MANAGING COTTON NITROGEN SUPPLY

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I. INTRODUCTION

Maintaining soil fertility is important in sustaining cotton (*Gossypium hirsutum* L.) productivity and profitability. Of the three macronutrients, nitrogen (N), phosphorous (P), and potassium (K), nitrogen is applied to cotton in the greatest quantity (Table I). Yet the complexity of N cycling in the soil and the indeterminate growth habit of cotton complicate our ability to estimate fertility requirements.

In the U.S. Cotton Belt the timing and method of N fertilization differs greatly among regions (Table II). Nitrogen is applied as preplanting (before planting) and postplanting (after planting) applications in most states, but less than 10% of U.S. cotton acreage receives N at planting. Most N is uniformly applied over the field as preplanting and postplanting applications that are broadcast or injected directly into the soil, but combining N fertilizer with irrigation (i.e., chemigation) is popular in the Arizona and California deserts. Less than 5% of cotton acreage received N as a foliar treatment. Although in 1994 most cotton growers typically used multiple N applications (Table I) to reduce losses associated with leaching, denitrification, or immobilization and to minimize risk of salinity injury to seedlings, growers in most states did not use soil or plant-tissue analysis for crop-fertilization decisions (Table III). Only 19–53% of the cotton acreage was tested in 1994 for soil N, and 1–33% of the cotton acreage was tested with tissue-analysis procedures in representative U.S. cotton-growing states (Taylor, 1995). Yet growers that used soil and/or tissue testing valued the information, since they overwhelmingly followed the resulting recommendations.

The N requirement and utilization for cotton is more complex than for other major field crops. The question is, Why do many cotton growers in the United States

Table I

Fertilizer Use and Planted Cotton Acreage in Different Regions of the U.S. Cotton Belt in 1994[a]

	Arizona	Arkansas	California	Louisiana	Mississippi	Texas
Fertilizer used (tons × 1000)						
Nitrogen	90	303	549	188	172	1040
Phosphorous	30	79	179	50	64	273
Potassium	1	120	162	78	104	159
Nitrogen-use change from 1993 (%)	0.23	0.13	0.02	0.17	−0.08	0.11
Planted cotton acres (× 1000)	313	980	1100	900	1280	5450
Nitrogen application						
Annual rate (lb/acre)	220	110	188	157	122	71
Average treatments per acre	2.8	2.3	1.9	2.3	2.0	1.4

[a]Data from Taylor, 1995.

Table II

Timing and Method of Application to Cotton Acreage in Different Regions of the U.S. Cotton Belt in 1994[a]

	Treated acres (%)[b]					
	Arizona	Arkansas	California	Louisiana	Mississippi	Texas
Nitrogen timing						
Fall, before planting	15	23	44	10	9	41
Spring, before planting	22	52	21	45	54	47
Spring, at planting	15	9	13	10	8	5
Spring, after planting	95	60	86	63	72	32
Fertilizer application method						
Broadcast (ground)	17	90	32	46	64	64
Broadcast (air)	8	10	5	18	12	1
Chemigation	43	1	32	NR[c]	NR	5
Banded	22	10	25	29	19	19
Foliar	2	1	4	NR	2	NR
Injected (with knife)	62	29	64	56	72	35

[a]Data from Taylor, 1995.
[b]Percentages may exceed 100, because an acre may be treated more than once.
[c]NR, not reported.

Table III

Timing and Method of N Application to Cotton Acreage in Different Regions of the U.S. Cotton Belt in 1994[a]

	Planted acres (%)					
Nitrogen testing	Arizona	Arkansas	California	Louisiana	Mississippi	Texas
Soil						
Acreage tested	27	36	40	53	38	19
Recommendation applied	78	85	92	96	82	68
Greater than recommendation applied	17	15	4	4	18	6
Less than recommendation applied	5	NR[b]	4	NR	NR	26
Tissue						
Acreage tested	23	15	33	22	20	1
Recommendation applied	100	100	95	100	97	98
Greater than recommendation applied	NR	NR	NR	NR	NR	NR
Less than recommendation applied	NR	NR	5	NR	3	2

[a]Data from Taylor, 1995.
[b]NR, not reported.

use multiple N applications but remain reluctant to evaluate soil and plant-N status in determining the fertility needs of the crop? Our objective is to review cotton-N response and requirements, soil-N cycling, and soil- and plant-testing procedures.

II. COTTON GROWTH AND NITROGEN RESPONSE

A. Plant Growth Habit

The growth habit of a plant defines the timing of phenological events and the duration of important growth stages. The perennial growth habit and indeterminate nature of cotton is characterized by five growth stages that are interdependent and overlap (Table IV) (Mauney, 1986; Oosterhuis, 1990). These phenological growth stages are emergence, first square (floral bud), first flower, first open boll, and harvest. The timing and duration between each stage is closely associated with temperature. The growth habit of cotton is often described in terms of growing-degree-days or thermal units (Mauney, 1986).

Leaf and fruit appearance follow a predictable pattern in the early stages of development (Mauney, 1986). Unless nutrient, water, or biotic stresses interfere, the plant grows unimpeded by producing a series of reproductive branches (also called sympodial branches) beginning at the sixth or seventh main-stem node. A main-stem leaf subtends each sympodial branch, and a leaf (called a sympodial leaf) subtends each fruit formed on successive nodes. New main-stem nodes and sympo-

Table IV

Range of Published Growing Degree Days for Morphological Periods and Growth-Stage Events of Cotton Using a Base Temperature of 15.3 °C[a]

Phenological events and morphological periods	Duration of period (days)	Seasonal sum to phenological events (days)
Emergence	45–130	45–130
Nonreproductive period	350–450	—
First square	—	480–530
Square period	250–500	—
First flower	—	740–1150
Peak bloom period	200–800	—
Boll period	910–950	—
First open boll	—	1690–2050
Harvest	—	2550–4600

[a]Data from Mauney, 1986.

dial branches form approximately every 40 thermal units, and fruit appears on reproductive branches every 60–80 thermal units, depending on the cultivar (Hesketh *et al.,* 1972; Jackson *et al.,* 1988). Under ideal growing conditions (e.g., average air temperature of 30°C), successive main-stem nodes with sympodial branches usually appear every 3 days, and successive fruit on each sympodial branch appears every 6 days (McNamara *et al.,* 1940; Kerby and Buxton, 1978). Thus, the growth habit results in a four-dimensional growth pattern in time and space (Mauney, 1986).

