

Chapter 4

NUTRITIONAL REQUIREMENTS OF COTTON DURING FLOWERING AND FRUITING

Ian J. Rochester¹, Greg A. Constable¹, Derrick M. Oosterhuis²
and Meredith Errington³

¹CSIRO Plant Industry, Narrabri, Australia

²University of Arkansas, Fayetteville, AR

³University of Sydney, NSW, Australia

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) yields may be limited unless adequate amounts of all required nutrients are accumulated in the plant during its growth. Most soils where cotton is grown commonly have deficiencies of at least one nutrient (e.g. N, P or K) that requires addition of fertilizers to optimise production. There have been some excellent reviews of cotton nutrition (Braud, 1974; Hearn, 1981; Mullins and Burmester, 2010). However, some of those reviews were from studies at relatively low yield levels (<1,500 kg lint/ha) and as such those experiments were conducted under conditions where nutrition was not necessarily the most limiting factor. Those older studies may have been relevant for the cropping system at that particular time and environment, but not necessarily helpful for understanding of nutrition principles under high yield. If water stress, pest damage, disease, soil constraints, unfavorable temperatures, etc are limiting, then real nutritional demands cannot necessarily be developed, particularly considering the importance of redistribution from vegetative to reproductive material during boll development. In this chapter we aim to concentrate on nutrition/physiology during flowering for cotton crops at yields >1,500 kg lint/ha. Under these circumstances the efficiency of nutrient use is improved (Mullins and Burmester, 2010) and the true demands of the crop and fruit can be determined.

Being of indeterminate growth habit, cotton is able to take advantage of conditions when they are favorable, so it is tempting to suggest that cotton might be more tolerant to nutrient stress than determinate species and so nutrition management could be more flexible. But under commercial production, cotton crop nutritional stress costs efficiency and yield to the producer, so a professional approach to cotton nutrition should be one that minimizes deficiencies and toxicities. Thus at high yield levels, managing nutrition is critical for high yield and efficiency as much for cotton as for other crops.

Uptake of nutrients via the roots is governed by nutrient transport to the root surface and absorbed with the water as part of the transpiration stream; or become concentrated in the xylem sap due to a facilitated (protein transporter) or an active uptake process that requires metabolic energy to overcome a concentration gradient (Bassirirad, 2000). Nutrient uptake by cotton is driven by the demand for nutrients from the developing crop, which is regulated by the supply of nutrients from the soil.

Nutrient Uptake by a Cotton Crop

Nutrients are taken up throughout the growing season and in proportion with the demand for nutrients as dictated by the developing crop biomass and boll load. The rates of nutrient uptake increase at flowering through fruiting, and then slow as the bolls mature (Mullins and Burmester, 2010). Nitrogen and K are taken up in greatest amounts – at least 200 kg/ha (Hodges, 1992), while micronutrients such as Cu may have less than 30 g/ha taken up in a season (Fig. 1; Table 1). Using typical uptake curves as depicted in Figure 1, daily rates of nutrient uptake can be calculated (Table 1). While the amounts of each nutrient taken up vary widely, the patterns of accumulation are similar for most nutrients with the timing of peak uptake ranging from day 101 for S to 130 for Fe (mid-flowering stage) (Table 1; Figure 1) and tend to follow the pattern of crop growth, although with higher concentration of nutrients in younger plants (reviewed by Mullins and Burmester 2010).

