sample has adequate P availability.

CHRIS DORAHY

Critical P levels in the plant

Plant tissue testing is a useful way to assist in the assessment of plant P status. The concentration of P in the youngest mature leaf (YML) is relatively independent of the stage of crop development, and is normally around 0.33% P for healthy cotton crops.

Phosphorus fertilisers

If P deficiency is suspected, either due to declining soil P availability or poor crop vigour, then P fertiliser may be needed. Phosphorus can be applied in small test strips to assess its need, and used in conjunction with soil and plant tissue testing. Mono-ammonium phosphate (MAP – N:P:K – 10:22:0) and blend and compounds containing MAP are the most common P fertiliser used. MAP is an acidic (pH 4 to 5) product that is known to maintain P in solution longer than calcium phosphate products in calcium-rich soils. It can be applied at higher rates in the seed trench of irrigated and dryland crops than DAP due to its acidity, relatively low ammonium content and low salt index. When broadcast, both MAP and DAP are likely to provide similar results if incorporated. There is more potential for volatilisation loss from DAP than MAP if not incorporated. Recommended rates are generally in the range of 10 to 30 kg/ha P (45 to 135 kg MAP/ha).

Banded placement of fertiliser P should be carefully considered. Previous recommendations were to place fertiliser P in a band with or below the seed. More recent work suggests that cotton is not particularly good at finding or exploiting bands of P in the soil. The current recommendation is to treat the largest volume of soil (horizontally and vertically) as possible. Phosphorus must be applied to the area of the soil profile where roots will be active. Treating a large soil volume maximises the fertiliser that is intercepted by plant roots.

MATTHEW HOLDING

Figure 3.4: Eight rows (right half of image) missed 70 kg of Starter Z fertiliser (22% P) on a Darling Downs irrigated field. Yield was halved in these rows even though N was not limiting across the field.

Low rates of P can be applied with the seed (up to 9 kg/ha P or 40 kg/ha MAP) where there is good seedbed moisture. There is a danger that the ammonia released and osmotic pressure from the MAP will affect germination and seedling establishment. For this reason, DAP (18:20:0) should not be applied with the seed. Side-dressing P fertiliser between sowing and squaring may not be as effective as applying P pre-sowing, but may be considered if pre-sowing application of P is not possible in responsive soils.

Soil P availability

Australian cotton-growing soils typically have a high clay content and a high cation exchange capacity (CEC), and are alkaline (pH>7.5). Under alkaline conditions, P availability is often low, despite the soil having a high total P content.

The range of pools of P in the soil have varying levels of solubility/availability to the plant. These pools, outlined in Figure 3.5, are discussed in detail under the monitoring of soil P using the Colwell and BSES P soil-testing methods (below). Australian cotton soils also have a low to moderate buffering capacity (phosphorus buffer index, PBI). This means that:

- As cotton plants grow and remove P from the soil solution, this pool of P is quickly replenished from less soluble pools (the sorbed P pool).
- When P fertilisers are applied, much of the fertiliser P reacts with soil cations, forming precipitates such as calcium phosphate in the soil, and reducing the immediate availability of the applied fertiliser P. These precipitates over time will break down and will feed into the other pools of P in the soil, some of which are plant available. This process is explained in Figure 3.5.

Monitoring soil P

The highest concentrations of P generally occur within the surface 30 cm of soil but significant quantities may also be found in the subsoil. Cultivation, land forming, and laser levelling will affect the distribution of P within the profile.

A range of soil-testing methods are now commonly used to assess the likelihood of: (a) the soil being deficient in plant-available P; and (b) achieving a response to applied fertiliser P. To understand the soil-testing methods and their relevance, we must understand the various pools of P in the soil and how they interact, and contribute to plant P nutrition over time (Figure 3.5).

P must be in solution for plants to take it up. It will move across a concentration gradient to be taken up by the plant roots via diffusion. Soil P moves in and out of solution from the 'sorbed P' (or labile pool) through processes known as sorption and desorption. This pool is generally measured using the Colwell soil-test extraction method, which, historically, has been the standard for the cotton industry because of its reasonable ability to predict responsiveness. Typically, the samples for this method have been taken from 0 to 30 cm for irrigated crops, and 0 to 10 cm, and from 10 to 30 cm for dryland crops. Critical soil-test levels from the 0 to 30 cm segment have historically been established as being 6 to 12 mg/kg, but recent work suggests critical levels may be much higher (up to 25 mg/kg).

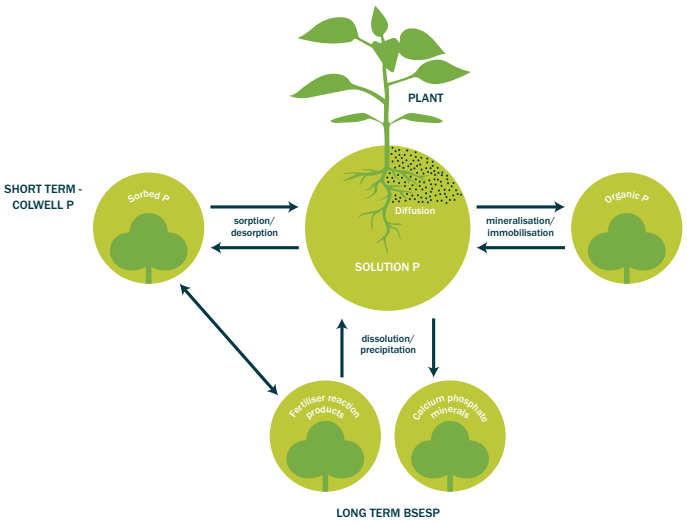


Figure 3.5: The various pools of phosphorus in the soil and how they interact.

More recently, the dryland broadacre cropping industries have been using the Colwell method in conjunction with another soil-testing method, the BSES P, to better predict responsiveness. The BSES method uses a weak acid as the reagent to dissolve some native phosphate minerals and fertiliser reaction products not measured by the Colwell method. The BSES P method is more strongly related to slower release pools of P within the soil. These pools usually consist of compounds formed in the soil, such as calcium phosphate. As the soil's P reserves, these pools keep the faster release pools of P (Colwell P) topped up to provide solution P to the plant. The BSES P method is generally tested for deeper in the

profile, from 10 to 30 cm, although it is useful to know soil-surface levels of P from this pool as well. Critical levels for this method in the 10 to 30 cm segment are less than 10 mg/kg for P (Colwell), and less than 50 mg/kg for P (BSES).

Another method used, generally in conjunction with the Colwell method, is the phosphorus buffering index (PBI). The PBI is a measure of the likelihood of applied fertiliser P being 'tied up' within the soil, making it unavailable, at least in the short term, to the plant. The PBI scale ranges from 0 to 2800, and is generally divided into 9 classifications. The higher the PBI value, the more likely the soil is to create reaction products from applied fertiliser P that are less plant available. The majority of cotton growing has PBI less than 280. Soil tests with PBI values <140 are considered low; 140 to 280 is moderate; and above 280 is considered high.

Mycorrhizae (VAM) and P uptake

Because phosphorus is an immobile element in the soil, increasing soil-root contact can increase a crop's uptake of P. Many crops, including cotton, achieve this through an association with mycorrhizal fungi. The fungal hyphae infect the root and accumulate nutrients for the plant. The fungi increase the volume of soil accessible to the crop several fold and are essential for cotton plants to accumulate sufficient P (and zinc) from the soil.

The response of cotton to P fertiliser is more likely where mycorrhizal colonisation is reduced with low soil temperatures or following long fallow periods. Long fallow disorder has been associated with poor mycorrhizal colonisation, since long periods of bare, weed-free fields, or growth of non-mycorrhizal crops, such as canola, reduce the amount of VAM in the soil. The critical soil P limits may be higher where mycorrhizal colonisation is reduced (Colwell P of 10 to 15 ppm).

MELANIE JENSON

Summary of P management issues

- We may not get an immediate response to all of the applied fertiliser P in the season in which it is applied, but in the majority of low to moderate PBI soils, the P not taken up in year one of application has a high chance of uptake in following seasons.
- Apply fertiliser P to the largest volume of soil and to depth, if possible (to the area where the roots will be most actively working).
- We must understand crop removal amounts of P (up to 30 kg/ha P), and replace at least the amount the crop is removing.
- There is a range of interactions with P occurring in the soil and the various pools in the soil.
- Use the Colwell P method to assess the likelihood of soil P levels meeting crop demand in the short term (critical level <10 mg/kg). Consider critical level as high as 25 mg/kg in cool production areas.
- Use the BSES P method to assess the likelihood of the soil meeting crop demand in the long term in dryland crops, and to measure the longer term reserves of P in surface soils (critical level <50 mg/kg).
- Use the phosphorus buffering index to measure the likelihood of applied fertiliser P being tied up in the short term; the higher the number, the more likely fertiliser P is to be tied up (<140 low; 140 to 280 moderate; >280 high).
- Use soil testing in conjunction with plant tissue testing (critical level around 0.33%).
- Use nil and high P strips in the field to help assess whether P is limiting, and whether responses to applied P are being achieved.

Further reading

Bell, M., Lester, D., Griffiths, B., 2015. *Cotton root systems and poor recovery of P and K fertilisers*, poster.

Dorahy CG, Blair GJ, Rochester IJ, Till AR. 2007. Availability of P from 32P-labelled endogenous soil P and 33P-labelled fertiliser in an alkaline soil producing cotton in Australia. *Soil Use and Management,* 23, 192–199.

Griffiths B, 2016. It's wet, so what do we do now with pre- and at-plant nutrition?, *Australian Cottongrower* magazine.

Griffiths B., 2016. *Phosphorus in Cotton: What do we know and the next frontier?*, 18th Australian Cotton Conference, Gold Coast.

Guppy C., Bell M, Moody P, 2012. *Interpreting soil tests in the light of P, K and S research*. GRDC adviser update, Goondiwindi.

Moody P.W., 2007. Interpretation of single-point P buffering index for adjusting critical levels of Colwell soil P tests. *Australian Journal of Soil Research* 45(1): 55–62. CSIRO Publishing.

McLaren T.I., Bell, M.J., Rochester, I.J., Guppy C.N., Tighe M.K., Flavel, R.J. 2013. Growth and phosphorus uptake of faba bean and cotton are related to Colwell-P concentrations in the subsoil of Vertosols. *Crops and Pasture Science*, 64: 825–833. CSIRO Publishing.

McLaren T.I., Guppy C.N., Tighe, M.K., Moody, P., Bell. M., 2014. Dilute acid extraction is a useful indicator of the supply of slowly available phosphorus in vertisols. *Soil Science Society of America Journal*, 78: 139–146. Soil Science Soc. America.

Rochester Ian J. 2006. Nutrient uptake and export from and Australian cotton field. *Nutrient Cycling Agroecosystems* 77:213–223, Springer Science + Business media.

RUTH REDFERN

4. Potassium (K)

Potassium (K) is the most abundant nutrient in the plant after nitrogen. Potassium is relatively abundant in most Australian cotton-growing soils, although there are increasing areas where reserves have declined and K status is more marginal. This chapter deals with two components of potassium deficiency: the first where soil potassium levels are low, such as in parts of the Emerald irrigation area, the northwest slopes in NSW, the grey box soils on the Darling Downs, and some basalt-derived clay soils that have developed in situ in southern Queensland; the second being an inability of the plant to take up potassium at the rate in which it is required, often resulting in a disorder known as premature senescence.

Role of potassium in the plant

As a mobile element within the plant, potassium can readily move between plant organs. It has an important role in a number of enzymes, including those involved with energy transfer. It is vital for transferring carbohydrates throughout the plant as well as osmotic regulation (maintaining turgor). Potassium is also involved in nitrogen metabolism and protein synthesis.

Overseas research has indicated that K fertilisation reduces the incidence and severity of cotton diseases caused by Verticillium sp. (California), Fusarium sp. and pathogenic nematodes (Egypt). Maintaining adequate plant K concentration has also been reported to reduce the incidence of damping off diseases, although none have been validated under Australian conditions.

The provision of adequate K levels has been shown to increase boll weight, and improve fibre quality, fibre length (characteristics dependent on the maintenance of cell turgor) and maturity (determined by the degree of fibre secondary wall thickening, which is dependent on carbohydrate supply).

Uptake and removal of potassium

Potassium is absorbed as the K^+ ion from the soil solution. Its uptake is affected by competition with the other cations in the soil solution, including NH_4^+, Na^+, Mg^{2+} and Ca^{2+}. Other soil factors that affect K uptake include cation exchange capacity (CEC) and soil structure. As CEC rises, the soil solution K concentration typically falls due to selective adsorption of K onto exchange sites on the clay surface, with the rate of K supply to the plant reduced. Sodic or poorly structured soils can create problems with root activity and other physical, chemical and biological issues potentially reducing the ability of the soil to meet crop K demand (Rochester 2010). As such, exchangeable K soil test values may not always reflect the ability of soil to satisfy the plant's appetite for K. With respect to K nutrition of cotton there are two key points to consider: the amount of K the plant will require, and the rate that the plant requires K.

Cotton can take up more than 200 kg K/ha, with the amount removed in seed cotton dependent on crop yields. The removal of K is split between seed (about 2/3 of removal) and lint (about 1/3). Research results on the impact of soil K status on rates of K removal are variable. There is a narrow range in K removal rates (3.5 to 4.0 kg K/bale) on a single, lighter textured soil with a wide range in soil K availability (Bell, 2015). However, when removal rates are considered across contrasting soil types, the range is considerably wider (3.4 to 7.3 kg K/bale), with the higher values typically driven by higher seed K concentrations. The latter can range from 0.9% to 1.3% between soil types, irrespective of crop K status (Rochester 2006). When these amounts of uptake are considered, another point to be aware of is the phenomenon of stratification of nutrients such as K. With this phenomenon, nutrients are taken up by the roots in large quantities from deeper in the profile, then deposited to the upper part of the profile as the decaying organic material decomposes, post-season. K is relatively immobile in the soil and when redistributed through the profile in this process of stratification, deep K soil reserves will be depleted from the area where they are most likely to be needed, particularly to satisfy late season crop demands. It is important then to monitor soil K levels deeper in the profile, so from 10 – 30 cm, rather than just from 0 – 10 cm as has become common practice.

Another consideration in the uptake of K is that of the rate of supply. During periods of peak demand, K requirements can be in excess of 4 kg/day. This rate of demand will be influenced by a number of factors such as variety, growing season conditions, fruit retention, soil texture, soil moisture status, and a range of other stresses that might influence the plant's ability to uptake K. All of these points need to be considered when determining the ability of the plant's demand for K, and the ability of the soil to satisfy those demands. This is particularly apparent in shorter vs long season areas, where the actual time to produce a crop from sowing to maturity could vary by as much as 60 days, creating a much more intense period of peak demand under the shorter season conditions.

MIKE BELL

Figure 4.1: Severe potassium deficiency symptoms induced by a combination of low-soil K and the sudden onset of a period of waterlogging that restricted root activity.

MIKE BELL

(a)

MIKE BELL

(b)

Figure 4.2: (a) Rapid leaf shedding of cotton canopies caused by low K status and a disruption of crop root activity due to waterlogging; leads to (b) low yields, early maturation but many unopened bolls.

Potassium deficiency symptoms

In the plant, the mobile potassium ion will move to new growth from the older leaves. Hence, K deficiency first appears in older leaves. Initially, the leaf margins and interveinal areas show a yellowish-white mottling, then a rusty bronze colour. Necrotic spots between the leaf veins cause the leaf to appear rusted or dotted with brown specks at the leaf tip, margins, and between the leaf veins. As the leaf breaks down, the margins and leaf tip shrivel. Eventually, the whole leaf dies and is shed as the condition moves up the plant. In severe deficiencies, young leaves are affected and the terminal dies. Premature shedding of leaves prevents boll development, resulting in small immature bolls, many of which fail to open.

The symptoms of severe deficiencies are likely to occur only in soils with low K reserves, where dry weather has restricted root activity in relatively K-rich topsoils, or where a sudden waterlogging event has restricted root activity in a proportion of the soil volume. The latter situation can induce sudden and severe onset of premature senescence, particularly if the waterlogging events coincide with periods of high plant K demand (e.g. during boll loading and filling).

When deficiencies are experienced later in the season, as the developing boll load is a strong and competitive sink for available K, the youngest mature leaf (YML) at the top of the canopy is often the first to show symptoms.

Premature senescence

As in the instance of direct potassium deficiency, premature senescence is also related to an inability of the plant to uptake K at the rate that is required, and usually occurs late season. As opposed to typical K deficiency, the symptoms of premature senescence usually appear on the young leaves during rapid boll filling when peak demand for K, and to a lesser extent P, and other nutrients occurs. Under high demand for K, the developing bolls intercept a large amount of the mobile K before it reaches the new leaves, significantly reducing their availability for normal leaf development. (Wright 1999) reported that while P and other nutrients appear to be associated in the disorder, K is by far the most severely reduced nutrient.

The first visible signs of premature senescence are a slight yellowing of the veins of the youngest leaf. The third or fourth leaf turns yellow then rapidly red or bronze while the underside of the leaf remains green. The bronzing then spreads down the plant, and the upper leaves fall from the plant. In severe cases, bronzing occurs in the middle canopy. As the season progresses, premature senescence symptoms can spread throughout the canopy, and the crop is defoliated. Plants in the edge rows or near gaps are often less affected and appear significantly greener than plants in the immediate rows beside them. Crops other than cotton grown on the same soil may not show any symptoms.

DR IAN ROCHESTER

Figure 4.3: The edge row is often not affected (i.e. greener) in prematurely senescent crops.