Although the growth habit of cotton is indeterminate, fruit formation does not continue indefinitely—even in the absence of water, nutrient, and biotic stresses. Cessation of fruiting, commonly called cutout, typically occurs about 90 days after planting and is usually associated with the appearance of flowers in the upper canopy. Bourland *et al.* (1992) found that white flower appearance on the fifth main-stem node from the apex of normal fruiting cotton plants signals the development of the last harvested boll of acceptable size and quality. Thus, five nodes above white flower (5 NAWF) may be definitive criteria for identifying cutout in cotton.

B. Plant Response to Nitrogen Deficiency

Plant response to N deficiency usually begins with limitations in uptake. Cotton only uses inorganic forms of N, either as nitrate (NO_3^-) or ammonium (NH_4^+). Nitrate is the principal source of N, since ammonium is quickly transformed in the soil solution to nitrate through nitrification when typical weather conditions for cotton prevail. Like most higher plants, cotton absorbs nitrate through the roots and transports it directly to the leaves in the transpiration stream. Once in the leaf, nitrate is reduced to ammonium and combined with organic acids to form amino acids and proteins. These processes require considerable energy in the form of reductants, like NADH, and a ready supply of organic acids from carbon assimilation. Up to 55% of the net carbon assimilated in some tissues is committed to N metabolism (Huppe and Turpin, 1994).

Most attention has focused on the relationship between photosynthetic rate and leaf N (Fig. 1) (Natr, 1975; Radin and Ackerson, 1981; Radin and Mauney, 1986; Wullschleger and Oosterhuis, 1990). This probably arises from the most obvious visual symptom of N deficiencies—chlorosis, which increases with increasing N deficiency. Yet no direct evidence supports the hypotheses that lower chlorophyll content limits normal photosynthesis (Benedict *et al.,* 1972).

Nevertheless, N reduction and carbon assimilation processes are so interdependent that Huppe and Turpin (1994) concluded that neither could operate to the detriment of the other. For example, when N deficiency occurs, photosynthetic efficiency declines and assimilated carbon accumulates in the plant as starch and oth-

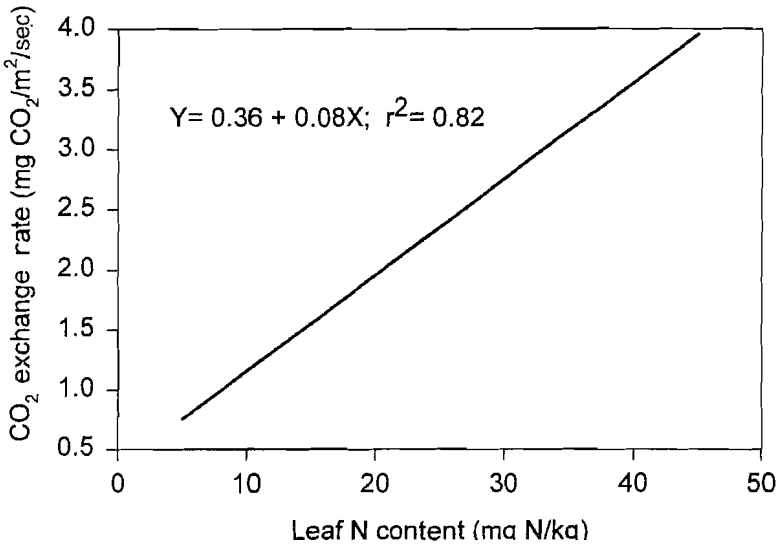

Figure 1 The relationship between leaf-N content and the carbon exchange rate of greenhouse-grown cotton (T. J. Gerik, unpub. data).

er carbohydrates (Rufty *et al.*, 1988; Foyer *et al.*, 1994). Carbohydrate accumulation in N-deficient plants is often greater in the roots than in other parts of the plant. When leaf-N supplies are replenished, there is a rapid increase in respiratory activity and starch degradation through the oxidative pentose phosphate pathway and tricarboxylic acid cycle (Smirnof and Stewart, 1985). Both pathways supply reductant and ketoacids (Ireland, 1990) for nitrate reduction and amino acid synthesis. Once available starch reserves are depleted, photosynthetic activity increases (Elrifi and Turpin, 1986; Syrett, 1981). Thus, leaf carbohydrate and N appear to signal the priority of metabolic substrates used in the different pathways controlling carbon and N assimilation. Thus, the suppression in photosynthetic activity by N deficiency appears to be transient.

Equally important to declining photosynthesis are reductions in leaf expansion and leaf area and increased sensitivity to water stress when N deficiency occurs. Physiological responses of N-stressed cotton are similar to those encountered with water stress (Radin and Mauney, 1986). Similar to water stress, N stress decreases stomatal and mesophyll conductance of CO_2 (Radin and Ackerson, 1981), decreases hydraulic conductivity, e.g., water uptake and transport in the plant (Radin and Parker, 1979; Radin and Boyer, 1982), reduces leaf expansion and leaf area (Radin and Matthews, 1989), increases starch and soluble carbohydrates in roots (Radin *et al.*, 1978), and decreases leaf osmotic and turgor potential (Radin and Parker, 1979). Given these similarities, scientists argue that the behavior of N-stressed plants prolongs plant survival after the onset of drought in three ways: (1)

by conserving water; (2) by redirecting assimilates from leaf to roots, thereby enhancing root growth at the expense of leaf growth; and (c) by redirecting assimilates into the formation of metabolites for osmotic adjustment (Radin *et al.,* 1978; Radin and Parker, 1979). Yet these gains in water conservation or changes in assimilate allocation have limited value in sustaining economic yield, since early stomatal closure reduces the plant's photosynthetic capacity and ability to accumulate dry matter.

Like most other higher plants, cotton absorbs more nitrate than is required to satisfy its metabolic requirements. It stores additional N as nitrate in leaf vacuoles (Smirnof and Stewart, 1985) and as additional leaf protein, such as ribulose 1,5-biphosphate carboxylase, which is often found in prodigious quantities in chloroplasts. Because N is mobile, the change in plant-N status as soil-N supplies become limited is not abrupt, but is gradual as the plant uses its reserve N to satisfy the plant's requirements when soil-N supplies are limited.