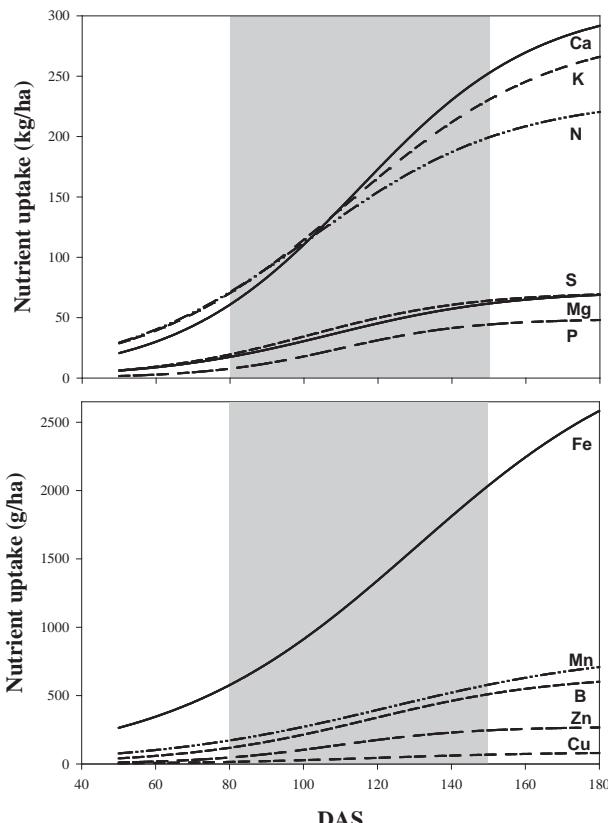


Figure 1. The pattern of nutrient uptake during the growth of an irrigated cotton crop that yielded 2250 kg lint/ha in Narrabri, Australia.

Table 1. 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). Values are calculated from Figure 1.

	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
Sulfur	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

Nutrient Accumulation in Cotton Leaves

Thompson *et al.* (1976) showed that individual leaf N concentration dropped from 6% to 2% as the leaf aged; with the reduction from day 40 to 60 in leaf age being due to redistribution. For a typical leaf the amount exported would be about 50% of leaf N; a similar amount was found by Zhu and Oosterhuis (1992).

Typical declines in the concentrations of most nutrients during the flowering and fruiting periods for high-yielding cotton in Australia are shown in Figure 2. Nitrogen, P, K, Fe, Cu and Zn levels normally decline in leaf tissue as the crop ages (as they are either more mobile or marginal in availability), whereas Ca, Mg, Na, Mn, S and B increase (i.e., not as mobile or in luxury supply). Figure 2 also demonstrates that a critical level of each nutrient can be devised indicating sufficiency or deficiency for each period of crop growth. Declines in the leaf concentrations of N, P, K, Fe, Cu, and Zn (Fig. 2) may indicate redistribution of nutrients from foliage to the developing bolls. Leaf K concentration declines from 2-3% at peak flower to 1% at harvest (Halevy, 1976). The very mobile nature of K, coupled with the ability of many physiological parameters and growth conditions to influence K tissue concentrations, has led to inconsistent reports of critical leaf K values (Kerby and Adams, 1985; Reddy and Zhao, 2005). During flowering, critical leaf K concentrations which impact plant growth, physiology and yield range from 0.60-2.45% (Hsu *et al.*, 1978; Oosterhuis *et al.*, 2003), although narrower ranges have been reported (Baker *et al.*, 1992; Bednarz and Oosterhuis, 1996; Reddy and Zhao, 2005).

Crop modelers use the concept of minimum and maximum concentration of nutrients in plant parts (e.g., Seligman *et al.*, 1975) and use that range to simulate organ growth and development. For cotton leaves, the minimum N leaf concentration for old leaves on a mature crop is about 1.8%; the maximum for young leaves on young plants is about 6.2% (Boquet and Breitenbeck, 2000). Field leaf samples are usually intermediate (Fig. 2).