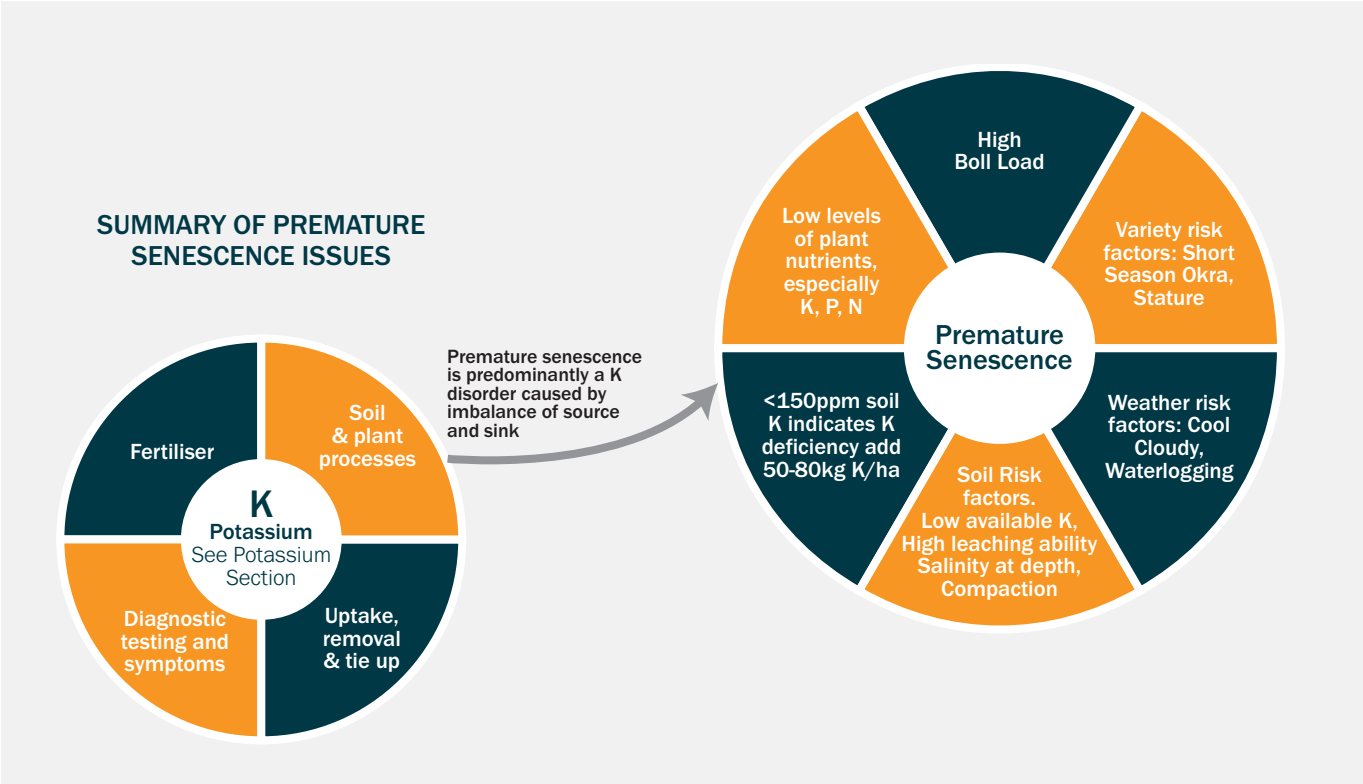


Figure 4.4: Summary of premature senescence issues. (Diagram courtesy Dr PR Wright).

The symptoms of premature senescence can be distinguished from other leaf-reddening symptoms caused by stress. In premature senescence, the area around the veins remains green and the underside of the leaf is rarely discoloured.

It is often too late to correct premature senescence when symptoms appear. Crops should be monitored and the risk of premature senescence assessed for boll load, field history, weather conditions, variety, and soil fertility.

Reducing the risk of premature senescence

PLANT- AND SOIL-CRITICAL K CONCENTRATIONS

Plant-critical levels may vary between cotton varieties. Petioles are the established plant part for assessing plant K tissue levels. Marginal levels of K in petioles generally range from 40,000 mg/kg (4% K) at first flower, to 20,000 mg/kg (2% K) at first open boll. Cotton can redistribute K between plant parts quite rapidly, especially during boll formation and expansion, which can confuse fertiliser recommendations. Petiole tests results may be affected by a range of factors, including plant water status, environmental conditions at the time of testing, such as cloudy weather, time of day, variability in sampling methods. These tests are useful if taken over time, to monitor plant tissue concentrations, and as such should be taken at several timings during the flowering and early boll fill period. The rate of decline should be monitored, as well as giving consideration to individual plant tissue measurements. Their usefulness is not so much to predict future K needs by the plant but to be used to give an indication as to whether soil K levels are meeting or have met plant K demand. (Maunder 2017)

There is little definitive work on critical soil-test K values derived from Australian soils with the commercial soil tests available to the Australian industry, although there is a recognition that the critical available soil K required to grow cotton is higher than that required for cereals and coarse grains. Critical soil-test concentrations for cotton can be as much as 40% to 50% above that required for other crops, presumably because of the coarse root systems that are not very effective at exploiting a given soil volume. While still in development, best estimates of critical soil-test exchangeable K are 0.3 cmol K/kg in the top 10 cm layer, and 0.2 cmol K/kg in the 10 to 30 cm layer. The values for cotton will be somewhat higher (e.g. 0.4 cmol K/kg in the top 10 cm, and 0.3 cmol K/kg in the 10 to 30 cm layer), with the critical values also increasing in soils with high CEC.

Other factors may influence the critical exchangeable K. They typically relate to factors that affect the efficiency of the root system at exploiting a given soil layer (e.g. death of fine roots due to waterlogging and low oxygen availability), or the efficiency with which K can diffuse from undepleted soil away from the zone of K uptake (soil physical condition and structure). As such, soils that are strongly sodic and/or magnesic, or under irrigation layouts where periodic waterlogging occurs, will require higher critical exchangeable K than soils where root growth and K diffusion are less constrained.

POTASSIUM FERTILISERS AND THEIR APPLICATION

Potassium chloride (muriate of potash) is the most widely used source of K, and the cheapest per kilogram of K applied. Potassium sulphate and potassium nitrate are used less commonly. With the exception of sandy soils with low CEC, fertiliser K is rapidly adsorbed onto the exchange sites on clays and organic matter where it is retained for subsequent crop uptake. In other words, applying fertiliser K into soil is like putting money in the bank.

The two most important factors in the decision to invest in K fertiliser are:

- Deciding why the application is being made (i.e. to maintain soil fertility status, or to overcome a deficiency and gain an immediate crop yield response)
- Applying the K in a way that will give the crop the best chance to acquire the nutrient (i.e. the right product in the right place at the right time).

For both considerations, you must remember two things:

1. K (and also P) are effectively immobile in all soils except the lightest of sands, so they stay where they are put by the fertiliser rig and any subsequent tillage. If you put them in part of the profile where there is limited root activity, there will be limited crop uptake.

2. Cotton is not very efficient at using bands of K. Unlike cereal crops, cotton cannot be ‘encouraged’ to multiply roots in and around a band of K by adding N and/or P to the K band. Therefore, the most effective K application strategy is to mix K through as much of the soil profile as is easily accessible, and then manage the crop to ensure root activity in those

layers is prolonged. This strategy is particularly effective in soils where K is not fixed in interlayer positions, as can occur in clays with particular mineralogies. There is limited evidence of this phenomenon being widespread in soils supporting the Australian cotton industry (Bell, Lester et al. 2015).

The optimum rate of applied K will depend on the background K status (e.g. is the soil deficient or marginal in terms of K supplying capacity? or are you simply trying to replace the K removed in the previous crop?) and the soil CEC. The latter is an indicator of how strongly K will be held on the clay surfaces, and hence how rapidly it can be released to replace K taken up by the crop roots. This feature is termed 'K buffer capacity'. In soils with high CEC (e.g. >30 cmol/kg), K buffer capacity is also high. Occasional K applications at high rates may be more effective than small annual applications of K fertiliser, especially when that K is being mixed through the soil volume with tillage.

Applying K into the soil is the most effective way of getting K into the plant and overcoming a K deficiency. While there is interest in the use of foliar K applications potassium nitrate (KNO_3), potassium sulphate (K_2SO_4) and potassium thiosulphate ($K_2S_2O_3$) are of similar effectiveness, particularly to treat K deficiencies later in the growing season, the amount of K that can be absorbed through leaves is limited relative to that required to meet crop demand. However, where soil K levels are adequate, and fruit load and other risk factors are high, foliar K application can prevent premature senescence before symptoms appear. Up to four applications may be required,
7 to 14 days apart, to correct K deficiency, starting at flowering. This approach is expensive and should be used only when there are strong indications that premature senescence is likely to appear later in the season.

References

Bell M (2015). Developing soil testing and fertiliser response guidelines to manage P, K and S fertility for irrigated and dryland cotton cropping systems. Final Report. Cotton Research and Development Corporation.

Bell, M. J., D. W. Lester and B. Griffiths (2015). Cotton root systems and poor recovery of P and K fertilizers. *Roots Down Under - Belowground solutions to global challenges*. Canberra, ACT.

Rochester, I. J. (2006). Nutrient uptake and export from an Australian cotton field. *Nutrient Cycling in Agroecosystems* 77(3): 213-223.

Rochester, I. J. (2010). Phosphorus and potassium nutrition of cotton: interaction with sodium. *Crop & Pasture Science* 61(10): 825-834.

Maunder M.P. (2017). *Potassium Sampling methods in Australian Cotton*. BRurSc Hons Research Project, University of New England.

Wright, P. R. (1999). Premature senescence of cotton *(Gossypium hirsutum L.)* - Predominantly a potassium disorder caused by an imbalance of source and sink. *Plant and Soil* 211(2): 231-239.

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5. Other essential nutrients

Other essential plant nutrients, namely zinc, iron, copper, boron, calcium, magnesium, sulphur, manganese and molybdenum are discussed in sequence. The relative quantities of each essential nutrient taken up by cotton and removed in seed cotton is shown in Table 5.1.

Table 5.1: Uptake and removal of essential nutrients by high-yielding (12 b/ha) irrigated cotton crops. (Rochester 2007)

Macronutrients	Nutrient	Uptake (kg/ha)	Removal (kg/ha)	% Removal
	N	350	180	51
	K	300	45	57
	P	50	30	15
	S	75	12	17
	Ca	300	7	2
	Mg	78	18	23
Micronutrients		**Uptake (g/ha)**	**Removal (g/ha)**	**% Removal**
	Zn	225	130	58
	Cu	100	30	29
	Mn	800	18	2
	Fe	1900	190	10
	B	685	70	10

ZINC (Zn)

INTRODUCTION

Zinc is the micronutrient that is most likely to be limiting in soils used for cotton production throughout Australia. Yield losses and crop productivity decline have been attributed to this Zn deficiency, and therefore, need to be considered in a balanced soil fertility and crop nutrition program. Zinc is very immobile in the soil, and long fallow disorder is often manifested as Zn deficiency.

a. Role of zinc in the plant

Although zinc is an essential nutrient for normal plant growth, it is needed in only small amounts. It is a constituent or regulatory co-factor of a variety of enzymes associated with many important biochemical pathways, including protein synthesis, growth regulation, pollen formation, phyto-hormone production, and carbohydrate metabolism.

b. Uptake and removal of zinc

Zinc is dominantly acquired by plant roots via diffusion and its uptake also relies on root extension to provide new areas of high soil Zn concentration. Natural and imposed growing conditions that impair root density and elongation are likely to reduce Zn availability. Cotton crops normally take up between 150 and 300 g Zn/ha for 10 to 15 bale crops (Rochester 2007). Removal can also vary considerably as a result of variation in seed Zn concentration. US data suggests that between 47% and 55% of the Zn uptake is removed, but recent removal measures for Australia suggest a higher removal range of 60% to 99%. Zinc removal in harvested material is generally in the range of 10.5 to 12 g/bale; the quantity removed per bale generally reduces as yield increases (Mullins and Burmester 2010, Rochester 2012). Most of the Zn is taken up from first-square to peak boll fill, during which time 1.9 to 4.1 g Zn/ha/day is accumulated (Constable et al. 1988). Between 25% and 45% of the total plant uptake can be accumulated during the peak two-week period around mid-flower (Mullins and Burmester 2010).

c. Zinc deficiency symptoms

Zinc is relatively immobile in the plant. First deficiency symptoms can be seen shortly after the first true leaves appear. Plants lack vigour and appear unthrifty.

They are often shorter with thin stems, and have less branching, flowering and boll set. In young plants, symptoms appear as dark brown interveinal necrotic lesions (bronzing) on the older true leaves. They develop without prior chlorosis, and leaf margins are often cupped upwards. Eventually, the lesions join up and the leaf dies. If the deficiency persists, young leaves develop a pale yellow, blotchy chlorosis (yellowing between the leaf veins) appearance. Leaves become very small and are malformed, having holes or torn margins (Grundon 1987).

Crops may appear to grow out of Zn deficiency, especially when cotton is grown after long fallows, however yield, maturity and fibre quality may be severely affected. It is important to note that sub-clinical Zn deficiencies (no visual deficiency symptoms) can reduce yield and impair fibre quality.

d. Critical zinc concentrations in the plant

Adequate concentrations range from 20 to 60 mg Zn/kg in youngest mature leaf at first flower. Zn concentrations below 20 mg/kg in leaves indicate the crop may not be taking up sufficient quantities of Zn. The concentrations of P and Zn should be in the ratio of about 100:1. Also, the concentrations of manganese and Zn should be in the ratio of about 1.2:1, with very high values indicating long fallow disorder.

e. Zinc in the soil

Most of the Zn found in the soil is of low solubility and unavailable to plants. It is found in five main chemical pools in the soil: (1) soil solution; (2) on exchange sites of reactive soil components; (3) in complexes with organic matter; (4) co-precipitated with oxides and hydroxides of aluminium, iron and manganese; and (5) held in primary and secondary minerals. The pools are listed in successively decreasing degrees of availability (Viets 1962).

The Zn found in soil solution, such as the ions Zn^{2+}, $ZnCl^{+}$, and $ZnOH^{+}$, is readily available for plant uptake, however concentrations are very low and sensitive to changes in pH (Armour and Brennan, 1999). Being very immobile in the soil, zinc tends to concentrate in the surface soil, with lesser amounts detected in deeper soil layers. Soluble Zn, for example, when applied as a fertiliser, quickly becomes unavailable in the soil. The removal of the surface soil (i.e. by laser levelling) can significantly reduce the quantity of Zn available to the crop.

Several factors influence the availability of Zn (Armour and Brennan, 1999):

- **Soil pH:** very important soil factor associated with Zn deficiency. Zinc availability significantly reduces with increasing soil pH over the agriculturally important range of 5.5 to 7.0
- **High soil P:** high concentrations of P can reduce plant uptake of Zn (as well as the reverse)
- **Land forming:** removing the soil surface through land forming can remove significant amounts of soil-available Zn
- **Soil organic matter:** much of the Zn can be fixed in the soil organic matter and soil micro-organisms
- **Leaching:** there is very little movement of Zn through soils. Zinc is absorbed on soil colloids or under alkaline soils, and forms insoluble compounds
- **Cold, wet soils:** slow root growth and root exploration under these conditions can severely limit Zn uptake, especially in early spring
- **Soil biological activity:** the presence of vesicular arbuscular mycorrhizal (VAM) directly influences the uptake of Zn.

f. Soil testing

Zinc soil tests are useful for predicting the potential for soil Zn availability to limit yield, but are not expected to predict the quantity of Zn required by the crop (Armour and Brennan 1999). Given the many factors that influence availability, soil-test values need to be assessed with the list of key influencers during the interpretation process. Plant-tissue testing and test strips are more definitive guides to crop Zn supply.

A soil test using the chelating agent DTPA is now the most popular extractant in Australia, and is designed for simultaneously extracting micronutrients Zn, copper, manganese and iron in calcareous soils. Of the range of extraction methods offered by Australian soil laboratories, the DTPA extraction is considered most accurate (included in the ASPAC proficiency program), having a critical concentration of 0.5 mg Zn/kg (Hearn 1981).

With reductions in the frequency, intensity and depth of tillage in modern low-tillage cotton production, soil distribution of Zn (both depth and horizontal spread) is likely to be reduced. Applications of Zn in shallow bands with P, and broadcast with shallow incorporation, are likely to concentrate Zn in the top 10 cm. Soil testing of 0 to 30 cm may not truly reflect the Zn availability in the important 10 to 30 cm soil layer.

g. Zinc fertilisers

- Foliar fertilisers: Zn deficiency symptoms can be alleviated with foliar Zn sprays. A range of foliar fertilisers are available commercially, many with other trace elements. Products should be used in accordance with guidelines on the product label. Care should be taken to apply sufficient Zn to supply the crop's requirement. Zinc sulphate heptahydrate (23% Zn) or monohydrate (36% Zn) at a rate of 1 kg/ha is effective and inexpensive, but should be used with some caution due to its potential to cause osmotic damage (burn) to the leaf surface during some weather conditions. Using it in a directed spray may be sufficient to overcome current zinc deficiency in cotton.
- Soil-applied fertilisers: Traditionally, superphosphate supplied sufficient Zn to many crops (Zn being an impurity), however the use of MAP and DAP, lower in Zn impurity, has contributed to the need to apply Zn in other forms or as an additive in blended and compounded fertiliser products.
- For rapid availability of Zn from products containing P and Zn, in the year of application, it is desirable to use products with a high percentage of water-soluble Zn and low pH.
- Zinc oxide (Z_nO) is very insoluble and therefore immobile in the soil. However, plant roots have the ability to solubilise Z_nO in their vicinity. Between 10 and 20 kg Z_nO/ha broadcast applied should maintain adequate available Zn concentrations for several years, provided it is thoroughly incorporated.
- As a result of its dominantly diffusion-uptake pathway, Zn is better applied to the soil as broadcast and worked into the soil. Following land development, either Z_nO or zinc sulphate should be applied and worked into the surface soil before 'hilling up'. Where banded, the application site should be offset from previous bands to increase the spatial distribution.

h. Vesicular Arbuscular Mycorrhizal (VAM)

VAM fungi normally infect root systems of many crops, including cotton, and form a symbiotic relationship. The fungal strands (hyphae) act as long root hairs and aid nutrient uptake of cotton by increasing the volume of soil explored by the root system. This favours the uptake of the less soil-mobile nutrients, such as P and Zn.

Plants with poor VAM infection may show Zn deficiency symptoms. As VAM infection increases with time, the Zn deficiency symptoms may disappear, but the poorer development of the crop may result in some loss of yield. Applying high rates of P when soil Zn is marginal may suppress VAM and create a Zn deficiency in the crop. Therefore, the requirement for nutrients after a long fallow should include consideration of P and Zn together. Land forming and tillage may disrupt and destroy the continuum of fungal hyphae in the soil, such that the infection of VAM can be reduced in the next cotton crop, resulting in Zn deficiency.

i. Long fallow disorder

This syndrome is often manifested as Zn deficiency. Long fallows can reduce the amount of VAM fungi in the soil, reducing the ability of cotton plants to take up Zn and phosphorus during early season growth. The crop usually grows out of the deficiency, but often with a yield penalty.

IRON (Fe)

INTRODUCTION

Iron is an essential micronutrient and, although extremely abundant in the soil, can be crop limiting. Deficiencies in Australia are mainly seen on high pH (alkaline) calcareous soils, most commonly associated with young cotton that has recently been subjected to waterlogging. Deficiencies can lead to reduced production and lint quality.

a. Role of iron in the plant

Iron is required for chlorophyll synthesis, acts as an oxygen carrier, and is involved in production of some enzymes involved in energy cycles. Iron is immobile in the plant, hence a continuous supply of Fe is required for chlorophyll production.

b. Uptake and removal of iron

The low solubility of Fe compounds in soils severely restricts the plant capacity to take up sufficient quantities of Fe to meet crop demand. Consequently, plants have developed strategies based on rhizosphere acidification, excretion of reductants or chelators, and an increased root reductase activity to increase Fe supply (Fernandez and Ebert, 2005; Rogers and Guerinot, 2002).

Total crop uptake varies directly with crop yield. A crop yielding 1000 kg lint/ha takes up about 230 g/ha, while a crop yielding 2400 kg lint/ha takes up about 1600 g/ha. The percentage removal in seed cotton decreases from 40% of uptake for crops yielding 1000 kg lint/ha to only 11% of Fe taken up for crops yielding 2400 kg lint/ha (Rochester 2012).