Cotton's response to N deficiency is well understood and falls into three areas: (1) altered photosynthetic rate, (2) altered leaf expansion, and (3) altered responses to water stress. Although altered photosynthesis has received the most attention, all three responses contribute to alterations in plant growth and yield. However, the mechanisms underlying reductions in carbon assimilation (photosynthesis) and growth of N-deficient cotton remain unclear. These mechanisms and yield can be greatly affected by different environmental conditions that occur each year (McConnell *et al.,* 1993).

C. Interactions between Growth Habit and Nitrogen

Although N deficiency does not usually influence the timing of phenological events, it has a negative effect on the number of leaves and fruit formed, thereby reducing the duration of the squaring and flowering period (Radin and Mauney, 1986). In this way, the plant-N status has a big impact on the accumulation and partitioning of dry matter during each morphological period. For example, Jackson and Gerik (1990) found that N fertility was highly correlated with leaf area and boll number but not with boll weight or the number of main-stem nodes (Fig. 2). Vegetative growth, as evidenced by increases in the length and cross-sectional area of main-stem internodes, increases with applied N, resulting in greater plant height and weight without increases in boll number or yield (Wadleigh, 1944; Tucker and Tucker, 1968). Thus, large applications of N combined with excessive moisture early in the season can overstimulate vegetative growth, causing problems with mechanical harvest, increased shielding of floral buds, (squares) and small bolls (Walter *et al.,* 1980) and contributing to delayed maturity and rot of lower bolls. But growth regulators, such as mepiquat chloride, retard internode

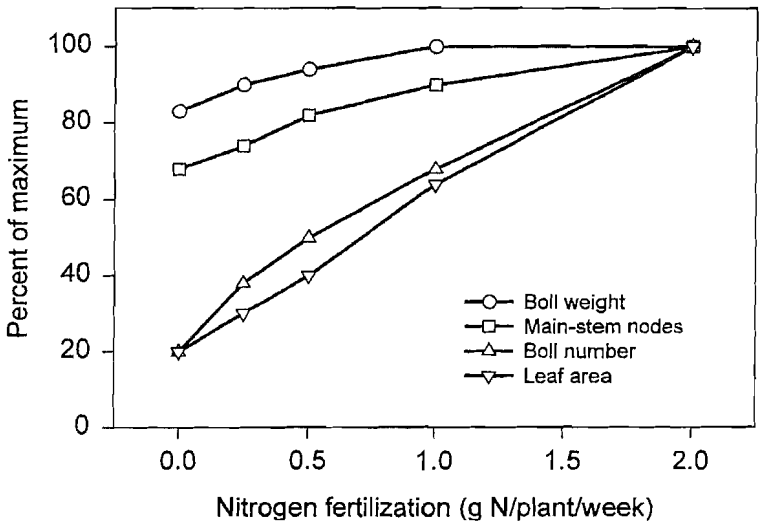

Figure 2 The effect of N on number of main-stem nodes, boll number per plant, leaf area, and boll weight (Jackson and Gerik, 1990).

elongation (Walter *et al.,* 1980; Reddy *et al.,* 1992), thereby counteracting some of the adverse effects of high N and excessive soil moisture on plant height and internode length.

Boll number is the most important factor correlated with yield (Morrow and Krieg, 1990), with the number of bolls per plant and the number of plants per square meter contributing equally. Leaf development (e.g., vegetative growth) and reproductive developments (e.g., square production) occur simultaneously (Fig. 3). Jackson and Gerik (1990) found that the leaf area and boll carrying capacity were linearly related, with approximately 0.1 m^2 of leaf area required to maintain a boll in greenhouse-grown plants. Yet the leaf area required for each boll may be lower in the field. More recent studies suggest that only 0.02 m^2 of leaf area per boll may be required under optimum field-growing conditions (Bondada *et al.,* 1996). Vegetative growth in terms of leaf number and leaf area and boll number are tightly coupled—in the formation of fruiting sites and by providing N and carbon assimilates to support growing bolls. Nitrogen deficiency during the critical fruiting period from first square (i.e., >2 mm) to peak flowering (e.g., typically 40–85 days after planting; see Fig. 3) has a large adverse affect on cotton yield. Furthermore, excessive N contributes to excessive leafiness, which may adversely partition carbon assimilate away from bolls within the canopy—especially in cloudy weather midseason.

Cotton bolls have high N requirements. The seed, which accounts for about half of the total dry weight of the boll, contains almost twice the N concentration as corn—3.3% N in cotton compared with 1.75% in corn. However, bolls have low

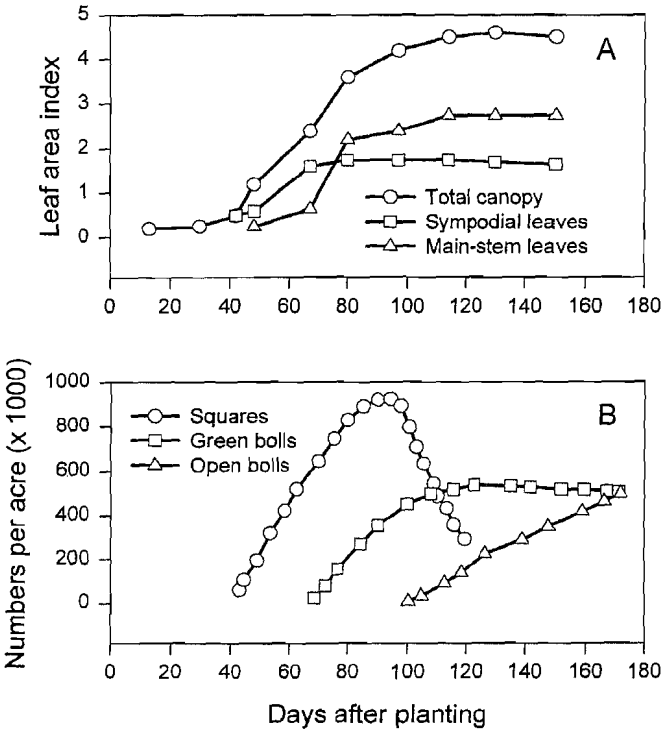

Figure 3 Typical leaf growth (A) and fruit development (B) of cotton grown in the United States (Oosterhuis, 1990).

nitrate reductase activity for reducing NO_3-N to ammonium for protein synthesis (Radin and Sell, 1975). The sympodial leaves, which subtend bolls, and the vegetative leaves, attached to the main-stem, are the primary sources of assimilated N for growing bolls (Oosterhuis *et al.*, 1989).