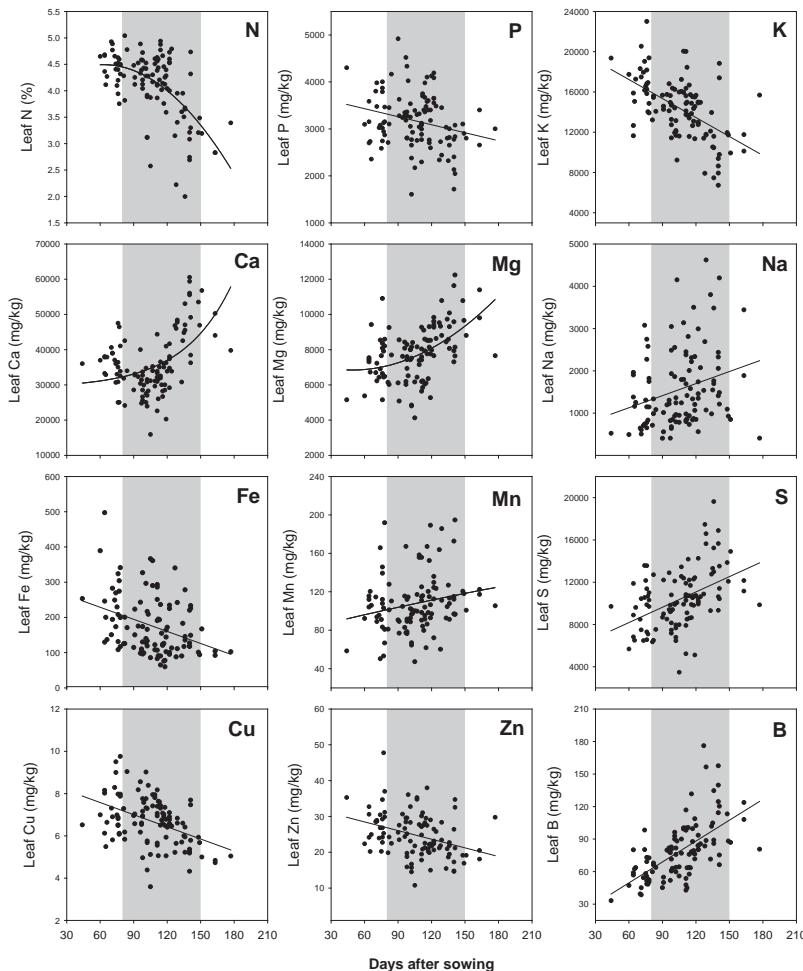


Figure 2. Change in leaf nutrient status during the growth of high-yielding irrigated cotton crops in Australia.

Nutrient Requirement during Flowering/Anthesis

The flower represents a central part of the plant's reproductive growth in which anthesis, pollination, and fertilization occur (Oosterhuis and Jernstedt, 1999). It has been speculated that nutrient imbalances in the flower may cause lower yield and unpredictable year-to-year yield variability (Oosterhuis *et al.*, 2008). These authors documented the mineral composition of cotton flowers, and showed that flower N increased with increasing N fertilizer rates, while P, K, and B decreased. The effect of environmental stresses on flower nutrient content is not known.

Calcium in the pistil of numerous plant species is essential in promoting directional pollen germination and tube growth (e.g. Ge *et al.*, 2009) and ovule fertilization (Faure *et al.*, 1994; Digonnet *et al.*, 1997). During heat stress, potentially damaging reactive oxygen species (ROS) accumulate in plant tissues (Tang *et al.*, 2006), and cytosolic Ca levels have been shown to increase in vegetative tissues (Gong *et al.*, 1998; Jiang and Huang, 2001). Calcium is essential in enhancing the antioxidant enzyme activity required to protect the plant under oxidative stress conditions via ROS scavenging (Gong *et al.*, 1998; Jiang and Huang, 2001), and exogenous Ca application has been shown to enhance antioxidant protection in heat-stressed leaves (Jiang and Huang, 2001). In contrast with antioxidant enzymes, nicotinamide adenine dinucleotide phosphate oxidase produces O₂⁻ in a Ca-augmented fashion, and is needed to soften cell walls and promote cell expansion during pollen tube growth (Potocky *et al.*, 2007). In a study of high temperature stress on cotton, Snider *et al.* (2010) found that exogenous Ca application had no effect on reproductive thermostability due to poor Ca uptake under high temperature. Under 30/20°C day/ night temperature conditions, exogenous CaCl₂ application resulted in an 11% increase in total calcium concentrations, but under the 38/20°C temperature regime, there was no response of total pistil calcium to exogenous CaCl₂ application. However, pre-stress Ca content (together with higher antioxidant enzyme activity) in the pistil was higher in thermo-tolerant compared to thermo-sensitive cultivars. They concluded that pre-stress Ca content, together with antioxidant enzyme activity and adenosine triphosphate (ATP) of the pistil may be associated with reproductive thermo-tolerance in cotton.

Nutrient Accumulation in Cotton Bolls

Nutrient accumulation within a single boll shows steady increases in most macronutrients in phase with the increase in boll weight (Fig. 3; also see Leffler and Tubertini, 1976; Constable *et al.*, 1988). Daily rates and timing of accumulation of nutrients into bolls are shown in Table 2. Notably N, P, K, B, Cu and Zn are taken up relatively early but Ca, Mg, S, Fe and Mn tend to accumulate as the boll matures.

Table 2. Accumulation and timing of nutrients in a boll (mg for N, P, K, Ca, Mg and S and ug for Fe, Zn, B, Cu and Mn). Values are calculated from Figure 3.