Most Fe is taken up prior to boll filling. Peak daily influx rates of 23 to 27 g Fe/day have been reported in the early to mid-flowering period, during which 41% to 60% of the total Fe uptake is accumulated (Mullins and Burmester, 2010, Rochester 2012).

c. Iron deficiency symptoms

Iron deficiencies are mainly confined to the young growth, as Fe is immobile within the plant. Crops lack vigour and yield poorly but are only slightly smaller than normal crops. The young leaves become yellow between the veins (chlorosis) while the veins usually remain green. Under severe deficiencies, veins fade and eventually the whole leaf may turn white (Grundon, 1987). Leaves may appear limp, with the tips and margins hanging down as if wilted. Severely Fe-deficient plants show significant reductions in plant and root growth, roots thicken and do not develop root hairs (Vretta-Kouskoleka and Kallinis 1968). Although the plant may contain high concentrations of Fe, most of it is in an unavailable form, in which case chlorophyll production stops and the leaves lose their green colour.

d. Critical iron concentrations in the plant

Plant-tissue analyses for Fe are problematic to interpret unless the leaf surfaces have been cleaned. This problem arises because Fe is ubiquitous in dust and can be a contaminant on the surface of plant leaves. Most tests rely on analysis of young leaves from the upper parts or extremities of the plants. Young leaves are chosen because Fe, once deposited in the leaf tissue, is not readily retranslocated; hence, older leaves of deficient plants may have a relatively high Fe concentration. Fe deficiency is indicated in the plant where the Fe concentration is less than 30 mg Fe/kg in the youngest mature leaf at first flower. Concentrations above 50 mg Fe/kg indicate adequate Fe nutrition. The P/Fe ratio can aid identification of problems with Fe nutrition; values of about 30 are desirable, whereas very high values (greater than 60) indicate iron deficiency, and leaves may show symptoms of Fe chlorosis.

Iron availability is largely dependent on many soil and environmental factors, such as soil pH and bicarbonate concentration, redox state in addition to the extractable amount of Fe. Therefore, a very reliable soil test method is improbable unless these factors are better understood. It is useful to have information on soil pH and bicarbonate content of the soil sample, and relate that information to Fe availability. For soil analyses, the critical concentration is 2 mg Fe/kg (DTPA extraction).

e. Iron in the soil

Iron is plentiful in the soil, but mainly in forms not available to plants. Plant availability drops rapidly as soil pH rises above pH 7 to 7.5. Iron deficiency can also be induced by an imbalance with other metals or high concentrations of other cations, particularly manganese, but also copper and molybdenum. High concentration of P and Zn, for example, applications of P and Zn fertilisers in a concentrated band, can reduce Fe uptake. P reacts with soluble Fe, producing insoluble Fe minerals.

Other factors that can induce Fe deficiencies include soils with low organic matter levels and irrigation water with high bicarbonate (HCO_3^-), i.e. hard water. Iron deficiencies have been observed in cotton grown on heavy clay alkaline soils, following short periods of waterlogging. When a soil is waterlogged, the passage of carbon dioxide (CO_2) out of the soil is blocked. The CO_2 concentration builds up in the soil solution, forming bicarbonate ions. This increases soil pH, which in turn increases the concentration of bicarbonate and alkalinity in the leaf tissues. Under these conditions, Fe becomes unavailable, i.e. the active iron (Fe_2^+) is converted to the inactive forms (Fe_3^+ and others) and symptoms of chlorosis appear. For further details, see the ‘Waterlogging of cotton’ section in this manual.

f. Iron fertilisers

- **Foliar fertilisers:** A range of foliar fertilisers is available commercially, many with other trace elements. Products should be used as per guidelines on the product label. Iron deficiencies are more often corrected using foliar applications of iron sulphate or iron chelate. Applications should be before first flower at a rate of 200 g Fe/ha. Care should be taken to apply sufficient Fe to supply the crop’s requirement. Product containing iron sulphate should be used with some caution due to its potential to cause osmotic damage (burn) to the leaf surface during some weather conditions.
- **Soil-applied fertilisers:** Soil-applied Fe fertilisers are rarely used to correct soil limitations. This is because soluble, plant-available Fe is rapidly converted to unavailable forms in the soil. Iron chelate fertiliser effectiveness depends on soil pH. For example, Fe EDTA is less stable in highly calcareous soils, whereas the Fe-EDDHA chelate is more stable in alkaline soils.

COPPER (Cu)

INTRODUCTION

Copper (Cu) deficiency has not been observed in Australian cotton, although marginal levels of Cu are often observed in soil and plant analyses.

a. Role of copper in the plant

A constituent of plant enzymes, copper is involved in carbohydrate metabolism and chlorophyll formation. It also has a role in pollen formation; fertilisation and plants have more resistance to fungal attack. Copper deficiency can interfere with protein synthesis.

b. Uptake and removal of copper

Copper is taken up by plants in very small quantities. Iron and zinc (ions of similar size and charge) inhibit the uptake of Cu, and vice versa. The uptake of Cu ranged from 25 g/1000 kg lint/ha to 81 g/2400 kg lint/ha (Rochester 2012).
The percentage exported from the field varied from 51% of the Cu taken up from a crop yielding 1000 kg lint/ha, to 31% of Cu taken up from a crop yielding 2400 kg lint/ha. During the peak uptake period (mid-flower), 29% to 58% of the total Cu uptake is accumulated. Uptake rates of 0.34 to 1.33 g Cu/ha/day have been reported (Mullins and Burmester 1993a, Rochester 2012).

c. Copper deficiency symptoms

Initial indications of Cu deficiency are unthrifty and poor-yielding crops, stunted with short stems and dull green leaves. Branching is reduced, and fewer flowers produced and bolls set. Leaves initially appear limp and wilted, but as the deficiency progresses, a faint, dull yellow interveinal chlorosis develops in the older leaves. In severe cases, dieback of the terminal bud is preceded by peculiar distortions, and tissues die at the tip or base of the terminal (Grundon, 1987).

d. Critical copper concentrations in the plant

Concentrations greater than 5 mg Cu/kg in the youngest mature leaf at flowering indicate sufficient Cu uptake for US cotton (Jones, 1974). Plant tissue critical range has not been established for cotton grown in Australian conditions. A typical seasonal range of youngest mature blade (YMB) copper concentration from squaring to early boll fill is 5 to 8 mg/kg (Rochester 2012).

e. Copper in the soil

In the soil, a value of less than 0.3 mg Cu/kg using DTPA extraction should prompt further investigation of possible productivity restriction due to copper availability. Because copper is tightly bound to soil constituents, little is lost by leaching. Copper availability is reduced in alkaline soil.
Cotton soil tests are as yet uncalibrated in Australian cotton growing conditions so a combination of plant-tissue analysis and harvested test strips (soil or foliar) are suggested before committing to a widespread copper application program.

f. Copper fertilisers

- **Foliar fertilisers:** Where likely to limit yield, copper can be applied as copper sulphate, as a foliar spray at 2 kg Cu/ha. It is contained in a range of other propriety products. Caution should be exercise when applying copper as a sulphate as it can cause osmotic damage to leaf surfaces in some climatic conditions, even at the recommended rate. Apply proprietary products according to label directions.

- **Soil-applied fertilisers:** Copper is most commonly applied to soils in blends and compounds containing N, P, K. Some insoluble copper compounds, e.g. copper oxide, copper hydroxide, and copper oxychloride, may be used as soil-applied copper fertilisers, provided they have a fine particle size. This makes dry application to the soil difficult, if not impossible, but specially prepared products are used in the preparation of suspensions for foliar application. Copper chelate can be applied in solution, either to the soil or as a foliar spray. Chelate trace elements are less subject to fixation in the soil than sulphate, but are more costly.

BORON (B)

INTRODUCTION

Boron, an essential non-metallic micronutrient, is unique—it is the only element normally present in the soil solution as a non-ionised molecule (Gupta 1979). Plants take up boron in the uncharged form as boric acid $B(OH)_3$. Boron is present in most soils in extremely small quantities. It is primarily derived from the organic matter and minerals. Because B is water soluble, it can be leached into the subsoil beyond the depth of crop roots, and can accumulate to toxic concentrations in soil layers where drainage is impeded.

a. Role of boron in the plant

The primary role of B in plants is in cell wall formation and structure. It is essential for germination of pollen grains and the growth of pollen tubes. It is associated with sugar translocation, protein formation and flowering, the development of seed and fruit, and cell membrane function. Boron is also involved in the uptake of calcium.

b. Uptake and removal of boron

Boron is relatively immobile in plants. Under B-limited conditions, B can be mobilised from older leaves to the new growth but not in sufficient quantities to meet the growing crop's demand. When foliar-applied, B can be relocated through the plant to the growing point, temporarily meeting demand, but ultimately, B must be supplied from the soil to allow full growth (Bogiani et al. 2014).

Uptake of B varies with yield. A crop producing 1000 kg of lint has a B uptake of about 75 g/ha and a removal rate of 16.5 g/ha (22%). On the other hand, a crop yielding 2400 kg of lint/ha had a B uptake of 560 g/ha and a removal rate of 61 g/ha (11%) (Rochester 2012). Peak uptake during flower (1100 to 1200 DD) is about 5 to 6 g/ha/day (Constable et al. 1988).

c. Boron deficiency symptoms

Boron deficiency symptoms vary with the stage of growth and the severity of the deficiency. The problem is most commonly found in sandy soils prone to leaching, although may also occur during prolonged dry periods, or in alkaline soils when B availability is reduced.

Mildly deficient crops lack vigour and yield poorly. The plants appear bushy and stunted, with shorter branches and internodes, dark green leaves and stout stems. Flower production and boll set is significantly reduced. In severely deficient crops, the plants often die before any flowers are formed.

The first symptoms of B deficiency appear in new growth, as B is relatively immobile in plants. The youngest leaves are the most severely affected; they hang down and margins are cupped under. The upper internodes are very short, resulting in the new developing leaves in the apical bud to crowd together and eventually die, preventing further growth of the stem. If the deficiency persists, the apical buds in lateral branches also die and, eventually, the whole plant (Grundon 1987). Other symptoms that have been described include deformed and small bolls, boll shedding, hard locks, sepals around the bolls are hard and fail to open, root growth can be severely inhibited and secondary roots stunted (Stevens and Dunn 2008, Gupta 1979).

The range between B deficiency and toxicity is narrow. Toxic concentrations of B result in leaf cupping, chlorosis and death of leaf tissue in localised spots.

d. Critical boron concentrations in the plant

Boron deficiency symptoms may be observed in the youngest mature blade (YMB) at first flower where the B content is less than 15 mg B/kg. Boron content of 20 to 60 mg/kg in the YMB at first flower generally indicates sufficient B uptake. As a result of B soil mobility and tendency to increase in availability with depth in cotton soils, B may be low in young crops that later find adequate supply as the roots explore the subsoil. Timing of plant sampling is therefore important and should be similar to that when assessing other soil-mobile nutrients, such as N and S.

Boron toxicity symptoms appear at concentrations >1000 mg/kg in the plant, and 70 mg/kg in the soil.

e. Boron in the soil

Boron concentrations in soils vary greatly, normally ranging from 20 to 200 ppm (Berger and Pratt, 1963), but only a fraction of this is available to plants (Gupta, 1968). The available forms of B (borax - $B(OH)_3$ and $B(OH)_4$) are mobile in the soil solution but their availability is influenced by several soil properties (FIFA 2006, IPNI 2017):

- **Organic matter:** Organic matter is the most important soil source of B. Factors that affect the rate of decomposition of organic matter (soil moisture and temperature) directly influence B availability. A dry soil surface, where most of the organic matter is found, significantly reduces decomposition and boron release. Cold weather has a similar effect.
- **Weather conditions:** Dry and cold weather restricts root activity in the soil surface, which can cause temporary boron deficiency. Symptoms may disappear when conditions improve (rainfall, increase in temperature), and root growth and activity increases.
- **Soil pH:** Plant availability of B is at its optimum between 5.0 and 7.0. At higher or lower pH values, B uptake is reduced. The use of lime on acid soils can lower B availability if the pH rises above 7.0. In these situations, response to B-containing fertilisers can be enhanced.
- **Soil texture and leaching:** Coarse-textured (sandy) soils, especially when organic matter levels are low and subject to conditions conducive to leaching, can be boron deficient. B is mobile in the soil and can leach out of the rooting zone.
- **Irrigation water:** Some irrigation water, particularly from underground sources, can contain high concentrations of B.

f. Boron fertilisers

Caution is required when using B fertilisers. Appropriate application rates and methods for the use of B fertilisers should be strictly adhered to because of the very narrow range between deficiency and toxicity. Care should be taken to ensure uniformity of application and accuracy in rate. High fertiliser rates and high concentration within rows where B is incorporated into blends and compounds can cause B toxicity (FIFA 2006, IPNI 2017).

- **Soil-applied fertilisers:** Boron fertilisers are best applied to the soil before sowing either as a broadcast and incorporated, banded or dissolved in water, and sprayed onto the soil using borax, boracic acid or other soluble B salts. Usual application rate is about 1 to 2 kg B/ha. It will often remain effective for many years before another application is needed (Grundon 1987, FIFA 2006, IPNI 2017).
- **Foliar fertilisers:** Foliar applications can be used but might be less successful. They should be applied five to six weeks after seedling emergence, or as soon as symptoms appear. Because foliar sprays have no residual value, they might need to be reapplied (Grundon 1987, FIFA 2006, IPNI 2017).

CALCIUM (Ca)

INTRODUCTION

Calcium (Ca) is abundantly available in most Australian cotton-growing soils, and deficiency has not been reported in Australia. These soils are alkaline (high pH) and often contain large amounts of lime ($CaCO_3$). Limestone concretions (small white or grey round pellets) are evident in many soils.

a. Role of calcium in the plant

Calcium has a number of different functions within the plant, including:

- stimulating root and shoot development
- increasing mechanical strength of plant by binding to pectin in cell walls
- maintaining the integrity and selectivity of cell membranes
- activating several plant-enzyme systems
- neutralising organic acids in the plant
- protecting against the damaging effects of other elements.

Calcium also has several indirect influences on the cotton plant:

- Calcium carbonate (lime, $CaCO_3$) reduces soil acidity. This action lowers the solubility and toxicity of aluminium (Al), manganese (Mn), zinc (Zn), and in exceptional cases, copper (Cu).
- Increasing soil pH also increases the solubility of other nutrients, such as molybdenum (Mo), which increases release and uptake.
- The presence of soil calcium improves soil structure by promoting aggregation of soil colloids, improving root growth conditions and stimulating microbial activity.

b. Uptake and removal of calcium

Irrigated cotton crops can take up as much as 289 kg Ca/ha, but remove only about 10 kg Ca/ha in harvested seed cotton (about 0.6 kg Ca/bale) (Rochester 2012). On average, a cotton crop will take up approximately 155 kg/ha of Ca for 2400 kg/ha lint (10.5 bale/ha), of which approximately 5 kg/ha will be removed (3%). Most of the Ca remains in the leaves and stems. Maximum daily uptake occurs during early to mid-flower, when as much as 46% to 49% of the total Ca can be accumulated (Mullins and Burmester 1992).

c. Calcium deficiency symptoms

Calcium deficiency has not been observed in Australian cotton. When induced in the glasshouse, calcium-deficient plants are unthrifty, lack vigour and yield poorly. Affected plants are stunted, with thin stems and dark green leaves. Plants appear wilted even though sufficient soil water is available. Branching is severely reduced, with few flowers and bolls set. In severe deficiencies, apical buds die and plants die before maturity (Grundon, 1987).

Calcium is immobile in the plant and, as a result, deficiencies appear in the young tissue. Internodes fail to elongate, giving the plant a bushy appearance. The young buds on the primary stem turn brown and die. As the deficiency develops, lateral buds and leaf petioles also turn brown and die. Severely affected plants eventually die (Grundon, 1987).

Plants deficient in calcium have poorly developed root systems. They develop brown colouration, extension is inhibited and tap roots are small (Hodges and Constable 2009).

d. Critical calcium concentrations in the plant

Because Ca is rarely limiting, critical concentrations have not been established for Australian cotton. However, 23,000 to 30,000 mg Ca/kg (i.e. 2.3% to 3% Ca) in the youngest mature leaf (YML) at first flower is considered adequate for cotton in the USA (Jones 1974).

e. Calcium in the soil

A soil test critical range has not been established for calcium in Australian cotton-growing soils. Calcium is generally very plentiful in the majority of cotton-growing soils. Calcium carbonate content can vary significantly, from 0.1% in non-calcareous soils to as much as 25% in calcareous soils. It is an important cation being held as exchangeable Ca^{2+} to the soil clay and organic matter. It has a dual role in agricultural systems. As well as being an essential nutrient, it is a key cation in soil structural stability of clay soils. Calcium is often the most dominant cation in the soil, even at low pH. In high pH soils, it is often seen as small white or grey pellets of calcium carbonate.

f. Calcium fertilisers

Calcium can be supplied in several ways. Fertilisers, e.g. single and triple superphosphate, can contribute significantly to meeting crop Ca nutrient needs. Because most Ca-deficient soils are acidic, liming can supply the required Ca. Gypsum (calcium sulphate) can be used when the soil pH is high enough not to require lime (calcium carbonate). Caution is needed when lime is applied because excessive use can reduce the availability, and may lead to deficiencies of other nutrients, such as potassium, magnesium, iron, manganese, zinc or copper.

Fertilisers that contain Ca, e.g. lime for acid-dispersive clays and gypsum for neutral and alkaline-dispersive clays, are normally applied at rates of 2 to 5 t/ha to improve soil structure and reduce soil sodicity (high sodium content).

VON WARNER

MAGNESIUM (Mg)

INTRODUCTION

Magnesium (Mg) deficiency has not been observed in field-grown cotton in Australia. Soils are generally high in Mg, with higher concentrations in the subsoil.

a. Role of magnesium in the plant

Magnesium and N are the only soil nutrients that are constituents of chlorophyll. Mg is the central atom, playing an active and critical role in photosynthesis. It is also important for cell respiration, N metabolism, and oil synthesis. Plants with oily seeds, such as cotton, have a high requirement for Mg.

b. Uptake and removal of magnesium

Uptake of Mg ranges from 16 kg/ha for a crop yielding 1000 kg lint/ha, to 63 kg/ha for a crop yielding 2400 kg lint/ha. Removal ranges from 7.2 kg/ha (45%) to 15.75 kg/ha (25%) respectively, with peak uptake of 0.7 kg/day during flowering, accumulating 61% of total Mg uptake in early to mid-flowering (Rochester 2012).

c. Magnesium deficiency symptoms

Magnesium deficiency is yet to be recorded in the field in Australian cotton. Magnesium-deficient plants grown in glasshouse nutrient studies were very stunted, with thin stems and pale green foliage. Branching was significantly affected, and flower and boll numbers reduced severely (Grundon 1987). Because magnesium is very mobile in the plant, it is readily translocated from older to younger leaves. As a result, symptoms first appear in older leaves, where pale green to yellow interveinal chlorosis develops. Veins and young leaves remain green and prominent. If the deficiency persists, a progressive reddening of leaves and pale brown necrotic lesions develop between the veins, eventually joining up, and the leaf dies (Grundon, 1987).