Even when N supplies are sufficient in relation to the developing boll load, cessation of vegetative growth and fruit formation (e.g., cutout) occurs, provided the plant is well "fruited" with bolls. In the mid-South region of the United States, the cessation in growth occurs 90–100 days after planting or when the first flower appears on the fifth main-stem nodes from the apex (Oosterhuis, 1990). This hiatus in growth is thought to be associated with the decline in leaf N and carbon assimilation capacity due to leaf age (Table V, Zhu and Oosterhuis, 1992; Wullschleger and Oosterhuis, 1992) and the increasing assimilate requirements of developing bolls for assimilated carbon and N. The declining N and carbon assimilation capacity and increasing boll assimilate requirement temporarily halt vegetative growth and fruit formation.

The plant's inability to fully satisfy the assimilate requirements of growing bolls suggests that weaker sinks, like squares and small bolls (e.g., bolls $<$ 10 days in

Table V

Percentage of Leaves within a Cotton Canopy by Age and Level of Physiological Activity at Three Growth Stages[a]

Leaf age (days after unfolding)	Physiological activity	Days after planting		
		60 (1st square)	90 (anthesis)	120 (boll fill)
		Leaves (%)		
0–14	Sink	36	11	3
15–28	Strong source	38	21	11
+29	Declining source	26	68	87

[a]Data from Oosterhuis, 1990.

age), might be shed, thereby reducing boll number and cotton yield. Plant maps of Wadleigh (1944) support this deduction, whereby N deficiency slightly increased the percentage of fruit shed on the first sympodial nodes and drastically increased fruit shed on the remaining nodes; whereas sufficient N increased the number of harvested bolls at these nodes. However, Jackson and Gerik (1990) found that shedding of squares and young bolls was proportional to the ratio of the number of actively growing bolls to the plant's boll carrying capacity (Fig. 4). The data

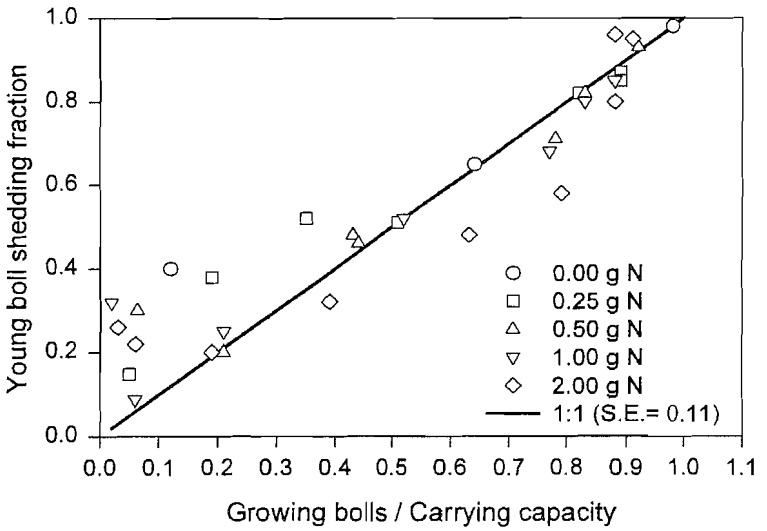

Figure 4 The relationship between boll shedding and the ratio of actively growing bolls to the plant carrying capacity (e.g., maximum boll number) (Jackson and Gerik, 1990).

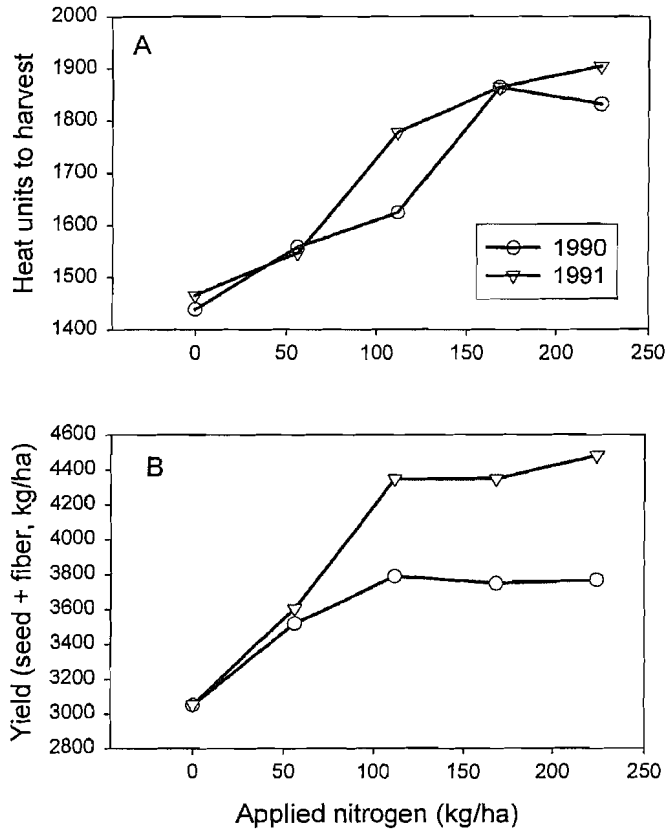

Figure 5 The effects of applied N on the time to harvest and cotton yield (reprinted from McConnell *et al.*, 1993, by permission of the publisher).

suggest that N deficiency does not increase fruit shedding beyond the levels already imposed through reductions in leaf area and the number of fruiting sites.