Nutrient	Maximum uptake per boll	Maximum uptake per day	Time of maximum uptake (days from anthesis)
Nitrogen	111	3.6	19
Phosphorus	21.4	0.71	19
Potassium	103	3.2	19
Sulfur	17.5	0.37	26
Calcium	31.0	0.82	27
Magnesium	17.2	0.45	21
Iron	221	5.6	24
Manganese	111	2.5	22
Boron	118	3.8	18
Copper	30	0.91	19
Zinc	104	3.0	18

Nutrients do not accumulate in the mature lint – it contains 80 to 95% cellulose (Meinert and Delmer, 1977; Beasley, 1979). The boll wall contains the highest amount of K in the boll, between 32 and 60% (Bassett *et al.*, 1970; Kerby and Adams, 1985; Mullins and Burmester, 2010). This is thought to act as a storage although large proportions of the K and Ca (more than 70%) remain in the boll walls and do not move to the seed. Most of the N, P, Mg, Fe, Cu and Zn in bolls end up in the seed (over 60%) rather than boll walls, while Mn and B tend to remain in boll walls. The seed N concentration equates to 3.5% when cotton is fertilized for economic optimum N use-efficiency (Egelkraut *et al.*, 2004; Rochester, 2012).

Cotton is reputed to be less efficient for potassium uptake from soil than other crops (Cope, 1981; Kerby and Adams, 1985; Cassman *et al.*, 1989) although these reports were from soils that had high K-fixation. That characteristic may be due to soil types and climate in *Gossypium hirsutum*'s original area of evolution. Additionally, K is required for maintaining cotton fiber cell turgor pressure and so facilitating cell growth (fiber elongation) in cotton - a critical aspect. Dhindsa *et al.* (1975) showed that K and malate could account for 55% of total osmotic potential during cotton fiber elongation. If K is in limited supply during active fiber growth, there would be a reduction in the turgor pressure of the fiber resulting in less cell elongation and shorter fibers at maturity. Also, seen as K is associated with transport of sugars, a likely implication of a K deficiency is an effect on secondary cell wall deposition in fibers affecting fiber strength and micronaire. Indeed, Pettigrew *et al.* (1996) reported reductions in fiber elongation and other fiber quality properties in response to K deficiency. However, few field studies demonstrate that this critical role is reflected in fiber properties: Kerby and Adams (1985) noted that the literature on K deficiency shows relatively small effects on fiber length (e.g. Bennett *et al.*, 1965; Cassman *et al.*, 1990; Pettigrew *et al.*, 1996; Pettigrew, 1999) or no effects (Read *et al.*, 2006). It is likely that a severe K deficiency is needed before an effect on fiber quality is observed. It is possible that K deficiency reduces fruit production to ensure sufficient K for surviving bolls.

Removal of Nutrients

In measurements from high-yielding irrigated cotton in Australia, removal of nutrients in seed cotton is a function of crop yield and differs between nutrients (Table 3). There is good agreement between boll data (Fig. 3) and crop data (Table 3) in that larger proportions of the N, P Mg, Zn and Cu taken up by the crop into vegetative material are redistributed to the developing bolls and removed at harvest (also see Rochester, 2007). The values for crop nutrient uptake removal in Table 3 are a good guide to replace nutrients and therefore to maintain soil chemical fertility.

Table 3. The ranges of each nutrient taken up and the proportion of each nutrient exported relative to that taken up by the crop at three yield levels (from Rochester 2007).

Lint yield (kg/ha)	nutrient uptake			% exported		
	1000	1800	2400	1000	1800	2400
Nitrogen (kg/ha)	63	175	290	66	52	46
Phosphorus (kg/ha)	13	27	41	82	69	60
Potassium (kg/ha)	77	167	250	21	17	15
Sulfur (kg/ha)	10	39	62	42	21	18
Calcium (kg/ha)	71	94	155	3	3	2
Magnesium (kg/ha)	16	36	63	45	34	25
Iron (g/ha)	227	820	1620	40	17	11
Manganese (g/ha)	152	355	655	5	3	2
Boron (g/ha)	75	320	560	22	13	11
Copper (g/ha)	25	52	81	51	38	31
Zinc (g/ha)	58	119	203	99	73	61