Plants recover slowly from deficiency after Mg fertiliser is applied. High application rates of Mg fertilisers can cause Mg toxicity in the crop.

d. Critical magnesium concentrations in the plant

Critical concentrations for Mg have not been determined in cotton grown under Australian conditions, however, based on US experience, adequate concentrations for the youngest mature blade (YMB) should contain about 5000 to 9000 mg/kg (0.5% to 0.9%) at first flower (Jones 1974).

e. Magnesium in the soil

Most Mg is found in a mineral, non-exchangeable form. The exchangeable Mg ion is subject to cation exchange in the soil, and can be found in the soil solution and absorbed to the clay and organic matter surfaces. It normally constitutes between 4% and 20% of the CEC of the soil. Because Mg is not adsorbed as tightly as Ca by clay or organic matter, it is more subject to leaching, and tends to accumulate in the subsoil.

High Mg content in soils is a significant problem in Australian cotton production. A low Ca:Mg ratio (less than 2:1) or high percentage of Mg cations (>30%) usually indicates high Mg content of the soil. High Mg may be related to decreased structural stability and increased clay dispersion, particularly after these soils are cultivated when the water content is above their plastic limit. To overcome this, apply either gypsum in neutral and alkaline pH soils, or lime (but not dolomite) in acid soils. High soil ammonium (NH_{4+}) and K can suppress the uptake of Mg. Clay soils with Mg percentage of cations above 40% have been related to a higher incidence of K deficiency in other K-sensitive crops, such as maize and soybeans.

Cotton soil tests are as yet uncalibrated in Australian cotton-growing conditions, so a combination plant-tissue analysis and harvested test strips (soil- or foliar-applied) are suggested before committing to a widespread magnesium application program.

f. Magnesium fertilisers

Very little Mg fertiliser is used in Australian cotton production to address known Mg-related productivity limitations. If fertilisers are required, dolomite lime ($CaMgCO_3$), providing both Ca and Mg, is the preferred option for acid soils. Other sources more suitable for neutral and alkaline soils include magnesium sulphate ($MgSO_4$), magnesium nitrate ($Mg(NO_3)_2$) or potassium-magnesium sulphate ($KMgSO_4$).

RUTH REDFERN

SULPHUR (S)

INTRODUCTION

Essential for plant growth, sulphur (S) is required in similar quantities as P. It is absorbed primarily as the sulphate anion (SO_4^{2-}) from the mineralisation of organic matter. It is highly mobile in the soil and can be readily leached. Sulphur deficiencies have been observed in Australian cotton, in particular, in lighter sandy soils, dryland crops, or following extended periods of waterlogging or flooding. It can be confused with nitrogen deficiency because plant symptoms are very similar.

a. Role of sulphur in the plant

Sulphur plays an important role in photosynthesis. Although not a constituent of chlorophyll, it is required for the synthesis of chlorophyll. Sulphur is required for protein synthesis, activation of enzymes, production of vitamins, and synthesis of oils.

b. Uptake and removal of sulphur

A cotton crop yielding 1000 kg lint/ha has an uptake of about 10 kg S/ha and a removal of about 4 kg/ha (42%). On the other hand, a crop yielding 2400 kg lint/ha has an uptake of about 62 kg S/ha, and a removal of 11 kg S/ha (18%) (Rochester 2012).

Peak S uptake occurs during flowering, with the maximum rate of S uptake ranging between 0.3 and 0.8 kg/ha/day during peak flowering. As much as 63% of the total crop uptake occurred during the flowering period (Mullins and Burmester 2010, Rochester 2012). Plants take up S as sulphate (SO_4^{2-}), which is derived mainly from the mineralisation of soil organic matter. Soluble sulphates don't generally accumulate in the soil surface but are leached into the subsoil. Small amounts of S can be derived as sulphate dissolved in irrigation water.

c. Sulphur deficiency symptoms

Because sulphur is relatively immobile in the plant, it does not transfer readily from old to young leaves. Deficiency symptoms begin with the whole plant turning pale green. The youngest leaves develop a pale yellow chlorosis, including the veins. As the deficiency persists and becomes more severe, pale brown necrotic lesions may develop, margins may become excessively wavy or cupped upwards, and leaves may be rigid and brittle. Older leaves remain pale green (Grundon 1987; Ergle and Eaton 1951).

Plants appear unthrifty and spindly, with short, slender stems. Severely deficient plants have fewer flowers or fruiting branches. Also, boll size is reduced and, as a result, yield is reduced.

S deficiency is rare in irrigated cotton, although it has been noted in dryland crops, possibly due to leaching of sulphate down the soil profile.

The need for S is closely related to the amount of nitrogen available to plants. The development of deficiency symptoms depends to some degree on the supply of N. If N is deficient, S symptoms may occur first in the older leaves, while plants well supplied with N will exhibit symptoms in the newer, upper leaves (FIFA 2006, Hodges and Constable 2009).

d. Critical sulphur concentrations in the plant

Concentrations less than 2000 mg S/kg (0.2%) in the youngest mature leaf at flowering may produce deficiency symptoms. Adequate concentrations range from 2000 to 4000 mg S/kg (0.2 to 0.4%S) in the youngest mature leaf at flowering (Jones 1974).

e. Sulphur in the soil

Most of the S in soil is associated with either organic matter, which acts as the main S reserve within the surface soil, or within gypsiferous layers that occur at varying depths in the root zone of many more-arid production areas. In well-aerated soils, more than 90% of the sulphur in surface layers is tied up in organic forms. The small inorganic fraction is predominantly present as sulphate (Lewis 1999). Through mineralisation, the organic sulphur is broken down into inorganic sulphate forms available for plant uptake.

Sulphate ion is not strongly adsorbed by soil clay and organic matter surfaces. It can remain in the soil solution where it can be readily leached, especially in lighter textured soils. Sulphate-S can accumulate in the subsoil, particularly in heavier textured clay soils. Sulphur concentrations at depth should be taken into account when determining crop S recommendations.

Sulphur deficiency is not common. It is frequently transitory, being mostly associated with shallow soils, subsoil waterlogging and early-season, low soil-surface supply after a wet winter.

f. Soil testing

With very limited field-calibrated trials having been conducted in Australian cotton, it is important to consider the soil tests in the light of other important response variables, such as sampling depth, knowledge of root zone water extraction, soil texture, rainfall, soil organic matter, and local experience.

In other crops where response calibrations have been established, sulphate-S (MCP) average concentration for a 0 to 60 cm sample, lower critical range varies from 3 mg/kg (cereal) to 8 mg/kg (canola). If an average soil concentration is in the lower part of the above range, further investigation is warranted. Check with a leaf test during early flowering when roots are accessing the subsoil, or establish and harvest nutrient-rich test strips.

g. Sulphur fertilisers

In the past, the use of superphosphates had to some extent masked the need for S fertilisers. In recent times, the application of high-analysis N and P fertilisers (low S) and the greater use of nitrogen has resulted in the potential to consider the need to use S-containing fertilisers to meet some of the crop demand.

Soil-S content can be augmented by other fertilisers that supply different nutrients, such as ammonium sulphate (N), superphosphate (P) and in compound- and blend-containing ammonium sulphate, superphosphate or potassium sulphate. It can also be supplied by soil ameliorants, such as gypsum, and in irrigation water.

If S fertiliser is needed but cannot be supplied with other nutrients, the most suitable fertiliser is generally gypsum.

- **Soil-applied fertilisers:** Most granular S fertilisers are in sulphate forms, such as potassium sulphate or ammonium sulphate. It can also be applied as elemental S, however elemental S may not be as immediately available as sulphate products because it must be biologically converted to sulphate first.
- **Foliar fertilisers:** Not usually recommended because of the quantities required to meet crop demand.

MANGANESE (Mn)

INTRODUCTION

Manganese (Mn) is required and taken up in very small quantities, and it rarely limits cotton growth in Australia. It has been reported that deficiencies are associated with calcareous, alkaline soils with high organic matter. Available Mn is rapidly oxidised in the soil to an unavailable form. High levels of Mn can accumulate in the tissue of waterlogged cotton.

a. Role of manganese in the plant

Manganese is a constituent of enzyme systems in plants. It activates several important metabolic reactions and plays a direct role in photosynthesis by aiding chlorophyll synthesis (FIFA 2006).

b. Uptake and removal of manganese

A cotton crop yielding 1000 kg/ha of lint takes up about 150 g/ha of Mn, while a crop yielding 2400 kg/ha lint takes up about 650 g/ha of Mn. About 8 g Mn is removed per bale of lint (Rochester 2012).

Actively growing cotton requires about 4 g Mn/ha/day throughout the growing season. Peak requirement occurs between squaring and boll filling. Mullins and Burmester (1993a) reported that peak uptake ranged from 8.2 to 14.4 g Mn/ha per day during this period. As much as 60% of the total Mn taken up occurs during flowering (Rochester 2007).

c. Manganese deficiency symptoms

Manganese-deficient crops lack vigour and yield poorly. Crops appear patchy; plants are stunted, with reduced branching, flowers and bolls. Mn is relatively immobile within the plant. Symptoms first appear and are more severe in the young leaves. Young leaves are small and turn pale green. Faint interveinal chlorosis develops, which becomes more distinct, and leaf margins cup down if the deficiency persists. The veins remain green and are easily seen. Small brown necrotic lesions develop, and leaves appear distorted if the deficiency becomes severe. Root growth can be greatly reduced. (Grundon 1987; Hodgson and Constable 2009).

d. Manganese toxicity

Manganese toxicity is more common in acid soils than other soils. Under these conditions, cotton leaves become abnormally distorted or crinkled, with irregular chlorotic mottling between the veins that can become necrotic spots (Foy et al. 1995). High concentrations of Mn can induce Fe and Zn deficiency in plants.

e. Critical manganese concentrations in the plant

Manganese deficiency is rarely seen in the field but is more likely to occur on highly alkaline soils. The critical concentration for the youngest mature blade is 25 mg/kg. At first flower, the Mn content of the YMB should be between 50 and 350 mg/kg (Jones 1974). The range of manganese concentrations in plant-defining deficiency and toxicity is relatively narrow.

f. Manganese in the soil

Most soils supply sufficient Mn for plant growth, however deficiencies and toxicities in plants can occur. Several forms of manganese exist in the soil, of which only one, (Mn^{2+}), is taken up by plants. The availability of Mn in the soil is determined by several soil and plant factors, the most important of which are those that determine solubility. These factors include microbial activity, soil pH, and the reducibility of Mn oxides (Uren 1999).

The availability of Mn to the plant is largely determined by the activity of Mn^{2+} in the soil solution, and in the capacity of other forms (exchangeable and readily reducible oxides) to maintain an adequate supply. Mn^{2+} is only loosely adsorbed on the outer sphere complex of the organic and inorganic colloids, and is readily exchanged into the soil solution by calcium, iron and other cations (Uren 1999). It can then be rapidly oxidised from the available Mn^{2+} form into the unavailable Mn^{4+} forms in alkaline soils.

Because the solubility of Mn in soils depends very strongly on pH, uptake of Mn also depends on pH, so much so that Mn toxicity occurs in plants growing on acid soils. Mn deficiencies occur in plants growing in soils of high pH, particularly calcareous soils with surface calcium carbonate content >5% to 10%.

Manganese deficiency can be induced where the soil pH is raised through the application of lime or N or P fertilisers. During flood irrigation, the availability of Mn may dramatically increase in the soil. Crop uptake may exceed requirement, with the potential for toxic Mn concentrations in the plant.

g. Soil testing

It is generally recognised that due to widely differing tolerances to deficiency and toxicity, such a strong pH dependence on solubility, complicated soil chemistry

or influences by environmental conditions that soil tests alone cannot correctly diagnose either Mn deficiency or toxicity of field-grown plants (Uren 1999). Determination of the Mn status of a soil for adequate plant growth requires not only soil testing for available and exchangeable concentration of Mn, but also soil pH and field data, including field conditions, sampling techniques, site history and field experience. All of these factors influence Mn availability and crop response to fertiliser application.

Soil with less than 2 mg/kg DTPA-extractable Mn warrants further investigation using plant-tissue analysis or test strips.

h. Manganese fertilisers

Given the difficulties in identifying Mn deficiencies, it is not surprising that no yield responses by cotton to Mn application have been reported in Australia. Supplying Mn as a fertiliser can be difficult given that high pH calcareous soils rapidly immobilise Mn in the soil. It is generally thought that if Mn deficiencies are observed, foliar applications are generally more successful (Grundon 1987).

- **Soil-applied fertilisers:** Mn deficiency can be overcome by applying a soluble Mn fertiliser in a band using 5 to 10 kg Mn/ha. Banding is thought to be more effective than broadcasting and incorporation. Ammonium-based fertilisers, such as MAP and DAP, tend to increase the availability of Mn in the soil. High-P fertilisers help mobilise Mn into the plant (FIFA 2006).

- **Foliar fertilisers:** Two or three foliar applications of 1 to 2 kg Mn/ha as manganese sulphate may be more effective where soils are alkaline.

RUTH REDFERN

MOLYBDENUM (Mo)

INTRODUCTION

Molybdenum (Mo) is an essential micronutrient required in very small quantities by the plant. Deficiency has not been encountered in field-grown cotton in Australia, but it has been observed in other crops, such as brassicas and pulses.

a. Role of molybdenum in the plant

Molybdenum has three important roles. It is:

- required for synthesis and activity of the nitrate reductase enzyme
- involved in phosphorus metabolism in the plant
- essential for effective nitrogen fixation by rhizobia bacteria (nitrogenase enzyme) associated with legume roots. Active nodules contain 6 to 20 mg/kg Mo.

b. Uptake and removal of molybdenum

Molybdenum is taken up by plants in the molybdate form (MoO_4^{2-}). As little as 3 to 5 g Mo/ha is taken up by cotton. Only a portion of this (possibly only 1 to 2 g/ha) is removed in seed cotton. Uptake of Mo is improved with phosphorus application (Joham 1953).

c. Molybdenum deficiency symptoms

Where Mo deficiency occurs, it would normally be detected in legume and brassica crops because they have a higher requirement for Mo. Nitrate will accumulate in Mo-deficient plants that exhibit signs of N deficiency. Poor and delayed flowering and pollen grains are also associated with Mo deficiency. Where Mo deficiency has been induced, leaves show interveinal chlorosis, followed by the development of a greasy leaf surface with interveinal thickening, leaf cupping, and eventually, white or grey necrotic spots on the leaf margin (Romheld and Marschner 1991).

d. Critical molybdenum concentrations in the plant

Molybdenum occurs in very low concentrations in the plant. Analyses of soil and plant material by commercial laboratories without specialised processes may find Mo concentrations below the limit of detection of their equipment, or incur significant measurement errors with magnitudes similar to the lower crop adequacy level. Responses in cotton grown under greenhouse conditions have been measured in young cotton leaves containing 1 to 2 mg Mo/kg (Kallinis and Vretta-Kouskoleka 1967).

e. Molybdenum in the soil

The availability of Mo to plants in the form of MoO_4^{2-} depends primarily on soil pH, the total amount of Mo in the soil, and soil phosphate status. Acid soils containing free iron and aluminium oxides strongly fix Mo, rendering it unavailable for plant uptake. The concentration of soluble Mo in soils is generally quite low, however under alkaline conditions may reach significant levels (Brennan and Bruce 1999), making pH a reasonable surrogate for Mo availability.

f. Soil testing

It is generally recognised that accurate soil testing for Mo levels and plant availability is unreliable and extremely difficult to achieve other than by suitably equipped laboratories. Little Australian data is available on soil Mo status despite laboratory test methods being available. Combinations of soil pH, species sensitivity, plant-tissue testing, and test strips are more appropriate parameters for assessing the need for Mo.

g. Molybdenum fertilisers

Molybdenum deficiency can be overcome by application of small amounts of Mo fertilisers, however overuse can induce an imbalance with copper.

- **Soil-applied fertilisers:** Mo coated onto or incorporated into phosphorus and compound fertilisers as Mo trioxide can be used to correct Mo deficiencies and achieve uniform application.
- **Foliar fertilisers:** Ammonium and sodium molybdate are more soluble fertiliser forms and can be applied in solution to the soil or as a foliar spray.

CHLORINE (Cl)

INTRODUCTION

Chlorine (Cl) is nearly always found in the chloride (Cl^-) ion form, the form that plants absorb and use. It is mobile in the plant and the soil. Chloride deficiencies have never been recorded in Australia, but chloride toxicity is widespread.

a. Role of chloride in the plant

Chloride is involved in energy reactions, activation of several enzyme systems, transporting potassium, calcium and magnesium within the plant, and regulation of stomatal guard cells (FIFA 2006).

b. Chloride in the soil

Chloride exists primarily in the soil solution and is not adsorbed on soil particles. Consequently, it can be easily leached down through the profile.

c. Chloride deficiency symptoms

Deficiency symptoms have never been recorded in Australia.

d. Chloride toxicity

Chloride toxicity is widespread in Australian soils. It is the dominant anion in common salts, including sodium chloride, calcium chloride and magnesium chloride. Toxicity can lead to significant losses of yield.

e. Sodium chloride toxicity

Excess sodium chloride (NaCl) soils cause poor vigour, unthrifty plants, and poor yields of lint and seed. Plants are stunted with short stems and may developed pigmentation. Leaves are dark green and often much smaller than normal (Grundon 1987). Symptoms first appear in the older leaves. Small purple-brown lesions appear on the margins and advance into interveinal areas. Eventually, small grey necrotic lesions appear interveinally. If the toxicity develops rapidly, i.e. in salty irrigation water, grey lesions appear first, can join up and cause interveinal necrosis (Grundon 1987). Because the overt expression of salinity, chloride and sodium toxicity is similar, tissue analysis is needed to identify the specific cause.

Where salt damage is detected, further investigation should be undertaken to locate the source. Actions can include the following:

- deep soil samples to measure soil-profile salt and depth to watertable
- irrigation water chemistry—all sources across high- and low-flow periods, and at appropriate time after significant water-related weather events
- EM maps of the field and surrounding area to understand spatial and depth variability.

References

Armour JD, Brennan RF (1999) Zinc. In 'Soil analysis: an interpretation manual'. KI Peverill, LA Sparrow, DJ Reuter (eds), 281-285, CSIRO Publishing: Melbourne.

Brennan RF, Bruce RC (1999) Molybdenum. In 'Soil analysis: an interpretation manual'. KI Peverill, LA Sparrow, DJ Reuter (eds), 303-307, CSIRO Publishing: Melbourne.

Bogiani JC, Sampaio TF, Abreu-Junior CH, Rosolem CA (2014) Boron uptake and translocation in some cotton cultivars. Plant Soil 375:241–253

Berger KC, Pratt PJ (1963). Advances in secondary and micro-nutrient fertilization. In: McVickar MH, Bridger GL, Nelson LB (eds). Fertilizer technology and use. SSSA, Madison, W I. pp. 281–340.

Constable GA, Rochester IJ, Cook JB (1988) Zinc, copper, iron, manganese and boron uptake by cotton on cracking clay soil of high pH. Aust. J. Exp. Agric. 28, 351–356.

Ergle DR, Eaton FM (1951) Sulphur nutrition of Cotton. Plant Physiol. 26, 639–654.

Fernandez V, Ebert G (2005). Foliar iron fertilization: A critical review. Journal of Plant Nutrition 28: 2113–2124.

FIFA (2006) Australian Soil Fertility Manual, Third Edition. CSIRO Publishing.