Nitrogen can have a big impact on crop maturity by prolonging vegetative growth and fruit formation (Jackson and Gerik, 1990; Gerik *et al.*, 1994) and by delaying harvest. Yet delay in maturity due to excessive N does not always result in higher yield (Fig. 5). Data from McConnell *et al.* (1993) illustrate that N rates beyond the N optima (e.g., 112 kg N per hectare in this case) delayed harvest without an increase in yield. It is important to note that the maturation period of individual bolls (e.g., the time from anthesis to open boll) does not appear to be altered by N deficiency (Table VI). Therefore, delays in harvest beyond the point representing the yield maximum and N optima are a function of continued vegetative growth–fruit formation beyond the limitations in growing season for maturation of young fruit. Thus the length of the growing season, plant density, water supply, and the cultivar's yield potential must be in balance with the N supply to maximize yield (Maples and Frizzell, 1985; Morrow and Krieg, 1990).

Table VI

Average Boll Periods for Bolls That Flowered at 10-Day Intervals for the Cotton Cultivar Stoneville 213 Grown at Five N Fertilization Levels in a Greenhouse[a]

Applied nitrogen (m*M*/week)	Days from flower appearance				
	58	68	78	88	Mean
	Boll period (days)				
0	43.8	44.3	44.0	—	44.1
18	44.1	43.6	43.5	—	43.6
36	45.3	44.8	43.6	—	44.8
72	44.5	43.6	42.7	38.3	43.3
144	45.3	42.7	42.4	40.6	43.5
Pooled error	1.8	2.4	2.4	1.5	2.4

[a]Data from T. J. Gerik, unpub.

D. Plant Nitrogen Requirements

It is evident from the preceding discussion that a balanced interdependence exists between cotton growth and N uptake. Nitrogen uptake is proportional to the plant's photosynthetic capacity and dry-matter accumulation. Nitrogen requirements and distribution within the plant have been studied (Wadleigh, 1944; Bassett *et al.,* 1970; Halevy, 1976; Oosterhuis *et al.,* 1983; Mullins and Burmester, 1990). Most recent reports indicate that cotton requires 16–20 kg of N per 100 kg of lint (Table VII). This translates into N use efficiencies of 5.0–6.6 kg of lint per kilogram of N. However, large discrepancies exist between recently published reports (Table VII). This suggests that further research is needed to establish the plant-N requirement and factors responsible for this variation.

Dry-matter accumulation and yield of cotton are highly correlated to seasonal evapotranspiration (Orgaz *et al.,* 1992). Thus, water supply is critical in maintaining the crop's photosynthetic capacity and growth. Morrow and Krieg (1990) studied the interaction of water and N supply on cotton yield in a short-season environment. Although they reported that increasing N supply from 0 to 100 kg N/ha at peak flowering increased yield regardless of irrigation intensity, sufficient water supply during the fruiting period was the most important factor leading to increases in boll number and yield. Furthermore, they found that maximum cotton yields were obtained when N and water were applied in a ratio of 0.25 kg N ha^{-1} mm^{-1} H_2O. However, the ratio of N to water received should not change unless cultural practices or climate substantially alter evaporative water loss or unless losses in soil N occur as a result of denitrification or leaching. Similar studies in long-season environments (>150 days) have not been reported.

Table VII

Reported N Requirements for Cotton Lint Production

Location	Source	Lint yield requirement (kg N/100 kg lint)[a]	Lint yield efficiency (kg lint/kg N)[b]
Texas	Fraps, 1919	25.0	4.00
Mississippi	McHargue, 1926	16.0	6.25
Georgia	Olson and Bledsoe, 1942	29.0	3.45
California	Bassett *et al.*, 1970	10.0	10.00
Israel	Halevy, 1976	13.2	7.50
Arkansas	Maples *et al.*, 1977	10.0	10.00
Unknown	Olson and Kurtz, 1982	16.0	6.25
Zimbabwe	Oosterhuis *et al.*, 1983	20.3	4.91
Texas	Morrow and Krieg, 1990	16.6	6.60
Alabama	Mullins and Burmester, 1990	19.9	5.00

[a]Data from MacKenzie *et al.*, 1963.
[b]Data from Gardner and Tucker, 1967.

The N requirement of the cotton plant varies with the growth rate and growth stage (Fig. 6). Before flowering, cotton leaves contain 60–85% of the total N, but the N content declines after flowering as it translocates from leaves to developing bolls. At maturity, the fiber and seed removed in harvest contain almost half of the total N accumulated in the shoot during the growing season (i.e., about 42% of the total above-ground N) (Oosterhuis *et al.*, 1983). Thus, cotton N requirements

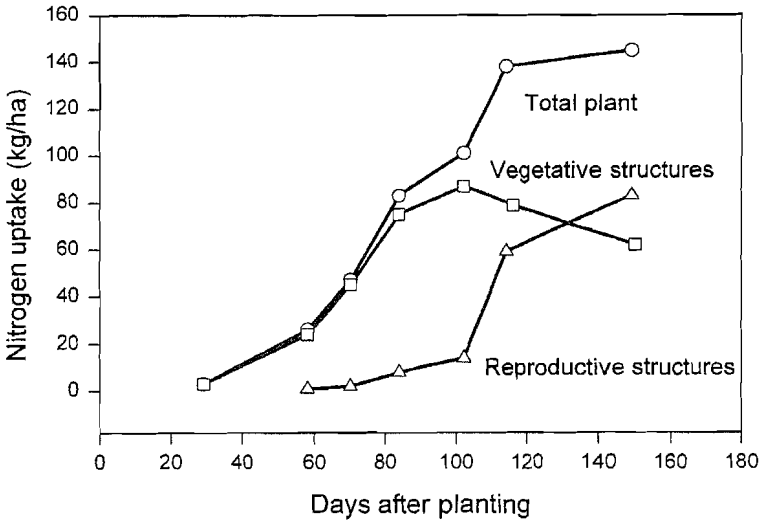

Figure 6 Cumulative N uptake for the total plant and the vegetative and reproductive structures during the growing season (Oosterhuis *et al.*, 1983).

are highest during the latter growth stages, when N supplies typically diminish and root activity is less.

III. SOIL NITROGEN AVAILABILITY AND DYNAMICS

Most N for cotton growth is supplied from soil nitrate, although the plant uses ammonium when available. Less than 4% of the cotton acreage in the United States receive foliar N application (Table II). Therefore, the interacting chemical, physical, and biological functions in the soil are extremely important in determining N supply to the cotton plant. Taken as a whole, the interacting biological processes in the soil are termed the N cycle. A simplified version of the N cycle is depicted in Fig. 7; a more detailed description of N processes in agricultural soils can be found in Stevenson (1982a,b).