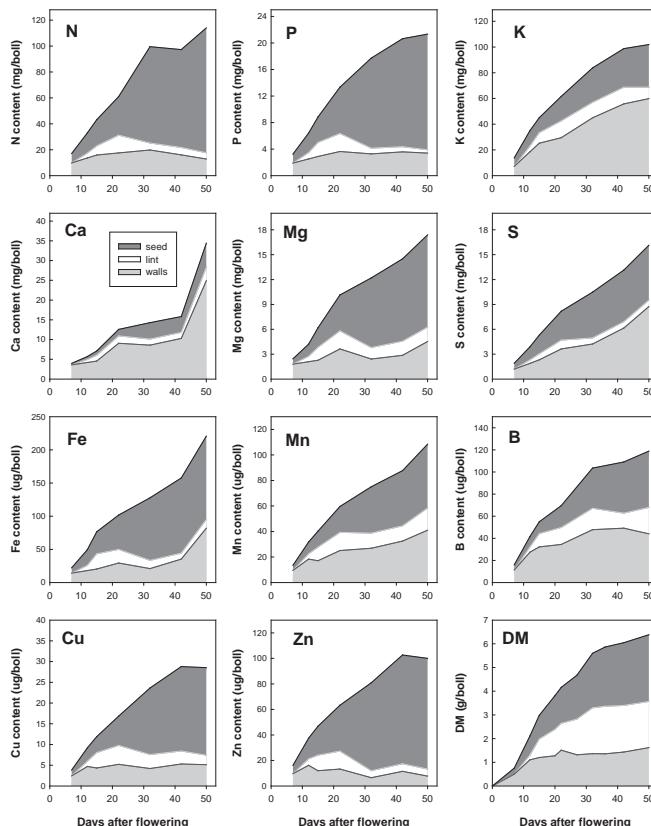


Figure 3. The accumulation of nutrients in bolls that flowered 97 days after sowing at first position on the tenth node from the base of the plant. Narrabri, Australia.

Redistribution of Nutrients - Supply and Demand

Redistribution of nutrients from vegetative to reproductive plant parts is common in crop plants. Determinate grain crops redistribute nutrients during grain filling. For example, Pan *et al.* (1986) showed 50% of the N in maize grain was from N taken up before silking. Dekhuijzen and Verkerke (1984) showed that 83% of N in *Vicia faba* seeds at maturity came from redistribution from vegetative parts present at flowering.

The importance of nutrient redistribution in cotton can be gauged by using the data contained in Tables 1 and 2. Comparing the relative requirements of bolls with total uptake, N and P would be most reliant on remobilization, more so than Ca, Mg, Fe, Mn, B, and S, when nutrient requirement is not limited by soil nutrient supply. Potassium and Zn were intermediate.

In a cotton field study, Zhu and Oosterhuis (1992) found that for a main-stem node segment consisting of the main-stem leaf, three sympodial leaves, the branch and three bolls, about 300 mg N were contained in the three bolls 60 days from appearance of the subtending main-stem leaf (first position boll 29 days after anthesis). The reduction on total leaf N on this branch was about 30 mg N, the majority of which came from the main-stem leaf which lost half its N from day 20 to day 60. Thus, the nominal redistribution of N in this branch segment over that time period was about 10% of boll requirement. Given that canopy boll retention is about 60% (Kerby *et al.*, 1987; Constable, 1991), this data would suggest only 17% of total plant boll N requirement was supplied by redistribution from leaves alone. However other studies show higher redistribution.

Rosolem and Mikkelsen (1989) in a glasshouse ¹⁵N study found that leaves were the main source of N after first square. The total leaf N at 120 to 150 days dropped by 200 mg; at the same time the total boll N increased by about 500 mg. Similar distributions of 30-40% N from the vegetative components to the bolls have been reported (Halevy, 1976; Oosterhuis *et al.*, 1983). This would indicate the redistribution accounted for 30- 40% of boll requirement, particularly later in crop development. The proportion of N redistributed was, therefore, not necessarily constant: the N for early bolls could be supplied by current N uptake from the soil; the N for later bolls was more likely to be supplied from redistribution from leaves. By first open boll, most of the N in seeds was from redistribution. Similar results were found by Hocking and Steer (1995) with sunflower.

Although stem reserves can also supply some N through redistribution (Rosolem and Mikkelsen, 1989) and there is high redistribution of N from the capsule wall to seeds (also Leffler and Tubertini, 1976), particularly at the top of the plant (45%), the absolute amounts of N from the capsule wall in particular was small. As N is one of the more mobile nutrients (Fig. 3), other nutrients may have a lesser proportion redistributed.