Foy CD, Weil RR, Coradetti CA (1995) Differential manganese tolerance of cotton genotypes in nutrient solution. J. Plant Nutr. 18, 685–706.

Grundon NJ (1987) Hungry crops: a guide to nutrient deficiencies in field crops, Queensland Dept. of Primary Industries.

Gupta UC (1968) Relationship of total and hot-water soluble boron and fixation of added boron, to properties of Podzol soils. Soil Sci. Soc. Am. Proc. 32, 45–48.

Gupta UC (1979) Boron nutrition of crops. Adv. Agron. 31, 273–307.

Hearn AB (1981) Cotton nutrition. Field Crop Abstracts 34, 11–34.

Hodges SC, Constable G (2009) Plant responses to mineral deficiencies and toxicities. pp 143–162. In: J M Stewart, DM Oosterhuis, JJ Heitholt and JR Mauney (eds). Physiology of Cotton, National Cotton Council of America, Memphis, Tenn. pp. Springer, London.

IPNI (2017) Boron. Nutri-fact No 7. North American Edition. [online] Available at: http://www.ipni.net/publication/nutrifactsna.nsf/0/82608931245D1FBE85257CA70074A08F/$FILE/NutriFacts-NA-7.pdf [Accessed 9 August 2017].

Joham HE (1953) Accumulation and Distribution of Molybdenum in the Cotton Plant. Plant Physiol. 2 (28), 275–280.

Jones JB (1974) Plant analysis handbook for Georgia. Univ. Georgia Coll. Agric. Bull. 735.

Lewis DC (1999) Zinc. In 'Soil analysis: an interpretation manual'. KI Peverill, LA Sparrow, DJ Reuter (eds), 221–228, CSIRO Publishing: Melbourne.

Kallinis TL, Vretta-Kouskoleka H (1967). Molybdenum Deficiency Symptoms in Cotton. Soil Sci. Soc. Amer. J. 31(4), 507–509.

Mullins GL, Burmester CH (1992) Uptake of calcium and magnesium by cotton growth under dryland conditions. Agron. J. 84, 564–569.

Mullins GL, Burmester CH (1993a) Accumulation of copper, iron, manganese and zinc by four cotton cultivars. Field Crops Res. 32, 129–140.

Mullins GL, Burmester CH (2010) Relation of growth and development to mineral nutrition. pp. 97–105. In: Stewart JM, Oosterhuis DM, Heitholt JJ, Mauney JR (eds). Physiology of Cotton. London: Springer.

Rochester IJ (2007) Nutrient uptake and export from a Australian cotton field. Nutr Cycl Agroecosyst. 77, 213–223.

Rochester IJ, Constable GA, Oosterhuis DM, Errington M (2012) Nutrient Requirements of Cotton during Flowering and Fruiting. pp 35–50. In: DM Oosterhuis and TJ Cothren (eds) Flowering and Fruiting in Cotton. The Cotton Foundation. [online] Available at: http://www.cotton.org/foundation/upload/FLOWERING-AND-FRUITING-IN-COTTON.pdf [Accessed 14/8/2017]

Rogers EE, Guerinot ML (2002) FRD3, a member of the multidrug and toxin efflux family, controls iron deficiency responses in Arabidopsis. The Plant Cell 14, 1787–1799.

Romheld V, Marschner H (1991) Function of Micronutrients in Plants. pp 297–328. In: JJ Mortvedt, FR Cox, LM Shuman, RM Welch (eds). Micronutrients in Agriculture. Soil Science Society of America, Wisconsin.

Stevens G, Dunn D (2008) Sulfur and boron fertilization of cotton. Agricultural MU Guide G4257. University of Missouri Extension.

Uren NC (1999) Manganese. In 'Soil analysis: an interpretation manual'. KI Peverill, LA Sparrow, DJ Reuter (eds), 287–292, CSIRO Publishing: Melbourne.

Viets FG Jr (1962) The chemistry and availability of micronutrients in soils. J. Agric. Fd. Chem. 10, 174–178.

Vretta-Kouskoleka H, Kallinis TL (1968). Iron deficiency in cotton in relation to growth and nutrient balance. Soil Sci. Soc. Amer. Proc. 32, 253–257.

6. Soil sampling and analysis

Purpose of sampling

The reason for soil analysis generally guides the process of collecting samples. The most common reasons for sampling soil for chemical analysis are:

- guiding seasonal fertiliser tactics
- monitoring change in soil fertility over an extended time period
- problem solving/trouble shooting.

Environmental monitoring and regulatory compliance are some other non-production reasons for sampling.

Timing of soil sampling

Sampling to assess soil fertility to guide seasonal fertiliser tactics and monitoring fertility is more effective when performed at the same time each year, preferably before the crop is sown. Where an indication of the seasonal N fertiliser requirement is sought, the preferred time to sample soil is from July to September when significant changes in soil nutrient content before sowing is unlikely. When fertiliser is to be applied before this, a small, unfertilised area should be left from where soil samples can be collected, or the decision support tools used to interpret the soil test should be able to provide an estimate of likely net N mineralisation from sampling to sowing.

Variations in other nutrient concentration is generally significantly less than for N, hence timing is not as critical.

In a trouble-shooting situation, soil and plant tissue samples should be taken from the good and poor areas at the same time to ensure direct comparability.

Sampling for environmental monitoring and regulatory purposes is generally proscribed in formal guidelines associated with the program or operating licence.

Where to sample soil

The sample collection strategy for a paddock is a function of the purpose of the sampling, the degree of variability in crop performance across the area to be sampled, and the ability to apply fertiliser products and rates to meet existing variability. In the first instance, aim for a comprehensive soil sampling spacing of approximately 400 m across cotton fields, i.e. one sampling site per 16 ha, approximately. Use the sampling grid or management zones determined by yield maps in a flexible manner that allows the soil sampling plan to be adjusted to include high- and low-yielding areas and other zones of interest. In summary, sampling locations in developed cotton fields should include:

- high-yielding zone
- average-yielding zone
- low-yielding zone.

Avoid collecting samples on sites such as old fence lines, filled in irrigation channels, near trees or old stumps, or if the soil is excessively wet. It is important to avoid sampling fertiliser bands from previous (or current) years as this can seriously affect laboratory analyses. This is especially important where phosphorus (P), zinc (Zn) or potassium (K) fertilisers have been applied. Sample soil close to the plant line or from the middle of the bed, but avoid fertiliser bands. This problem is not normally encountered where fertilisers have been broadcast and incorporated.

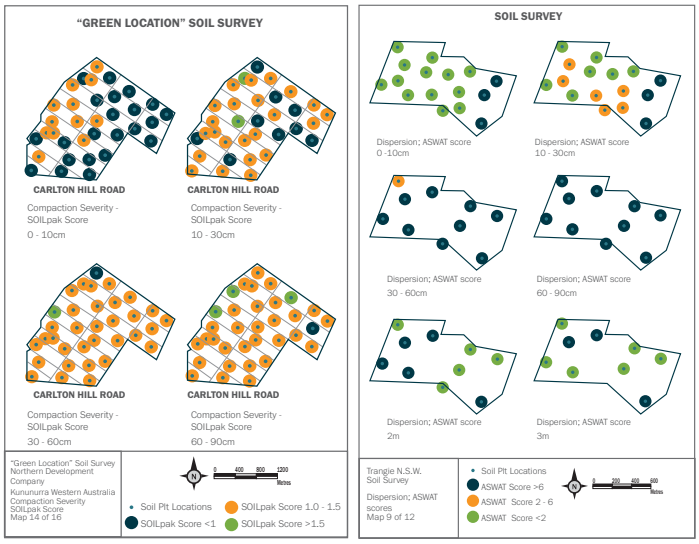


Figure 6.1: Examples of 'key soil factor maps' for: (a) A new furrow irrigation development near Kununurra WA; and (b) A cotton field near Trangie NSW about to be converted from flood irrigation to linear-move spray irrigation. Remote sensing techniques (e.g. colour air photos, EM surveys) can sometimes be used to provide extra details in between the dots where strong correlation exists: red dot = action required by soil managers; green dot indicates favourable conditions for cotton root growth (Figures courtesy Dr David McKenzie).

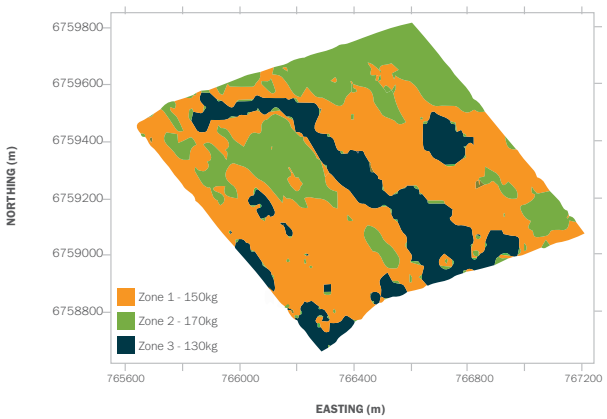


Figure 6.2: An example of management zones on a cotton field using EM and yield mapping. Soil testing within these areas enables variable rate nutrient application (Image courtesy Australian Centre for Precision Agriculture).

Depth of soil sampling

The recommended sampling depth for irrigated cotton for the majority of nutrients is 0 to 30 cm. When sampled from the top of the hill, this procedure provides information from the critical root zone area. Sampling deeper than 30 cm in irrigated cotton should also be considered for N following long fallow or after rotational pulse crops, and where subsoil constraints, such as salinity and sodicity, are likely to restrict nutrient and water uptake. For dryland fields, 0 to 10 cm and 10 to 30 cm are standard depths for most nutrients. Additional samples to 1 m may better indicate the amount of mineral N and S stored in deeper soil layers and for detecting the presence of subsoil constraints, such as salinity and sodicity.

Table 6.1 provides some guidance for selecting analyses appropriate for production type (irrigated or dryland), and depth of sample. Sampling at recommended depth increments ensures the best relationship between analysis result and recommended action.

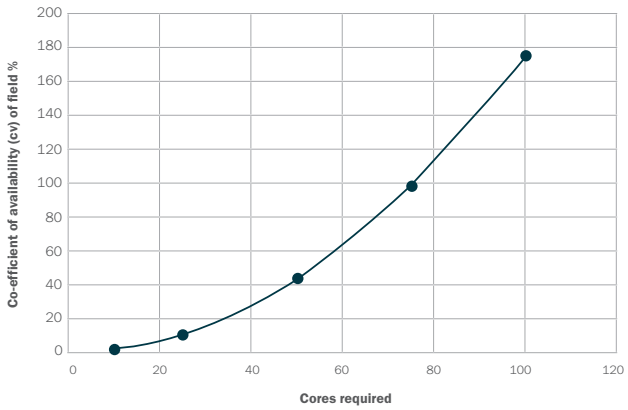
Number of soil samples

The number of cores and samples required depends on soil variability within the field. The concentration of most nutrients (especially N and P) can vary widely, even in apparently uniform fields, but the scale of soil variability may not be reflected in the variability of crop growth or yield. Figure 6.3 shows the relationship between variability and coring intensity required to maintain high confidence and accuracy. When sampling areas with high variability (CV%), overall core numbers can be reduced while maintaining confidence and accuracy by zoning and sampling from more homogenous zones. In general, at least 20 to 40 cores should be collected within a 200 ha area where the CV% of yield is less than 40%. Cores from within homogenous areas may be bulked (to reduce the cost of testing) and thoroughly mixed before being sent to a laboratory. About 500 g of field moist soil is required for a comprehensive soil analysis.

Table 6.1: Suggested analysis to be conducted according to production type, sample depth increment.

Analysis	Irrigated			Dryland		
	0–30 cm	30–60+ cm	60–100 cm	0–10 cm	10–30 cm	30+ cm
pH	x		x	x	x	x
Salinity (EC)	x		x	x	x	x
Chloride	x		x	x	x	x
Organic C%	x	x		x		
Mineral N	x	x	x	x	x	x
P (Colwell)	x			x	x	
P (BSES)	x			x	x	
PBI	x			x	x	
K (exchangeable)	x		x	x	x	
S (extractable)	x	x	x	x	x	x
Ca (exchangeable)	x		x	x	x	
Mg (exchangeable)	x		x	x	x	
Na (exchangeable)	x		x	x	x	
Zn (extractable)	x			x		
Cu (extractable)	x			x		
Fe (extractable)	x			x		
Mn (extractable)	x			x		
B (extractable)	x	x	x	x	x	x

Figure 6.3: Coring intensity increase required to maintain accuracy as field variability increases. In this example the level of reliability targeted was 80%, and acceptable error was 15% around a mean value.



Sampling technique

A coring tube with a diameter of 32 to 50 mm is often the most effective method of collecting soil samples. This can be performed quickly by hand for shallow samples or with a hydraulic ram for deeper samples. Where the volume/weight of intact cores for a sample exceeds 500 g, it is recommended that cores be split vertically rather than horizontally to ensure that any vertical nutrient concentration gradient is accurately reflected in the laboratory sample. For dry crumbling samples, reduce the amount of soil by mixing then mounding the soil into a cone shape on a clean plastic sheet, divide into four, and discard opposite quarters, and then repeat the process until the required weight is left.

Soil samples should be sent to the laboratory on the day they are collected, where possible. If this is not possible, they should be cooled (to about 4 °C) as quickly as possible to minimise chemical changes that can occur during storage or transit. Alternatively, soil samples can be dried in a low-temperature oven (40 °C) or spread on plastic sheets in the sun for longer storage.

Packaging samples

To ensure soil samples are not contaminated, put them in unused plastic bags, seal and label each bag with a permanent waterproof marker. It is useful to record pertinent information, such as field number, date sampled, sample depth, soil structure (good, poor, compacted), cropping history etc. A GPS reference for each sample may be useful so that each chemical analysis forms part of a larger map-based database, and subsequent samples can be collected from the same site.

Interpreting soil tests

NutriLOGIC is a web-based computer program available through the Australian Cotton Cooperative Research Centre's Technology Resource Centre at the Australian Cotton Research Institute, Narrabri. It includes tools to interpret soil and plant tissue tests. Nutrient recommendations using similar principles to NutriLOGIC are also given by some commercial soil-test decision-support system providers.

Interpretation guidelines are also contained in the tables in the 'Interpretation of soil, petiole and leaf analyses' chapter of this manual, which indicate critical values for the nutrients analysed with various extraction methods. The guidelines also provide an indication of whether a particular nutrient is deficient or in excess. **Note:** Various laboratories use different soil testing procedures (e.g. extracting solutions) that indicate different levels of nutrient availability. They may also report those values with different units to other laboratories.

Soil testing laboratories

Contact your local rural merchandise supplier to organise the samples to be sent for you and to deal directly with laboratories. To ensure quality and consistency of analysis, check that your adviser selects from laboratories whose performance for each nutrient-extraction method is assessed annually by ASPAC (Australasian Soil and Plant Analysis Council), and has a credible Quality Assurance program, such as external auditing by National Association of Testing Authorities (NATA), Australia or equivalent. A summary of standard analytical methods used in the cotton industry is in the 'Interpretation of soil, petiole and leaf analyses' chapter of this manual.

The laboratory selected should provide (in order of preference):

- Australian standard methods, involvement in proficiency program performance (with results publicly available)
- external audited quality assurance
- quality result reporting structure
- guidelines for sampling
- sample handling.

7. Leaf and petiole analyses

Plant analysis provides information about the nutritional status of a crop, and can indicate nutrient deficiencies that, if identified early enough, may be rectified by applying the appropriate fertiliser. It is an important diagnostic tool for newly emerging nutrient problems before reliable soil tests calibrations are available.

Leaf and petiole analyses have been calibrated for cotton. Critical concentrations for all nutrients have been identified for cotton at various stages of development. Leaf samples can be taken throughout the growth of the crop to provide information on a wider range of nutrients. The petiole is normally used to determine the crop's nitrogen (and potassium) status early in the season. Petiole nitrate-N and K analysis can be a reliable means of indicating crop N and K nutrition, and indicate where further N and K fertiliser application is necessary. Generally, it has less tolerance for variations in sampling conditions than leaf analysis. Neither analysis indicates the quantity of each nutrient taken up over the growing period.

Leaf sampling

The leaf blade can be used to monitor all nutrients, including micronutrients. Sampling twice (at flowering and cut out) produces the most useful information. Leaf tissue tests can be used to identify nutrient imbalances, deficiencies, and toxicities (more precisely than soil testing), and help to optimise fertiliser programs.

Leaf samples should be collected from the youngest mature blade (YMB) from a uniform area within a crop. The petiole should be removed from each leaf at the time of collection and retained in a separate sample if petiole analysis is to be conducted at the same time. The YMB is usually the fourth or fifth unfolded leaf from the top of the plant. Weather can be an important factor in leaf tissue testing. Waterlogging, cold weather, low radiation through cloudy conditions immediately before or at the time of collection can all affect nutrient levels.

Ideally, collect leaf samples only in an actively growing crop that is not stressed either from waterlogging or lack of moisture, or where insect or disease problems are severe. About 30 to 50 leaves normally supply sufficient fresh material for nutrient analysis (laboratories need about 20 g of dry material). Collect the samples systematically from average-sized plants from throughout the crop, following a transect across the field, or simply moving up and down and across rows. The plants selected should be at the same stage of growth. Where a nutritional problem is suspected, separate collections of healthy and unhealthy plants may aid the diagnosis.

With a monitoring approach to soil-fertility management, collection of plant samples at locations of soil samples and water monitoring adds extra information to the interpretation.

Petiole sampling

In Australia, petiole tests have been calibrated for nitrate-N and potassium but are not recommended for other nutrients. Of the other nutrients, petioles normally contain about half of the concentrations found in the leaf blade, but this varies, making them less reliable as a sampling tool.

Petioles are ideal for monitoring nitrate-N and potassium concentrations up to and just after flowering. Petiole nitrate-N level declines with time (Figure 7.1). By flowering, petiole nitrate-N levels are usually declining, and it is easy to distinguish between crops with sufficient or insufficient N. Beyond flowering, leaf tissue tests are a better method for identifying crop nutrition problems where only a single sample is to be taken.

Petiole samples are collected from the youngest mature blade (YMB) from a uniform area within a crop. The YMB is usually the fourth or fifth unfolded leaf from the top of the plant. Collect petioles only in an actively growing crop with adequate sunlight and that is not stressed either from waterlogging or lack of moisture, or where insect or disease problems are severe. About 50 to 100 petioles (more earlier when leaves are smaller) normally supply sufficient fresh material for nutrient analysis. Collect the samples systematically from average-sized plants from throughout the crop, following a transect across the field, or simply moving up and down and across rows. The plants selected should be at the same stage of growth. Where a nutritional problem is suspected, separate collections of healthy and unhealthy plants may aid the diagnosis.

With a monitoring approach to soil-fertility management, collection of plant tissue samples at locations of soil samples and water monitoring adds extra information to interpretation.