Important functions of the soil-N cycle are the *N-transformation process,* such as (1) NH_4^+ adsorption, (2) nitrification, (3) immobilization, and (4) mineralization; the *N-input processes,* such as (1) N fertilization and (2) biological N_2 fixation; and the *N-outflow processes,* such as (1) denitrification, (2) leaching, and (3) plant

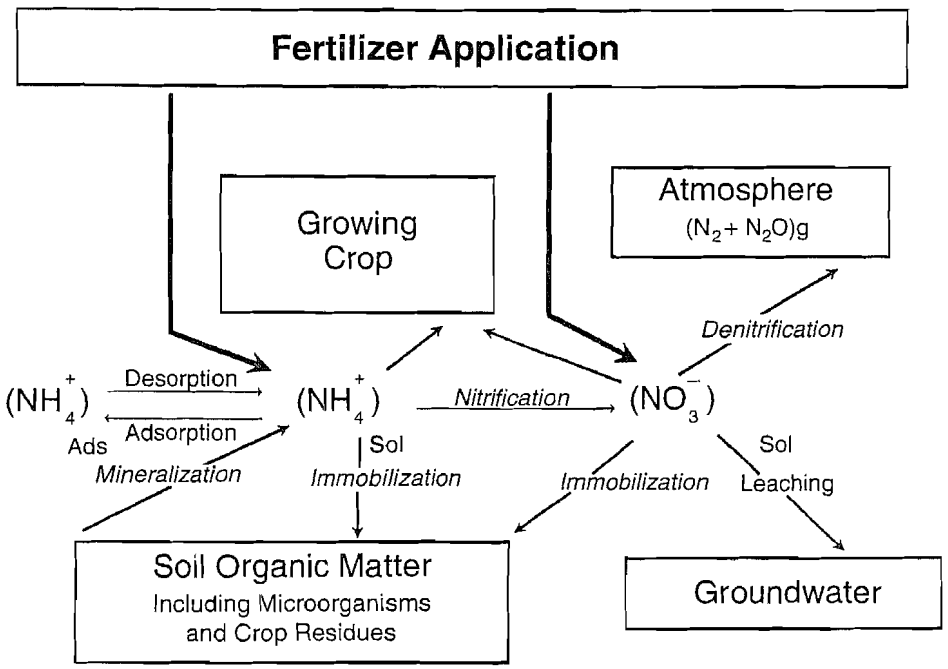

Figure 7 The fate and utilization of applied-N fertilizer within the plant–soil continuum.

uptake. These processes are interdependent and influenced by soil type and environmental conditions such as soil temperature and moisture content.

A. Inorganic Soil Nitrogen

Nitrogen in the NH_4^+ form is present either in soil solution or adsorbed to soil clay particles (Nommik and Vahtras, 1982). The adsorption of NH_4^+ is a chemical process that depends on soil cation exchange capacity (CEC). The amount of NH_4^+ in soil solution depends on the interaction between the CEC and the total cation concentration adsorbed and in soil solution and the NH_4^+ concentration adsorbed and in soil solution. In general, as the quantity of NH_4^+ in soil solution declines, the more NH_4^+ will be released into the soil solution from clay particles. While NH_4^+ is adsorbed, it is not susceptible to the soil N transformations, including plant N uptake. In some soils, NH_4^+ can be bound so tightly to clay particles that it cannot be readily released into the soil solution for plant uptake. When this occurs, the NH_4^+ is considered to be fixed or nonexchangeable.

Ammonium in solution is subject to immobilization or nitrification as well as plant uptake. Immobilization is a microbial process of converting N from the inorganic form into organic forms of N (Jansson and Persson, 1982). This occurs by the uptake of NH_4^+ by microorganisms to be used in their growth process. Microorganisms, like any living organism, use N in the synthesis of DNA, proteins, and other organic constituents. The source of N for microorganisms (similar to plants) is from inorganic N (NO_3^- and NH_4^+) in the soil solution.

Nitrification is the microbial process of converting NH_4^+ into NO_3^- with a release of energy to the microorganisms (Schmidt, 1982). The process is carried out primarily by *Nitrosomonas* bacteria, which convert NH_4^+ to NO_2^-, and by *Nitrobacter* bacteria, which convert NO_2^- to NO_3^-. Since these two bacteria depend on these processes for energy, the conversion of NH_4^+ to NO_3^- proceeds very rapidly as long as warm soil temperature and moisture are adequate.

Nitrate in soil solution is the most prevalent form of N associated with plant N uptake, immobilization, leaching, and denitrification within cotton production systems. Immobilization of NO_3^-, as with NH_4^+, is the utilization of soil nitrate N by the soil microorganisms for their normal growth processes (Jansson and Persson, 1982). Most plant N uptake is in the form of NO_3^-, because warm and moist growing conditions favor rapid conversion of NH_4^+ to NO_3^-. Because of this, many plants have adapted to NO_3^-.

Leaching is the physical movement of NO_3^- through the soil (Stevenson, 1982a). As water moves through the soil, so does the NO_3^- in solution. In soils where water moves rapidly through the soil profile and where water (either from rainfall or irrigation) exceeds evapotranspiration, nitrate is commonly found below the rooting zone and is no longer available for plant uptake.

Denitrification is a microbial process of converting NO_3^- into gaseous N_2O or N_2 (Firestone, 1982). This process occurs when soil is water saturated and microorganisms no longer have ready access to O_2. Most microorganisms depend on O_2 for energy conversion by utilizing O_2 as the last electron acceptor, thereby converting O_2 to CO_2. However, certain microorganisms can also utilize NO_3^- in the same way as O_2 in anaerobic conditions (due to water saturation), thereby utilizing NO_3^- as the last electron acceptor when converting NO_3^- to N_2O or N_2. Large amounts of NO_3^- can be lost from the soil to the atmosphere through this process. Losses from irrigated soils in California ranged from 95 to 233 kg N ha^{-1} $year^{-1}$ (Ryden and Lund, 1980).