Redistribution will obviously be affected by nutrient status: a crop deficient in N will not be able to mobilize as much N as a crop with high N status. Leffler and Tubertini (1976) hypothesized that there was a physiological continuum among boll components during development whereby the nutrient content declines throughout the plant and the seeds alone acted as net sinks. Errington *et al.* (2009) showed that the decline in N content of the leaves, stems, petioles, boll walls, bracts and lint may equated to 2/3 the N found in the seed at maturity. Seeds reached

peak dry weight and size at 45 days after flowering but did not reach peak N content until 60 days after flowering (Leffler, 1986).

In cotton, even if redistribution of N accounted for 50% of boll requirements, continued nutrient uptake from the soil is required to develop those bolls. Under high yield levels, the total amount of N required would be substantial, indicating that available soil N and good plant health are required to enable that soil N to be taken up through the boll filling period.

Rochester (2007) indicated large proportions of the N, P and Zn taken up by the crop were redistributed into the developing bolls and removed in seed cotton (Table 3).

Nutrition in Practice - Applying Nutrition Physiology

Mineral nutrient deficiencies can limit the growth and yield of cotton, particularly when they occur during the reproductive phase. For this reason, cotton producers should aim to eliminate the chance of mineral nutrients becoming limiting during the flowering and fruiting period. This can be achieved by analyzing the soil before sowing to assess the limitations of nutrient supply from the soil and to plan the amounts and timing of fertilizer application. During the growth of the crop, leaf tissue analysis can indicate whether the crop is taking up sufficient amounts of nutrients to be corrected by side dressing or foliar application if necessary. Nutrients applied after cutout will not necessarily be utilized effectively by the crop.

Assessing In-Season Nutrient Status

Assessing crop nutrient status with plant tissue testing is becoming more commonplace. While petiole testing for nitrate and potassium concentration has been used for several decades (Tucker, 1965; Kerby and Adams, 1985; Miley and Maples, 1988; Constable *et al.*, 1991), leaf blade testing has the advantage of being used throughout the growing season (Fig. 2). Petiole testing is more dynamic and nutrient concentrations fluctuate in accordance with prevailing weather conditions, making it less reliable with unfavorable weather conditions (i.e., cold shock or heat stress, drought or water logging). Furthermore, petiole testing has been reported to be too variable and not correlated to yield (Oosterhuis and Morris, 1973). Petiole nitrate (Constable *et al.*, 1991) and K concentrations decline quickly, making these analyses less useful through the late-flowering and fruiting period than leaf blade testing. While the smaller decline in tissue nutrient concentrations may make the detection of changes difficult, the concentration of each nutrient can help growers make informed fertilizer management decisions when the ideal level is known for each nutrient at that stage of crop growth.

Other techniques for determining in-season cotton nitrogen status include chlorophyll meters (Wood *et al.*, 1992; Wu *et al.*, 1998) and leaf/canopy reflectance sensors (Raper, 2011; Zhao *et al.*, 2005). Moderate correlations between chlorophyll meter readings and N content have suggested these instruments can determine in-season N status without destructive tissue sampling (Wood *et al.*, 1992; Wu *et al.*, 1998). Techniques for determining in-season nutrient status based on spectral characteristics of deficiencies have received much interest in cotton due to success noted in other crops (Samborski *et al.*, 2009). Research characterizing spectral shifts in cotton

reflectance due to N deficiencies has suggested leaf and canopy sensors have the potential to determine N status in real time (Raper, 2011; Zhao *et al.*, 2005). However, determination of nutrient status from spectral characteristics is not production-ready and few studies have examined cotton spectral reflectance shifts of nutrients other than N (Fridgen and Varco, 2004). Although most spectral research has focused on the spectral characteristics of N deficiencies, the spectral characteristics of other nutrients are beginning to be explored (Fridgen and Varco, 2004).

Fertilizers

A strategy to plan the timing, rates and placement, as well as form of each nutrient will ensure that the nutrient demand of the cotton crop can be met. This plan can be moderated where in-season tissue testing indicates a nutrient is deficient (requiring remediation) or sufficient, thereby possibly reducing the need to apply the fertilizer that was planned. Timing of fertilizer application needs to take account of crop nutrient demand (Figs. 1 and 3) as well as the delay in availability or uptake of the particular form of fertilizer.