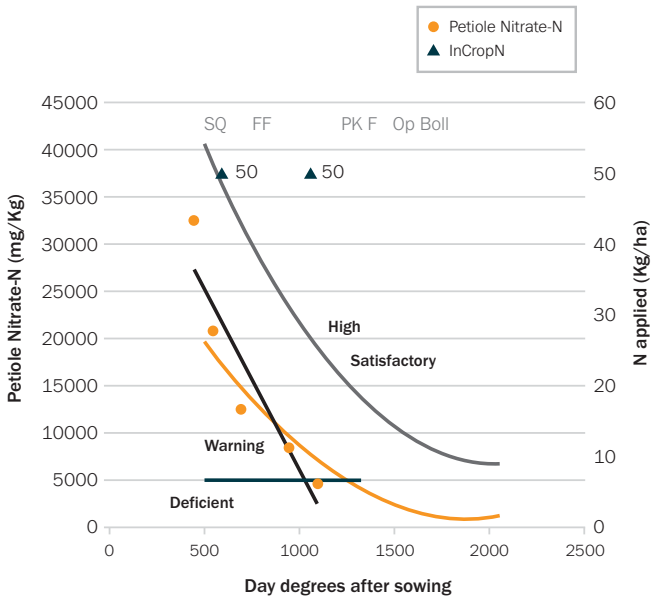


Figure 7.1: Typical petiole N decline across a season.

Timing of petiole collection

Concentrations of nitrogen and potassium are highest in very young plants and decline as the plant matures. Therefore, it is important to indicate the stage of crop growth in order to interpret the chemical analysis of the plant tissue. Because petiole nitrate-N declines very rapidly, it is imperative that the stage of growth (days after sowing, or more accurately, day degrees) is noted. The optimal time to sample to help guide in-crop N or K application is between 500 and 1000 day degrees after planting. Preferably, three petiole sampling times, 10 days apart, should be used for each crop, starting between squaring and first flowers. This method allows N deficiency to be corrected before crop development is substantially affected. Another sample at about 1350 to 1450 day degrees can be a useful guide to later-season N decisions for varieties and in seasons that have potential for late-season yield production.

The most informative means of using petiole nitrate-N analyses is to collect petioles each week, and examine the rate of decline in nitrate-N concentration. The NutriLOGIC program can do this, and indicate whether further N fertiliser is needed to maximise lint yield in a particular field, starting at squaring. This sampling time allows imminent N deficiency to be corrected before yield potential is reduced. Because petiole nitrate levels are dynamic, it is important to collect petioles only from crops not subjected to recent environmental stresses (e.g. cold shock or waterlogging or drought).

Because petiole nitrate-N concentrations normally change throughout the day, samples should be collected at the same time each day. Avoid sampling water-stressed cotton, i.e. do not sample immediately before or after an irrigation; preferably, sample at the same water deficit for each sampling. Sample petioles on sunny days only, because overcast weather for more than 48 hours can affect petiole nitrate-N concentrations.

Handling and packaging

Plant material (petioles and leaves) starts to deteriorate soon after sampling; decomposition and respiration can alter nutrient content. Deterioration will affect the analytical results, and the interpretation of the results may be misleading. Pack the samples loosely in a paper bag or envelope and store in a cool place (refrigerator) until they are dried or dispatched. Send plant samples to the laboratory as soon as possible, but ensure they do not arrive on weekends or public holidays when laboratories are closed. Don't use plastic bags because they make leaves sweat. Avoid sampling after foliar fertilisers have recently been applied. Rinsing leaves with water can reduce residues, but may leach nutrients from the leaves. Seek advice from the laboratory conducting the analysis if washing is needed.

Leaf adsorbance and reflectance

With further calibration and validation research, measurement of leaf spectral absorbance (e.g. SPAD meter) and reflectance (NDVI, Red Edge spectral analysis) may prove highly beneficial to cotton growers, whereby measurements of leaf greenness can be correlated to crop N nutrition status and the need for N fertiliser application. These non-destructive proximal or remote-sensed tests may replace the petiole nitrate test, enabling fertiliser management decisions to be made with a spatial dimension and without the need for chemical analyses.

Interpreting leaf and petiole results

The results of leaf and petiole nitrogen analyses can be interpreted using the NutriLOGIC program or commercial equivalents. A summary of the interpretation process and principles can be found in the 'NutriLOGIC: nutrient decision support' chapter in this manual.

To interpret the concentrations of other nutrients, refer to the tables in the 'Interpretation of soil, petiole and leaf analyses' chapter in this manual.

8. Interpretation of soil, petiole and leaf analyses

Several laboratories throughout the Australian cotton-growing regions perform routine analyses of soil, petiole and cotton leaves. Because they do not all use the same extraction procedures or analytical equipment, results are not necessarily comparable between laboratories. Laboratories showing ASPAC proficiency for a particular analytical method (www.aspac-australasia.com) have been assessed to have comparable results for samples tested in the preceding 12 months.

Soil analysis

Table 8.1 indicates the appropriate soil analysis method for each nutrient. The critical concentration of each nutrient is indicated, below which a response to fertiliser addition could be expected. For more information, refer to the 'Soil sampling and analysis' chapter of this manual.

Table 8.1: Soil analysis and interpretation (in brackets, ASPAC analytical method code).

Nutrient	Extractant	Critical value	Comments
Nitrogen (N)	1 M KCl (7C)	20–30 mg/kg	Range varies with the target yield; for 0–30 cm samples where there is little probability of significant quantities of N below 30 cm.
Phosphorus (P)	bicarbonate Colwell (9B)	10–30 mg/kg	Varies with PBI and early-season soil temperature. Higher critical levels for areas with lower soil temperatures and soils with higher PBI.
Potassium (K)	ammonium acetate (15D) or ammonium chloride (15A)	0.2–0.4 cmol(+)/kg or 100–200 mg/kg	Varies with clay species and the cation exchange capacity. Generally, higher critical levels for higher CEC sol.
Sulphur (S)	MCP (10B)	2–3 mg/kg	Sulphur-critical value is based on experience in other crops. S deficiency in cotton is rare due to gypsum in subsoils of many cotton-growing areas.
Calcium (Ca)	ammonium acetate (15D) or ammonium chloride (15A)	2–3.5 cmol(+)/kg or 400–700 mg/kg	These methods may overestimate eCEC and ESP in sodic/saline soils. Method 15C is more suitable for sodic/saline soils.
Magnesium (Mg)	ammonium acetate (15D) or ammonium chloride (15A)	1–1.2 cmol(+)/kg or 120–140 mg/kg	
Zinc (Zn)	DTPA (12A) EDTA	0.5 mg/kg 4 mg/kg	Trace element soil tests are poorly calibrated for cotton. Application of TEs should be backed by plant tissue to confirm action.
Iron (Fe)	DTPA (12A) EDTA	2 mg/kg 80 mg/kg	
Copper (Cu)	DTPA (12A) EDTA	0.3 mg/kg 2 mg/kg	
Manganese (Mn)	DTPA (12A)	2 mg/kg	
Boron (B)	Hot $CaCl_2$ (12C) Hot water	0.4 mg/kg 0.15 mg/kg	
Molybdenum (Mo)		Not reliable	Mo availability increases with soil pH. Usually not a problem in alkaline soils.

Petiole and leaf analyses

Petiole and leaf tissue analyses are conducted using more uniform methodologies. There is generally more comparability between laboratories for than soil analyses. However, variation between laboratories may result from the type of analytical equipment used.

Petiole nitrate analysis

Collect petioles from the same main-stem node between squaring and late flowering (500 to 1000 day degrees). The NutriLOGIC program allows for petiole nitrate analysis data to be entered, a calculation of the growing day degrees made, and the N fertiliser requirement estimated. Table 8.2 refers to nutrient concentrations found in petiole sampled at 750 to 800 day degrees. Refer to chapters 'Leaf and petiole analysis' and 'NutriLOGIC: nutrient decision support'.

Table 8.2: Optimum nutrient concentrations in leaves and petiole samples at flowering.

Nutrient	Petiole	Leaf
Nitrogen (N)	2% 20,000 mg/kg	3.5–4.5%
Phosphorus (P)	0.08% 800 mg/kg	0.28–0.5%
Potassium (K)	1% 10,000 mg/kg	1.5–3.0%
Sulphur (S)		0.25–1.2%
Calcium (Ca)	0.5% 5000 mg/kg	2.0–3.0%
Magnesium (Mg)	0.2% 2000 mg/kg	0.3–0.8%
Zinc (Zn)		20–60 mg/kg
Iron (Fe)		50–350 mg/kg
Copper (Cu)		5–25 mg/kg
Manganese (Mn)		25–350 mg/kg
Boron (B)		20–60 mg/kg
Molybdenum (Mo)		0.22–1 mg/kg

Leaf analysis

The youngest mature leaf is normally sampled; it usually corresponds to the fifth node from the top of the plant. Leaves can be sampled from squaring to boll fill. The optimum concentration range for the essential plant nutrients is given in Table 8.2. However, the concentrations of some nutrients change with leaf age and the stage of crop growth. Leaf N, for example, declines with time, whereas leaf Ca increases. An indication of the changes in leaf nutrient concentrations is given in Table 8.3.

Table 8.3: Changes in lower level of the adequate nutrient concentration of 5th YMB throughout the cotton season.

Nutrient	Day degrees from sowing		
	800	1300	1800
Nitrogen (N)	3.5%	3.34%	2.79%
Phosphorus (P)	0.28%	0.24%	0.22%
Potassium (K)	1.5%	1.33%	1.12%
Sulphur (S)	0.25%	0.39%	0.56%
Calcium (Ca)	2.0%	2.23%	2.84%
Magnesium (Mg)	0.3%	0.5%	0.75%
Zinc (Zn)	20 mg/kg	19 mg/kg	17 mg/kg
Iron (Fe)	50 mg/kg	31 mg/kg	30 mg/kg
Copper (Cu)	5 mg/kg	4.9 mg/kg	4.2 mg/kg
Manganese (Mn)	25 mg/kg	35 mg/kg	44 mg/kg
Boron (B)	20 mg/kg	38 mg/kg	60 mg/kg

9. NutriLOGIC: nutrient decision support

NutriLOGIC is a web-based decision aid that can predict the fertiliser requirement of cotton from pre-sowing soil and/or cotton petiole or leaf tests.

NutriLOGIC is a tool from the CottASSIST suite of web tools (www.CottASSIST.com.au). These tools have been designed and developed to help Australian cotton growers and consultants make informed crop management decisions based on the latest cotton research. The calculations in NutriLOGIC are based on the research conducted by CSIRO's Dr Greg Constable and the late Dr Ian Rochester.

NutriLOGIC can help growers and consultants interpret their pre-sowing soil test results to optimise fertiliser rates, and provide a way to identify nutrient deficiencies in cotton crops based on early-season leaf analyses. NutriLOGIC is specifically focused on nitrogen (N) fertiliser management. It predicts the optimum N fertiliser rate based on a number of inputs, such as the soil nitrate-N level, the expected yield, the crop rotation, the region, and soil type.

NutriLOGIC can interpret petiole test results, enabling growers and consultants to identify in-season N fertiliser requirements. NutriLOGIC also contains the latest fact sheets on sampling methods for soil and plant analysis.

Soil nitrate-N calculations in NutriLOGIC

The optimum time to collect soil samples is between July and September to be analysed for nitrate-N and all other major nutrients. Calculations in NutriLOGIC assume that the soil samples have been taken from 0 to 30 cm depth in an irrigated production system.

The following seven steps describe the inputs and calculations that NutriLOGIC uses to calculate an N fertiliser recommendation.

1. **Soil nitrate-N reading.** Normally described in parts per million (ppm) or mg N/kg.

2. **Month sampled**. Soil nitrogen levels naturally fluctuate throughout the year, therefore NutriLOGIC will adjust the soil nitrate reading based on the sample month. For example, a June reading will be multiplied by 0.842, and an August reading by 1.15.

3. **Cropping history.** The uptake of N by the cotton plant will differ depending on the cropping system. For example, cotton grown in a field after a legume rotation crop will have a higher N uptake because of greater soil N cycling and better soil health for better root exploration. NutriLOGIC will group cropping history into legume, non-legume or long fallow. Each group has a separate calculation for N uptake values.

4. **Expected yield.** This figure is used to calculate the crop N uptake required to achieve optimum N fertiliser. Expected yield is also used again in the calculation of N fertiliser rate.

5. **Soil type.** The crop's ability to use the fertiliser differs between soil types. NutriLOGIC will adjust the calculated N fertiliser rate depending on the soil type. For example, it will be harder for a crop grown in a heavy clay soil type to use fertiliser than in a loam soil type. Therefore, the N fertiliser rate for heavy clay is multiplied by 1.1.

6. **Soil compaction.** Similar to soil type, the crop's ability to use the fertiliser differs between levels of soil compaction. NutriLOGIC will also adjust the calculated N fertiliser rate depending on soil compaction. For example, it will be hard for a crop grown in a soil with high compaction to use fertiliser. Therefore, the N fertiliser rate for high compaction is also multiplied by 1.1.

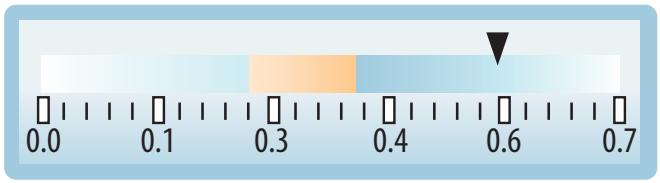
7. **Region.** Regions vary in season length. The season length will also affect how much N the crop will use. In a similar way to soil type and compaction, NutriLOGIC will calculate the final recommendation by multiplying the N fertiliser rate by a regional factor.

Leaf nutrient interpretations in NutriLOGIC

NutriLOGIC can interpret major (nitrogen, phosphorus, potassium and sulphur) and minor (calcium, magnesium, sodium, zinc, iron, copper, manganese and boron) nutrient levels in leaves sampled throughout the season. The analysis page presents each nutrient level on slide bars (Figure 9.1) to indicate whether the nutrient is in the optimum, deficient, or excess zones for the development stage of the crop.

Figure 9.1: Example of slide bar on the NutriLOGIC analysis page.

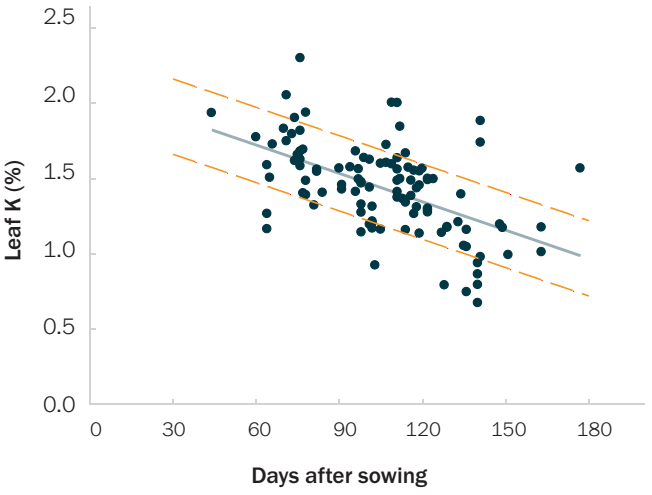
Phosphorus



The following two steps describe the inputs and calculations that NutriLOGIC uses to calculate the status of each nutrient.

1. **Nutrient reading**
2. **Sample time.** NutriLOGIC will calculate the number of days from sowing using the difference between the crop's sow date and the sample date. The optimum levels of leaf nutrients fall within a range, and decrease during the season. Therefore, a low reading towards the end of the season may be adequate for optimum crop growth. Figure 9.2 shows how the level of potassium in the leaf falls during the season. The leaf potassium percentage is adequate if it sits between the red lines.

Figure 9.2: Cotton leaf potassium levels during the season.



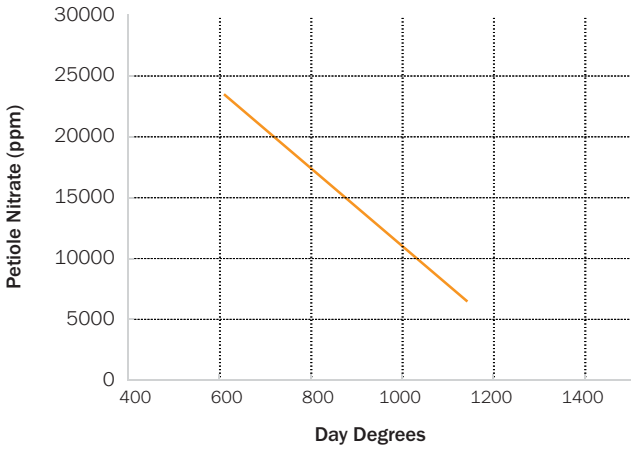
Petiole nitrate-N calculations in NutriLOGIC

Throughout the industry, cotton petioles are often tested to determine whether the crop will need more nitrogen fertiliser to achieve optimum yields. NutriLOGIC can interpret petiole nitrate-N for this purpose. The recommendation is generated by comparing the petiole test(s) with the optimum petiole nitrate status according to the stage of the crop.

The following four steps describe the inputs and calculations that NutriLOGIC uses in the interpretation.

1. **Petiole nitrate-N.** Normally described in parts per million (ppm). The program will use a single test, although greater accuracy will be achieved if three tests are conducted at weekly (or 10-day) intervals. NutriLOGIC will convert the samples to a nitrate-N reading at flowering which is used in the final recommendation. Three tests are more accurate because NutriLOGIC will then use the rate of change in nitrate-N concentration to calculate the nitrate-N reading at flowering.
2. **Sample time.** This will be converted to the number of accumulated day degrees (DD) since sowing. NutriLOGIC will automatically generate DD based on sow date, sample date, and location. Like leaf nutrients, the optimum levels of petiole nitrate-N will fall during the season (Figure 9.3).
3. **Region/location**. NutriLOGIC uses climate data for the location to calculate DD.
4. **Critical petiole nitrate–N at flowering.** The critical nitrate-N level calculation is based on a mean decline of 31.7 ppm/DD and flowering at 750 DD (Figure 9.3).

Figure 9.3: Decline in cotton petiole nitrate-N during the season.



The ideal time of the season to start petiole sampling is at squaring. This is usually early to mid-December. It is important not to sample in a crop experiencing water stress (i.e. waterlogged or dry) or has experienced prolonged cloudy periods in the past few days.

RUTH REDFERN

10. Waterlogging of cotton

Cotton is known to be poorly adapted to waterlogged conditions. In Australia, most of the cotton is grown using furrow irrigation on heavy clay soils. Because these soils drain slowly, many cotton crops can be subjected to some degree of waterlogging; and waterlogging can significantly limit irrigated cotton production. This problem can be accentuated by rainfall after irrigation and inadequate land preparation. Symptoms of waterlogged cotton include a general yellowing of the crop, stunted growth, and reduced fruit growth along with fruit shed (abscission). Crop yields may be affected even before symptoms are noticed.

Waterlogging can be avoided by optimising field design, bed formation, and irrigation scheduling. The application of some foliar fertilisers may also assist in fields known to waterlog. Following a waterlogging event, targeted nutrition management is needed that aids crop recovery and matches the yield potential for the remaining part of the season.

Causes of waterlogging

Waterlogging can severely restrict crop growth and may kill plants in extreme cases. This is because oxygen (O_2) diffuses 10,000 times more slowly in water than in air. Hence, soil O_2 supply from the soil atmosphere is reduced while other toxic gases (e.g. CO_2 and ethylene) generated by plant roots and microorganisms accumulate to high and possibly lethal concentrations in the soil. The major and immediate effect of waterlogging is blocking transfer of O_2 between the roots and the soil atmosphere. Plant roots may become so O_2 deficient that they cannot respire. As a consequence, root growth and absorption of nutrients is decreased. Availability of nutrients in the soil is also reduced.