B. Soil Organic Nitrogen

While cotton plants primarily use inorganic N, over 90% of soil N is usually held in the organic form (Stevenson, 1982b). This is part of the natural soil organic matter, which includes a mixture of plant residue (such as leaves and roots) in various stages of decomposition and microorganisms (both living and dead). As the organic matter decomposes, NH_4^+ is released into the soil solution through mineralization. In certain years, organic N is a key source. As organic matter progressively decomposes, it supports fewer microorganisms, because the energy content of the remaining organic materials declines and becomes more difficult to decompose. The result is greatly reduced microbial activity and highly decomposed organic materials, called humus. However, N-rich and biologically active phases of soil organic matter are continually renewed through the addition of plant roots and other crop residues. The result is a continuous process called mineralization immobilization turnover (MIT) (Jansson and Persson, 1982), whereby plant material and dead microorganisms are being decomposed, resulting in mineralization, and new NH_4^+ and NO_3^- are being assimilated into microorganisms, resulting in immobilization.

The MIT plays a pivotal role in the N nutrition of the cotton plant. It is estimated that only 10–15% of the total soil organic N is subject to the biologically active MIT processes. Since only a small portion of the total N required by the plant is available in the soil solution at any time during the life cycle, the mineralization process must continually replenish the soil solution with NH_4^+ to meet the plant demand. In heavily fertilized cotton fields in the humid southern United States, the fertilizer N supplied only half of the N found in the plant, with the other half coming from N already present in the soil from organic and previous fertilizer additions (Torbert and Reeves, 1994). For a short-season cotton grown in a semi-arid environment, Morrow and Krieg (1990) found that the residual soil N accounted for 35% of the final yield.

The fertilizer requirement of cotton is dependent on weather and differs between soil type and year, in large part because of variation in MIT and other components of the N cycle. The complexity, resulting from the interaction of N-cycle components and soil type and climate, makes the prediction of N fertilization very difficult and necessitates long-term N-rate and crop-response experiments to optimize N application with crop yield.

Most commercial fertilizers are either nitrate or ammonium in some form or mixture. For example, application ammonia nitrate (NH_4NO_3) will dissociate into the NO_3^- and NH_4^+ ions in soil solution. Once applied, fertilizer N is rapidly incorporated into the N cycle, where it functions under the same constraints as the N already present.

C. Nitrogen Additions to the Soil

Commercial fertilizer N consists of many different forms of inorganic N, but most is applied as one or in combination with the following forms: anhydrous ammonia, ammonium sulfate, ammonium phosphate, urea, ammonium nitrate, and potassium nitrate (Jones, 1982). Anhydrous ammonia, ammonium sulfate, and ammonium phosphate rapidly dissociate in soil solution and enter the soil-N cycle as ammonium. The enzyme urease dissociates urea and forms two gaseous molecules of ammonia. If this conversion occurs in soil solution, the NH_3 quickly forms NH_4^+ and enters the soil-N cycle; however, if urea is applied to the soil surface or to plant residue, substantial gaseous losses of the NH_3 can occur (Jones, 1982). Fertilizer applications of ammonium nitrate will dissociate in soil solution and enter the soil N cycle in both the NH_4^+ and the NO_3^- form, while potassium nitrate will dissociate into the NO_3^- form.

Nitrogen applications are often also made in organic N forms, including food-processing waste, municipal waste, and animal manures (Jones, 1982). While these materials contain some portion of NO_3^- and NH_4^+, a substantial portion of the N will be in the organic N form and will enter the N cycle in the organic pool (active MIT pool) and have to be converted through mineralization into NH_4^+ before plant uptake. The makeup and content of various N forms with animal manure and municipal waste depend on both the source and the handling characteristics of the material before application.

Another method of adding N to soil for cotton production is using crop rotation with legumes (Reeves, 1994). Legume species are capable of fixing atmospheric N_2 by means of a symbiotic relationship with soil microorganisms. Therefore, legumes grown as a cover crop or in rotation with cotton provide an additional source of N. The N attributed to soil from the legume is estimated as N-fertilizer equivalents—i.e., the amount of fertilizer N likely to be replaced by legume

N_2 fixation. The N-fertilizer equivalents typically range between 60 and 100 kg ha^{-1} but depend on the legume species and the climate conditions during the legume and cotton growing season (Reeves, 1994).

IV. FOLIAR-NITROGEN FERTILIZATION IN COTTON

Foliar application of nitrogen to cotton (*Gossypium hirsutum* L.) has frequently been used mid-to-late season across the U.S. Cotton Belt to supplement plant N requirements. It has been suggested that foliar-applied N may serve as an N supplement to alleviate N deficiency caused by low soil-N availability, to provide cotton plants with the N required by the rapidly developing bolls, and to avoid possible hazards of excessive vegetative growth resulting from excessive soil N (Hake and Kerby, 1988; Miley, 1988). However, reports on the effects of foliar-applied urea on cotton yields have been inconsistent (Anderson and Walmsley, 1984; Smith *et al.,* 1987), and information on the absorption and translocation of foliar-applied N in cotton is limited.

Urea is the most popular form of N used for foliar fertilization in cotton production. Yamada (1962) reported that the greater effectiveness of urea when applied to foliage resided in its nonpolar organic properties. Urea, containing ^{15}N-label, has been employed to measure rates of absorption and translocation of foliar-applied N, because it permits direct determination of the uptake and translocation of foliar-applied N. Oosterhuis *et al.* (1989) and Baolong (1989) reported that the sympodial leaf rapidly took up foliar-applied N. They found that 30 and 47% of applied N was recovered within 1 hour and 24 hours after application, respectively. Approximately 70% of the foliar-applied urea N was absorbed by 8 days after application. There have been similar reports for olive (*Olea europaea* L.) (Klein and Weinbaum, 1984), coffee (*Coffea arabica*), cacao (*Theobroma cacao*), and banana (*Musa acuminata*) (Cain, 1956), greenhouse-grown tobacco (*Nicotiana tabacum* L.) (Volk and McAulliffe, 1954), and soybean (*Glycine max* L.) (Vasilas *et al.,* 1980).

Foliar-applied ^{15}N to cotton was rapidly translocated from the closest treated leaf to the bolls and was first detected 6 hours after application (Baolong, 1989). The increase in ^{15}N in cotton bolls coincided with a progressive decline in percentage of ^{15}N recovery in the treated leaves. Rapidly developing fruits were the major sinks of foliar-applied N with bolls closer to the site of application (first-fruiting position on the sympodial branch) being a much stronger sink than the next closest boll (second position) along the branch. Baolong (1989) found about 70% of the total foliar-applied ^{15}N urea was found in the cotton bolls, with less than 5% remaining in the leaves, petioles, bracts, and branches.