Where micronutrients are deficient, in-season foliar applications may satisfy the nutrient requirement if those nutrients have not been applied to the soil pre-sowing. The timing of foliar applications should ensure that peak demands as shown in Table 1 are met. Care is required to avoid damaging leaves with high nutrient/salt concentrations; foliar fertilizers are best applied when the air temperature is low and humidity high such as early morning (Zhu, 1989).

Slow-release fertilizers and nitrification or urease inhibitors do not generally provide any substantial improvement in cotton nutrition, at least in some soil types, but may help reduce losses of applied nutrients (Chen *et al.*, 2007; Rochester *et al.*, 1994, 1996). Oosterhuis and Howard (2008) showed some advantage of slow release N and K fertilizers through improving nutrient use efficiency by maintaining yield at reduced fertilizer rates. There is a recent report of urease inhibitors increasing cotton yields (Kawakami *et al.*, 2011).

Nutrient Use-Efficiency

Crop nutrient use efficiency can be expressed as kg lint/ kg nutrient uptake, but this efficiency measure may change with yield level (*see review* by Mullins and Burmester, 2010). Little research has been published on the use-efficiency of any nutrient other than N (Bronson, 2008; Rochester, 2011).

Newer cultivars tend to accumulate greater quantities of nutrients than older cultivars, while producing higher yields, but nutrient use efficiency tends to increase over time (Rochester, unpublished). There is little evidence that transgenic traits affect nutrient concentrations tissues or the uptake of nutrients in cotton (Rochester, 2006). However, where those traits increase the yield due to reduced insect pest damage in the case of Bt technology or weed competition in the case of herbicide resistance, more nutrients may be removed from the system in seed cotton. Thus higher levels of nutrient replacement would be required to optimize nutrition of future crops and avoid soil fertility decline. The expression of Bt proteins in cotton can be reduced by crop N deficiency (Rochester, 2006). Deficiencies of other nutrients may also reduce the expression of transgenes by restricted growth and poor crop health.

Opportunities for Improved Cotton Nutrition

Salinity, acidity/alkalinity and sodicity each pose nutritional stress on cotton crops by restricting the availability and uptake of some nutrients. Selection of genotypes bred under specific conditions that may restrict crop production (e.g., soil type or extreme temperatures) may perform better than those bred under normal conditions (Rochester and Constable, 2003). Hostile soils, and particularly subsoils, pose severe restrictions to root growth and nutrient uptake.

Changes to the cropping system can afford improved crop nutrition. Choice of rotation crops for cotton can greatly impact nutrient supply, e.g., growing legume crops can supply N to subsequent crops and improve the condition of clay soils in particular (Rochester and Peoples, 2005). Cotton has evolved a mutualistic relationship with mycorrhizal fungi. The more widespread use to reduced tillage provides a better environment for the growth of roots and mycorrhizal fungi that promote nutrient acquisition, such that greater nutrient uptake may be seen in cotton grown under these conditions (Rich and Bird, 1974; Pearson and Jakobsen, 1993). Hence, Zn and P deficiency may be rarer in minimum-tilled sites (Mehravan, 2001).

Multiple Deficiencies and Nutritional Syndromes

Potassium deficiency syndrome in the US (Ashworth *et al.*, 1982; Oosterhuis, 1994) and premature senescence in Australia (Wright, 1999) have been associated with K deficiency, as well as phosphorus deficiency and high levels of sodium uptake (Rochester, 2010). These syndromes are more commonly seen at the end of the flowering period when the demand for nutrients may exceed supply and result in foliar symptoms typical of P and K deficiency (Table 1).

SUMMARY

Cotton has high demand for nutrients such as N and K in excess of 200 kg/ha and daily accumulation rates of up to 4 kg/ha/day, whereas trace nutrient needs are more easily met (up to 1 kg/ha) with fertilizer application where appropriate. Understandably, N has been more thoroughly studied than other nutrients, as N is most commonly deficient in agricultural systems without fertilizer addition. Redistribution of nutrients from vegetative to reproductive plant parts is a vital component of cotton plant nutrition, particularly for N and P.

Research gaps in this subject area include (a) nutrient deficiency effects on events in the flower, i.e. during anthesis for pollen tube growth and fertilization leading to early seed formation, and early partitioning in the seed between oil, protein and fiber; (b) amelioration of stress effects on nutrient imbalance/deficiency in the seed and developing boll; and (c) redistribution, removal and replacement of all nutrients, particularly those approaching deficiency in older cropping systems.

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