Waterlogging is often compounded by soil compaction. However, reduced tillage and permanent bed systems may alleviate soil compaction and the severity of waterlogging. Cloudy weather (reduced radiation) associated with wet seasons exacerbates the effect of waterlogging (especially if the waterlogging effect is mild) as well as increase the incidence of some cotton diseases. On the other hand, recent research by Najeeb (2016) has shown that when waterlogging is severe, there is no additional effect of a reduced radiation environment.

Impacts of waterlogging on crop yield and quality

Investigations in the early 1980s by the late Arthur Hodgson in Narrabri into the effects of waterlogging showed that yield of field-grown cotton declined with duration of inundation at each irrigation event. To generate the effects of duration of inundation, Hodgson varied the period of irrigation of the crops between 4 and 32 hours. When the data of his experiments were combined, yield was strongly related to the number of days when air-filled porosity of the soil (proportion of air present in the soil) at a depth of 10 to 20 cm was below 0.1 (i.e. 0.1 cm^3 of air/cm^3 of soil, or 10% air by volume). Lint yield was reduced by 48 kg/ha (0.2 b/ha) for every day that the soil was low in oxygen (Figure 10.1). Hodgson found that there were no further reductions in yield after 96 hours (4 days) of inundation across the growing season. Other field studies by Bange, Milroy, Thongbai and Najeeb in more recent times showed that waterlogging early in crop growth had far greater influence on yield than waterlogging at mid-flowering or later.

Figure 10.1: The relationship between yield and duration of inundation by irrigation from Hodgson (1982).

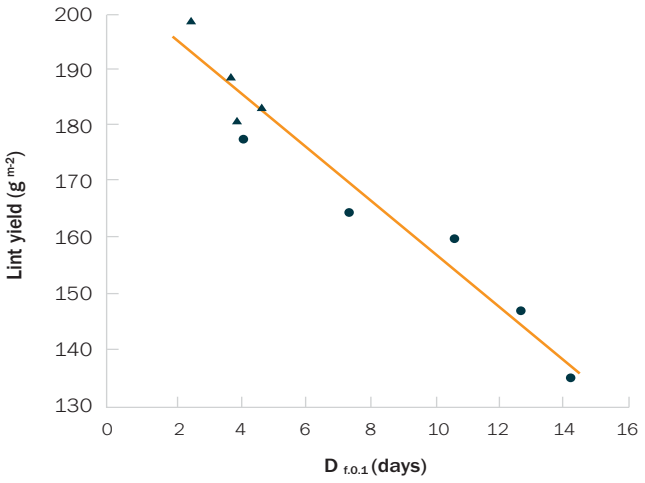


Figure 10.2: Abnormal shedding of late squares and young bolls is a common response to the stresses of waterlogging or continued cloudy, wet weather, which reduces yield.

DR MIKE BANGE

Results of detailed measurements of crop growth in studies of waterlogging mentioned above show that when yield was reduced due to waterlogging, it was associated with final boll number being reduced (Figure 10.2). Boll size and percentage lint were not affected. Reductions in boll number are commensurate with reductions in growth due to lower radiation-use efficiency (amount of dry matter produced per unit of intercepted light), which affects the amount of assimilates available for plant growth. Results from these studies also suggested that this drop in boll number is most likely associated with less fruiting site production rather than more shedding alone.

The suppression of radiation-use efficiency is consistent with the reduction in photosynthesis and the reduced function of photosynthetic enzymes by waterlogging. Lower concentrations of nitrogen (N) in a leaf can reduce leaf photosynthesis, and the amount of N in leaves is affected by N uptake. Hodgson and MacLeod (1988) showed that, while leaf N of cotton was reduced due to waterlogging, applying foliar N in the days before waterlogging did not fully alleviate the reductions in growth in all cases, nor did it rectify leaf yellowing. This finding suggests that other mechanisms, besides those acting through the reduced uptake of N, were likely to be acting on leaf performance.

The exact reasons for the reduction in photosynthesis and radiation-use efficiency with waterlogged cotton are still to be clarified. Recent research by Najeeb et al. (2015) has shown that a build-up in ethylene in the plant is contributing to fruit shedding and less photosynthesis. This research has also shown that the distribution of nitrogen through the canopy plays an important role in crops responding to waterlogging. Leaves lower in the canopy are more affected than those at the top of the canopy. This fact may have potential implications for foliar applications because they are probably less effective lower into the canopy where waterlogging is worst.

In addition to the physiological impacts of waterlogging on the crop, there are also significant impacts on nutrient availability and uptake.

Soil nutrient availability during waterlogging

The decline in soil O_2 concentration affects the oxidation stage of many nutrients. When molecular oxygen (O_2) is removed from the soil, a sequence of chemical reductions take place as the intensity of waterlogging conditions increases (Table 10.1). The time to reach each stage in Table 10.1 will vary considerably, depending on soil type (texture), compaction, soil organic matter, pH, and chemical composition. This duration can range from hours to days. The intensity of each waterlogging event will also vary from one event to the next. The availability of N, Mn and Fe is directly affected by waterlogging. Zinc availability is reduced due to the formation of insoluble $Zn(OH)_2$ and $ZnCO_3$.
In alkaline and/or calcareous soils, the availabilities of Fe and Zn tend to be low, due to adsorption onto clay surfaces or $CaCO_3$. A high concentration of bicarbonate may inhibit Fe and Zn uptake and translocation. Soil management that promotes good surface and sub-surface drainage will delay the onset of these chemical reduction processes, thereby reducing the severity of waterlogging.

Table 10.1: Sequence of chemical reduction of nutrients as waterlogging intensifies.

Chemical reaction	Increasing waterlogging intensity
Onset of NO_3^- reduction to nitrite	▼
Onset of Mn^{2+} formation	▼
Free oxygen (O_2) depleted; normal root respiration slows	▼
Nitrate (NO_3^-) completely reduced to N_2O and N_2	▼
Onset of Fe_{2+} formation (but plants cannot absorb due to low root activity)	▼
Onset of SO_4^- reduction (H_2S formed)	▼
Absence of SO_4^-	▼
CO_2 reduced to methane (CH_4)	▼

Nutrient uptake during waterlogging

The lack of oxygen in waterlogged soil impairs water and nutrient uptake. Nitrogen, potassium and iron uptakes are particularly affected in cotton subjected to waterlogging.

NITROGEN

Besides impairment of root uptake activity, an added penalty under waterlogging is the denitrification of soil mineral nitrogen. Therefore, even after waterlogging has ceased, there may be less nitrogen available for the crop. Figure 10.3 shows the impact of a severe waterlogging event early in crop growth versus one later in the season. The early event has a significantly greater effect on N uptake before the demand of N needed for fruit growth and high yield.

Yield reduction from waterlogging may be severe, but applying foliar fertiliser can prevent part of that yield loss if applied before waterlogging. Foliar applications can also 'nurse' a crop back to health following a severe event. Careful attention to rates are important as excess N can burn foliage. Applications on an already waterlogged field may have little effect.

Foliar N is also more effective in increasing the yields of waterlogged cotton when applied one day before irrigation under hot, sunny conditions. Foliar N is less effective when applied during cool, overcast conditions, or when high concentrations of soil N are available to the crop before waterlogging. Therefore, foliar N applications may be beneficial on fields with little slope and where suboptimum amounts of N fertiliser have been applied. Plant tissue testing may be used as a guide to indicate susceptibility to waterlogging and response to foliar N.

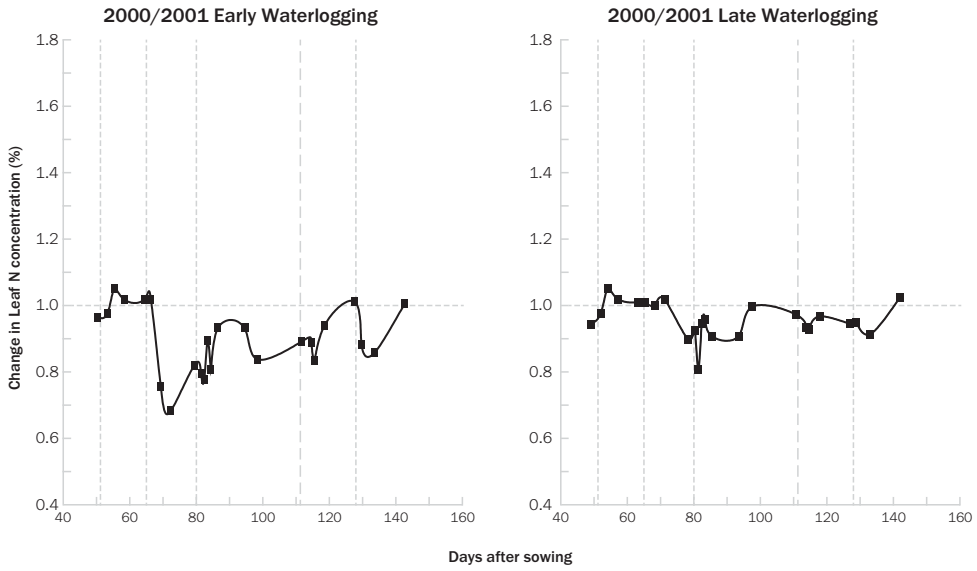


Figure 10.3: The impact of waterlogging on the N concentration of the most fully expanded leaf at the top of the plant. The graphs show the change from the non-waterlogged treatment. The heavy dashed line is the waterlogging event and the other lines are normal irrigation events. Note the large impact caused by the early waterlogging event (adapted from Milroy, Bange and Thongbai (2009)).

Figure 10.4: Post-flood-affected cotton will commonly show deficiencies of nitrogen. Recovery of cotton from nutritional problems may be slow where the plant's root system is impaired due to waterlogging.

DUNCAN WEIR

POTASSIUM

Waterlogging is possibly involved in premature senescence of cotton. Under waterlogged conditions, uptake of K by the cotton crop may be reduced, predisposing the crop to premature senescence (see 'Premature senescence' in this manual).

IRON

The young leaves of iron-deficient plants become yellow between the veins (chlorosis). The veins usually remain green, unless the deficiency is severe. The whole leaf may eventually turn white. Although the plant may contain high concentrations of iron, most of it is unavailable for chlorophyll production and the leaves lose their green colour. When a soil is waterlogged, the passage of carbon dioxide out of the soil is blocked. The CO_2 concentration builds up in the soil solution, forming bicarbonate ions. This increases soil pH, which in turn increases the concentration of bicarbonate and alkalinity in the leaf tissues. Under these conditions, iron becomes unavailable, i.e. the active iron (Fe^{2+}) is converted to inactive forms (Fe^{3+} and others) and symptoms of chlorosis appear. The soil syndrome is referred to as lime-induced chlorosis.

Waterlogging can also induce iron chlorosis, particularly where soil phosphorus is high. Phosphate reacts with soluble iron to form insoluble iron phosphates. The imbalance between iron and phosphorus in the leaf tissue is observed as very yellow leaves about two nodes from the terminal.

Diagnosing iron chlorosis is complicated because the total iron content of the leaf is not closely related to the physiologically active iron (Fe^{2+}) component of total iron content. To determine the Fe^{2+} content, fresh leaves must be analysed within a few hours of sampling; commercial laboratories cannot do this. The total Fe content of yellow leaves is often similar, or higher than that of green leaves, which may incorrectly indicate that iron is not deficient.

Foliar application of 200 g Fe/ha with a ferrous sulphate (e.g. one kg $FeSO_4$/ha) may return foliage to its normal colour in 2 to 3 days.

Management options to minimise waterlogging damage

The impact of a flood event can range from complete crop failure to less growth and yield. The effect depends on the severity (depth, water quality, flow) and length of inundation. The way the crop is managed for recovery may change, depending on the timing of these extreme waterlogging events during the season. If a significant amount of the season remains, then the primary aim should be to nurse the surviving crop back to a point where it can support new growth. If the waterlogging events have occurred late in the season, the focus should be on supporting fruit retention. A crop manager needs to ascertain whether enough of the season remains to allow new fruit to be set, develop, and mature before the onset of cold weather. The time for a new square to produce a flower is, on average, 23 days while it takes 63 days for a boll, on average, to develop into a harvestable boll. As the season progresses, these times (for nodes, squares and flowers to develop) increase as temperature and light decrease. While new squares can be produced, the risk of them not contributing to final yield is considerable, especially late in the season. In some cases, crops may have reached the point of (or are rapidly approaching) the last effective square that results in the last effective flower. Growers and consultants can determine squares and fruit that are likely to mature using the Last Effective Flower Tool in CottASSIST. This resource is available at http://www.cottassist.com.au.

For crops to gain access to soil water and nutrition, surface roots must once again come into contact with oxygen when the fields dry out. After this has occurred, leaf testing may provide some guidance as to the plant's nutritional needs. Foliar applications of nitrogen, phosphorus, iron, zinc, and boron may alleviate immediate deficiency symptoms and help nurse plants along.

Irrigation schedules may also have to be shortened to avoid stress because overall root function may have been impaired. With late-season affected crops, avoid over-fertilising. It might induce unnecessary regrowth, which makes defoliation more difficult, delays overall maturity and picking, affects quality, and could lead to pest and disease issues later in the season.

It is also important to ensure proper irrigation scheduling. Too frequent irrigations increase the risk of waterlogging. Soil moisture monitoring equipment can help with optimising irrigation scheduling to reduce waterlogging risks and to improve yields. Monitor growth. In some instances, waterlogging may induce shedding. If conditions significantly improve and there is adequate nutrition, excessive vegetative growth maybe an issue. Consider mepiquat chloride (Pix) only when crops are recovered fully, because the use of this growth regulator might add stress, or have no effect.

Other factors to consider to avoid waterlogging:

- **Weather**. If feasible, monitor weather and delay irrigation if there is a high chance of significant rainfall at the time of the scheduled irrigation.
- **Field design**. A uniform slope of at least 1:1500 is best for draining irrigation water or rainfall from a field. Tail drains should also be designed to remove run-off as quickly as possible.
- **Irrigation period**. Keep the period of single irrigation events to a minimum to minimise the risk of waterlogging. This could be achieved with larger siphons, or using two siphons per row, or by shortening the irrigation run.
- **Pumping.** Increasing the pumping and application capacity will help to get the water on and off the field quickly as well as cut the time it takes to irrigate the whole farm. Higher application capacity gives farmers more flexibility to respond to weather influences, such as a heat wave or forecast rain.
- **Hill height**. Well-formed high beds will decrease waterlogging in an irrigated field.

Further reading

Bange, M.P., Milroy, S.P. and Thongbai, P. (2004) Growth and yield of cotton in response to waterlogging. *Field Crops Research* 88(2): 129–142.

Milroy, S.P., Bange, M.P. and Thongbai, P. (2009) Cotton leaf nutrient concentrations in response to waterlogging under field conditions. *Field Crops Research* 113(3): 246–255.

Hodgson, A.S. (1982) The effects of duration, timing and chemical amelioration of short-term waterlogging during furrow irrigation of cotton in a cracking grey clay. *Australian Journal of Agriculture Research* 33: 1019–1028.

Hodgson, A.S. and Chan, K.Y. (1982) The effect of short-term waterlogging during furrow irrigation of cotton in a cracking grey clay. *Australian Journal of Agriculture Research* 33: 109–116.

Hodgson, A.S, and MacLeod, D.A. (1988) Seasonal and soil fertility effects on the response of waterlogged cotton to foliar-applied nitrogen fertiliser. *Agron.* J. 80, 259–265.

Najeeb U., Bange M.P., Atwell B.J. and Tan D.K.Y. (2015) Understanding of the Interactive Effect of Waterlogging and Shade on Cotton (*Gossypium hirsutum* L.) Growth and Yield. *Procedia Environmental Sciences* 29:85–86.

Najeeb U., Bange M.P., Atwell B.J. and Tan D.K.Y. (2016) Low-Incident Light Combined with Partial Waterlogging Impairs Photosynthesis and Imposes a Yield Penalty in Cotton. *Journal of Agronomy and Crop Science*.

Taylor, I., Bange, M., Wilson, L., Rochester, I., Grundy, P. and Yeates, S. (2012) *Responding to late season flooding.* Cotton Research and Development Corporation.

11. Stubble management in cotton farming system

This chapter covers cotton stubble management, and stubble management of rotation crops in a cotton farming system.

Cotton stubble management

The old system of stalk pulling, raking and burning to remove cotton stubble can have adverse effects on the productivity of cotton fields. The vast majority of cotton growers have adopted an alternative system, which involves slashing the cotton stubble near ground level and incorporating the stubbles and trash into the surface soil. Returning cotton stubble to the soil provides a source of energy for the microbial biomass, which in turn helps the breakdown of stubble. This maintains the supply of nutrients to the crop.

Advantages of retaining cotton stubble

- adds organic matter to the soil
- improves soil tilth
- decreases soil bulk density
- creates greater biological activity in the soil
- maintains active populations of soil organisms
- supplies energy to the soil microbial biomass
- enhances nutrient cycling
- improves fertiliser use efficiency
- improves moisture infiltration
- reduces wind and water erosion
- incorporating stubble forms part of the pupae-busting operation

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Figure 11.1: Cotton field during harvest

Disadvantages of retaining cotton stubble

- potential to encourage volunteer cotton plants
- may block cultivation equipment or irrigation channels when stubble not incorporated
- potential to reduce herbicide/soil contact where stubble remains on surface
- may exacerbate seedling disease, particularly when stubble is not incorporated

Cotton stubble management research

An experiment at Narrabri over three years (1992–1995) investigated both stubble management systems for cotton growth, lint yield and fertiliser N recovery. The experiment indicated that removing cotton stubble reduced lint yield and profitability over time. Compared with the lint yield of the stubble-retained treatment, the yield of the stubble-removed treatment was reduced by 3% and 9% respectively, in the second and third years of the experiment.

The experiment also revealed that the N fertiliser recovery was reduced by 10% where the stubble was removed compared to the retained plots, i.e. more N fertiliser was lost from the soil where stubble was removed.

Problems associated with raking/burning cotton stubble

A major disadvantage of the raking and burning system is that the operation often requires several machinery passes (stalk pull, rake, burn, rake again), which prolongs the time to prepare the field for planting. Burning stubble not only creates smoke and atmospheric pollution, but also causes the loss of many nutrients. Virtually all (depending on the temperature of the fire) of the nitrogen and sulphur contained in the stubble are released into the atmosphere as gases.

The heat generated by the fires destroys organic matter in the surface soil, which can substantially affect soil properties. Much of the N, P and S contained in the soil organic matter will be lost to the atmosphere during burning, depending on the heat of the fire. The raking of stubble into windrows creates variation in fertility across the field, as the nutrients contained in the stubble are concentrated in these rows while depleting the rest of the field. The ash in the windrows

contains high concentrations of some nutrients (K, Ca, Mg, Mn and Fe) that have been transported from the surrounding area. This produces uneven growth of following crops, which can be difficult to manage and very difficult to rectify.

Cotton disease control

There is a perception that raking and burning will help reduce cotton pathogens. Research indicates that this is not the case. As most of the leaf material is returned to the soil before raking and burning, sufficient inoculum persists in the soil to maintain pathogen levels. Burning stalks has little benefit in reducing inoculum levels for cotton diseases, such as Verticillium wilt, black root rot, bacterial blight, and Alternaria, which are retained on the leaves and petioles, most of which have dropped and mixed with the surface soil. Reducing the amount of stubble from cotton or other crops left on the soil surface may help reduce seedling diseases (Pythium and Rhizoctonia). To cut levels of Fusarium inoculum, retain crop residues on the soil surface as long as possible before incorporation.

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Figure 11.2: Stubble mulching

Recommended management of cotton stubble

The most effective means of dealing with cotton stubble will vary with the severity of each specific disease problem. Hence, growers need to be aware of the diseases present on their farms and the risk they pose to their enterprise in order to manage stubble appropriately. An integrated disease management guideline is presented in the annual publication of the Cotton Pest Management guide.

The most environmentally friendly way to manage cotton stubble is to slash the standing stubble close to ground level, leaving the stubble in short (<10 cm) pieces to be incorporated into the surface soil.

STUBBLE MANAGEMENT OF ROTATION CROPS (CEREALS AND LEGUMES)

The rotation crop stubble management (either incorporation or surface mulching) has their own benefits for nutrient cycling and water conservation in cotton farms. The incorporation of stubble will enhance nutrient cycling in the zone of incorporation (0 to 10 cm in permanent beds, or 0 to 30 cm under conventional tillage). Long-term research incorporating stubbles suggested a return of 1.17 and 0.50 t N/ha from legume and non-legume stubbles, respectively, over a 10-year period. The N content of wheat stubbles, cotton stubbles, and legumes were 0.78%, 1.56% and 3.39%, respectively (Rochester 2011). Stubbles retained on the surface will reduce evaporation and enhance soil water storage (Hulugalle et al. 2017). Crop residue return of minimum 2 to 3 kg/m^2 is recommended to prevent the decline of soil organic carbon (Hulugalle and Scott, 2008). Recent research into crop rotation and stubble management suggests cotton-wheat-vetch rotation is leading to a positive balance of soil organic carbon with both vetch-residue incorporation (Rochester, 2011) and surface retention (Hulugalle, 2014). However, it is acknowledged that special machinery development or modification of existing farm machinery is warranted to manage the vetch stubbles. The advantages and disadvantages of retaining cotton stubble (presented above) apply also to rotation crop stubble management.

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Figure 11.3: Root cutting

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Figure 11.4: Pupae-busting implement

STUBBLE MANAGEMENT IN DRYLAND COTTON CROP

Though stubble incorporation in dryland crops will have similar benefits as for irrigated crop, there is an additional risk of soil erosion and associated nutrient losses. The mandatory pupae-busting requirement of the commercial transgenic cotton cultivars adds complexity to managing stubbles in dryland cotton crops. Stubble management in a dryland system needs to consider the risk of diseases because the pathogen risk may outweigh the nutritional benefits of stubbles. Refer to the section on integrated disease management in the Cotton Pest Management guide. The recent relaxation of mandatory pupae busting, if defoliation is completed before 31 March each year, could potentially help growers develop a surface stubble retention practice that minimises soil erosion risk.

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Figure 11.5: Cotton field before and after pupae busting

Further reading

Hulugalle, N. R. & Scott, F. 2008. A review of the changes in soil quality and profitability accomplished by sowing rotation crops after cotton in Australian Vertosols, from 1970 to 2006. *Australian Journal of Soil Research*, 46, 173–190.

12. Soil organic matter

Introduction

Soil organic matter (SOM) is a critical component of healthy soils and sustainable agricultural production. Growers understand that crops grown in healthy soils perform better and are easier to manage. Soil organic matter is defined as 'all of the organic materials found in soils, irrespective of its origin or state of decomposition'[1]; that is, anything in or on the soil of biological origin, alive or dead. It is composed mainly of carbon (about 60%) as well as a variety of nutrients, including nitrogen, phosphorus and sulphur. Because it is difficult to actually measure the SOM content of soil directly, we measure the soil organic carbon (SOC) content, and then estimate SOM through a conversion factor:

Soil Organic Matter (%) = Organic Carbon (%) x 1.72

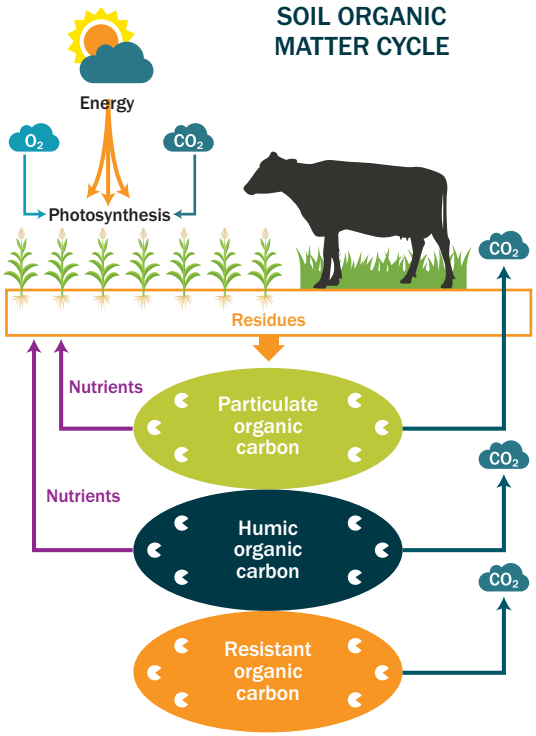
Soil organic matter can be divided into two groups—living components and non-living organic matter:

1. Living components include plants (flora) and animals (fauna)
    - microflora: bacteria and fungi
    - microfauna: protozoa and nematodes
    - mesofauna: mites and collembola
    - macrofauna: earthworms, ants, termites, dung-beetles etc.
2. Non-living organic matter includes all dead or decaying plant and animal residue, crop stubble, and old plant roots.

It is important to understand the role of plants in the SOM cycle (Figure 12.1). Photosynthesis is the process by which plants take in carbon dioxide (CO_2) from the atmosphere, combine it with water taken up from the soil, and, using the energy from the sun, form carbohydrate (organic matter) and release oxygen (O_2). This is the start of the SOM cycle. When the leaves and roots (carbohydrate) die, they enter the soil and become SOM. These residues are decomposed by soil organisms that provide them with the energy to grow and reproduce. The SOM cycle is a continuum of different forms (or fractions) with different timeframes under which decomposition takes place. Over time, SOM moves through three fractions: particulate, humic, and resistant fractions.

As SOM decomposes, carbon is released from the system along with any nutrients that are not used by the microorganisms. These nutrients are then available for plants. Eventually, a component of these residues will become resistant to further decomposition (resistant fraction).

Figure 12.1: Organic matter cycle (Source: Jayne Gentry, Queensland Department of Agriculture and Fisheries).



Functions of organic matter

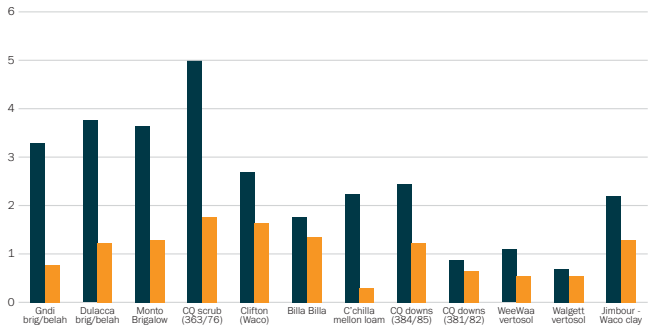
Soil organic matter plays a critical role in the functioning of many physical, chemical and biological processes in the soil. These include:

- Soil structural stability, aggregation and aeration
- Water infiltration, retention and availability
- Nutrient availability, turnover, and cation exchange capacity
- Soil buffering against rapid changes in pH, salinity and sodicity
- Moderation of extreme temperature changes
- Provision of nutrients and energy for biological processes and microbial decomposition
- Improvement in soil resilience.

Current situation

Australian soils are generally low in SOM. Initial SOM levels are limited by dry matter production (and thus climate) for each land type/location. SOM levels have declined under traditional cropping practices. On-farm measures (sampled 2012 to 2015) from over 500 sites in Queensland and northern New South Wales confirm that soil organic matter, measured as soil organic carbon, declines significantly when land is cleared and continuously cropped. This decline affects all soils and land types but is most significant for the brigalow/belah soils because their original organic carbon levels are so high (Figure 12.2).[2]

Figure 12.2: The decline of soil organic carbon in long-term cropping systems (Source QDAF[2])



Soil organic carbon levels are simply a snapshot of the current balance between inputs (e.g. plant residues and other organic material) and losses (e.g. erosion, decomposition) constantly happening in each soil and farming system. The decline over time is overwhelmingly driven by the extent of fallowing in our farming systems. Most fallow rain in the northern region (as much as 75 to 80% in a summer fallow) is lost as run-off or evaporation. This wasted rain does not grow dry matter to replenish the organic matter reserves in the soil. However, increasing moisture in the fallowed soil continues to support microbial decomposition. This helps accumulate available nitrogen for the next crop, but reduces soil organic carbon.

As organic matter is concentrated in the soil surface layers (0 to 10 cm), any process that results in the loss of topsoil can also affect the levels of organic matter and organic carbon found in the soil, e.g. soil loss, cultivation, and stubble removing or burning. Any loss of topsoil by erosion (wind and water) can significantly reduce soil organic matter. Soil loss is highly influenced by ground cover, storm intensity, and physical stability of the soil. Bare fallow systems can lose between 60 and 80 tonnes of topsoil per year, while a single, high-intensity storm can strip away up to 300 tonnes per hectare. Cultivation and soil disturbance can increase mineralisation by accelerating the decomposition of organic matter by the soil biota. This occurs because cultivation disturbs the soil, breaks up the organic matter and mixes it through the soil, thereby exposing more of it to the decomposing soil biota. Removing or burning crop stubble significantly reduces the volume of organic matter being returned to the soil to be recycled.

The soil organic matter and carbon levels will continue to decline until they reach a new lower level that the dry matter produced by the new farming system can sustain. Think of it this way—*Crops may make more money than trees and pastures, but they do not return as much dry matter to the soil.*

Total soil organic carbon levels vary within a paddock, from paddock to paddock, and from region to region. Comprehensive sampling was undertaken throughout the New South Wales and Queensland cropping regions, with more than 900 sites sampled and analysed for total organic carbon at the 0 to 10 cm level. Results varied enormously across sites. Although the average was 1.46%, results ranged from below 0.5% to above 5% (Figure 12.3).[2] A selection of data from representative soil clearly indicates how soil carbon levels can be significantly different due to soil type (Figure 12.4).[2]

Figure 12.3: Soil organic carbon levels on mixed farms from northern NSW and Queensland (Source QDAF[2]).

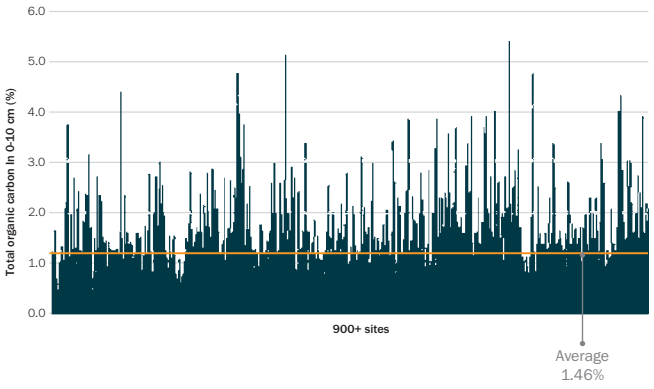
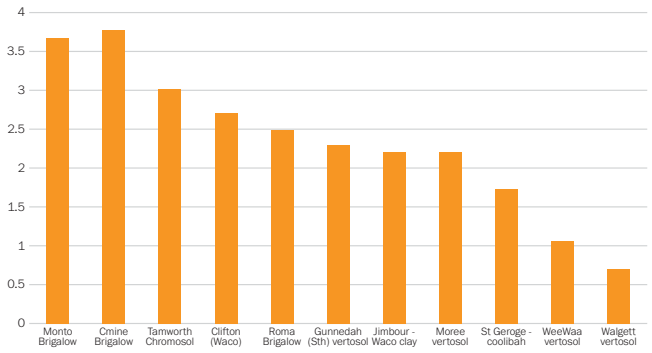


Figure 12.4: Effect of land type on total soil carbon levels (0 to 10 cm) across northern NSW and Queensland (Source: DAF[2]).



SOM critical in the supply of nutrients to plants

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 nitrogen (N) to plant-available N. On the higher clay soils, SOM's major role (through its mineralisation) is providing nitrogen and other nutrients in an available form to crops and pastures. To put the value of SOM into perspective, at current fertiliser prices, every 1% of measured SOC is associated with approximately $1500 to $2000 worth of nutrients. The other functions (e.g. cation exchange capacity and water-holding capacity) will still be influenced with increased SOM, but the impact will be greatest on sandy soils.

The rate at which nutrients become available is determined by the rate of mineralisation, which in turn is affected by a number of factors. Temperature and moisture are key drivers, however, soil pH, anaerobic conditions (waterlogging), the form of organic matter (particulate, humus) and the carbon-to-nitrogen ratio all influence the rate of mineralisation and immobilisation. These processes operate concurrently, cycling nutrients between the organic and mineral pools.

Options for reversing the decline in soil organic matter

Soil organic matter is an undervalued capital resource that must be managed properly. Levels of SOM (measured as SOC) are a result of a simple equation:

SOC = inputs – losses

Maximising biomass production (i.e. inputs) and minimising losses, such as erosion and burning/baling, will encourage higher SOC levels. Modern farming practices that maximise water-use efficiency for extra biomass production are integral in protecting SOM. For example:

- growing healthier, bigger crops (better agronomy)
- increasing cropping frequency (reducing fallows)
- adding organic matter, e.g. manure/compost
- reducing tillage, burning and bailing
- using pasture phases.

Better agronomy. Improving agronomic management of crops will maximise yield and biomass production, and produce higher stubble loads.

Increased cropping frequency. Increasing cropping frequency will reduce the time soil is in fallow, and use rainfall to grow dry matter that will contribute to the organic matter cycle.

Cover crops. They are used for a variety of reasons, including stabilising soil and reducing wind and water erosion; a crop rotation to control or suppress pest, weed and disease; use and absorb excess nutrients from the previous crop, reducing losses and enhancing nutrient cycling in future crops; more organic matter into soils; fixating nitrogen, using legume crops.

Stubble retention. The principle reasons for leaving stubble standing are to capture and hold moisture and to protect soil from erosion (wind and water). However, a significant proportion of the carbon is lost through biological decomposition, resulting in little benefit to soil carbon levels.

Cultivation. Cultivation breaks down the soil aggregates and exposes the organic matter previously not exposed to decomposition by microbial activity, and increases the rate of mineralisation. This results in a significant, rapid loss of organic matter. The soil is also exposed to losses from wind and water erosion, and impacts on soil macrofauna, such as worms and nematodes.

Bare fallow. Under bare fallow, organic matter is not being returned into the system. At the same time, the existing organic matter continues to be broken down by the soil biota reducing its level. There is also a greater risk of more losses from wind and water erosion.

Zero tillage. Under zero tillage systems, crop residues and, consequently, nutrients remain on the surface and become concentrated in the upper layers of the soil. This results in nutrient stratification through the soil profile, with high concentrations of nutrients, such as phosphorus and potassium, in the drier 10 cm of the soil surface and unavailable for plant uptake. It also exposes the organic matter to greater losses through wind and water erosion.

Most cotton systems require a pupae-busting operation as a result of the use of Bollgard® technology. Along with the need to form irrigation farrows and beds, the soil at the surface is normally extensively disturbed, and crop residue left on the surface is incorporated into the soil profile.

Balancing organic matter losses and gains can be difficult to achieve because some practices have conflicting impacts. For example, retaining stubble on the surface reduces build-up of Fusarium inoculum, increases water infiltration and soil water storage, reduces soil erosion, and protects the soil. But as the organic matter decomposes on the soil surface, a significant amount of carbon is lost to the atmosphere as carbon dioxide (CO_2). In contrast, research has shown that a strategic, targeted tillage operation to incorporate stubble and control Helicoverpa pupae can help increase soil carbon. On the other hand, cultivation can promote loss of soil water and expose the soil to erosion.

Using organic matter and organic amendments in cotton systems

Many growers have recognised the benefits of maintaining or increasing the organic matter levels in their soils and have introduced organic amendments (manures and composts) into their production systems.

The main issue in using these types of products is accounting for them in a balanced nutrient program. Measuring their benefits and costing their value is difficult, and it creates challenges when growers try to ensure that the crops' nutrient demands are met. There are three main problems:

- what to measure (nutrient balances, soil biota and diversity, soil chemistry changes, soil structure and function)
- how to measure it
- how to value soil changes.

Although results from multiple studies and extensive research have been variable and inconclusive, one point has been established—one-off use of these products is of little benefit unless they are used in large volumes. Conversely, growers who have used these products regularly over a long period believe they have seen improvement in soil condition and soil biology, and have slowly increased nutrient levels, such as potassium, phosphorus and micro-nutrients.

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Considerations when testing SOC

It is critical to test for SOC correctly to track changes in SOM and ensure meaningful results that can be accurately interpreted. Soil is normally collected in two increments: 0 to 10 cm, and 10 to 30 cm. The number of samples collected will be determined by the size of the paddock to ensure accurate representation. Avoid atypical areas, such as headlands and areas close to tree lines. Do not include crop residues because they are not yet a part of the SOM system.

There are various types of analyses available:

- **Total Organic Carbon (TOC)** – will provide a measure of all the carbon from an organic source. This contrasts with Total Carbon, which also measures inorganic $CaCO_3$ on high pH soils and can provide very high carbon test results.
- **Walkley-Black** – used in the past (about 85% of TOC). Caution: be careful when comparing old soil tests to current tests.
- **Particulate Organic Carbon (POC)** – measures the more labile, active carbon fraction that occurs in small particle sizes.
- **Microbial Biomass Carbon (MBC)** – measures the total amount of microbes in the soil.
- **Fluorescein diacetate hydrolysis (FDA)** – measures microbial activity because not all microbes are alive and active.

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References

[1] Baldock, JA and Skjemstad, JO. (1999). Soil organic carbon /Soil organic matter. In Peverill, KI, Sparrow, LA and Reuter, DJ (eds). *Soil Analysis: an interpretation manual*. CSIRO Publishing, Collingwood, Australia.

[2] DAF (2016) *Queensland Grains Research – 2015*. Regional Research Agronomy Network. Department of Agriculture, Fisheries and Forestry Queensland, pp.112–117.

Acknowledgements

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Further reading

Hoyle, F (2014). *Managing Soil Organic Matter: A Practical Guide.* Grains Research and Development Corporation.

Nachimutha G, Hulugalle N (2016). On-farm gains and losses of soil organic carbon in terrestrial hydrological pathways: A review of empirical research. *International Soil and Water Conservation Research* 4(4), 245–259.

www.sciencedirect.com/science/article/pii/S209563391630065X

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