Foliar-applied urea solution will reach many different cotton organs of varying ages when applications are made to the canopy. Baolong (1989) also showed that main-stem leaves, sympodial leaves, and bolls were all capable of absorbing foliar-applied urea, regardless of physiological age. Bondada *et al.* (1997) demonstrated correlation between increasing leaf cuticle thickness as the leaf aged and decreased absorption of foliar-applied ^{15}N. Absorption was reported to be more rapid in young leaves than in old leaves for coffee, cacao, and banana (Cain, 1956) and apple (*Malus pumila*) (Miller, 1982), although Boynton *et al.* (1953) found no significant difference in the absorption of foliar-applied urea applied to apple leaves of different age.

Many factors can affect the uptake of foliar-applied urea, including the condition of the leaf and the prevailing environment. It has been shown that the leaf water status affects the physical structure of the cotton leaf cuticle (Oosterhuis *et al.*, 1991) and consequently affects the absorption of the foliar-applied nutrients (Wittwer *et al.*, 1963; Boynton, 1954; Kannan, 1986). Baolong (1989) showed that water deficit stress impeded the absorption of foliar-applied urea N by sympodial leaves, as well as the subsequent translocation within the branch. Furthermore, applications made either late afternoon or early morning was more effectively absorbed than those made at midday, and this was more pronounced for water-stressed plants. This was associated with crystallization of the urea on the leaf surface and also with changes in the cuticle caused by water stress.

Bondada *et al.* (1994) demonstrated the importance of the size of the developing boll load in determining plant response to foliar-N fertilization. The location of the foliar-N spray within the canopy affected uptake and lint yield in cotton (Oosterhuis *et al.*, 1989). There was a significant increase in yield when ^{15}N-urea was applied to the top of the canopy compared to the lower canopy. This was probably due to the larger N requirement of developing bolls in the upper canopy late in the season. These results show that N-deficient cotton can benefit from foliar-applied N. However, indiscriminate application of N without due consideration of soil N availability, plant-N status, and environmental conditions can be wasteful.

V. MONITORING COTTON NITROGEN STATUS

The uncertainty in soil-N availability generated by the N cycle and seasonal changes in plant-N utilization makes it difficult to predict the crop's N requirements. Methods of monitoring soil and plant-N status have been developed to alleviate these difficulties. These methods include both direct and indirect measurements of soil and plant mineral N and plant response to fertilizer. For soils, direct methods include fertilizer tests and measurement of soil nitrate, ammonium, or-

ganic matter, and carbon mineralization. For plants, direct methods include measurements of petiole nitrate concentration, total leaf N, and nitrate reductase activity. Indirect methods include measurements of leaf chlorophyll content and use of physiologically based crop models.

A. Fertilizer Tests

Soil fertilizer tests are the oldest and most widely used method of determining fertilizer-N requirements and developing recommendations for cotton. These tests indirectly account for the mineralization potential of soil, N leaching, denitrification, N immobilization, availability of fertilizer N, and climatic variability on N uptake and yield. They involve empirical measurement of yield response to increasing levels of applied N fertilizer from experiments conducted at specific locations over several years. A fertilizer-response equation (typically curvilinear) developed with data from these experiments enables the user to estimate the amount of fertilizer required to attain an anticipated or projected yield (Fig. 5B). When tests are conducted in combination with crop rotation, manure application, or legume rotation, N credits are estimated and used to adjust predicted N requirements for crop history or organic fertilizer. Yet changes in weather (i.e., precipitation and temperature) and cultural practices (i.e., tillage, variety, fertilizer formulation, plant density, row spacing, crop rotation, and pest management) from those experienced during the fertilizer test limit the accuracy with which the equation can predict future fertilizer requirements. Ideally, an independent evaluation of the crop yield and fertilizer-N response should be conducted whenever changes in edaphic and crop-management factors occur.

At best, fertilizer tests are retrospective estimates of the crop's N requirement and should be viewed as a calibrated response of crop yield to the applied N fertilizer for the soil type under the prevailing growing conditions. Although the analyses are often generally applied to estimate N fertilizer needs of cotton and other crops, their application should be confined to the location and soil type where testing was performed. They should be conservatively used to estimate the N requirements of cotton.

B. Soil Testing

Soil analyses are direct measurements of the soil-N status. Several approaches have been adopted to directly assess soil N (Stanford, 1982). In western states, where arid conditions prevail, soil NO_3^- analyses have been successfully used to determine existing N levels and to adjust N-application rates. Other locations have

adopted a preseason soil NO_3^- test for adjusting fertilizer-N rates based on existing NO_3^- levels. As with fertilizer tests, soil analyses should be confined to the general location and soil type where testing was performed.

Methods to assess the organic-N mineralization potential of soil have been developed (Nadelhoffer, 1990; Torbert and Wood, 1992). These procedures typically require soil incubation to assess microbial biomass or microbial activity by measuring the CO_2 evolution from the soil. Yet adoption of these methods by soil-testing laboratories has been limited by inefficiency and high costs resulting from cumbersome soil-handling procedures, sample turnaround time, and procedure inaccuracy. Recent improvements in methods of assessing the N-mineralization potential of soil samples may eliminate some of the impediments (Franzluebbers *et al.,* 1996).

C. Plant-Tissue Analyses

Plant-tissue analyses were developed to overcome variation inherent in fertilizer tests and soil analyses. For cotton, tissue analyses supplement information from soil analyses and from soil mineral and organic N analyses, enabling growers to better manage the crop-N content after flowering. From a practical perspective, the procedure must be economical and simple, and the results must be quickly available.

Establishing critical reference points is the first step in diagnosing the N deficiency using tissue analyses. However, identifying the critical value that imparts N-deficiency response is difficult. Because plant-N levels are dynamic—they change over the growing season; differ between years; differ among organs, plant age, and growth stage; and differ between genotypes—the critical point cannot be considered a single value but must be interpreted as a range of values within which to work. In the following sections, we discuss tissue-analysis procedures that have been used to monitor the N status of cotton.

D. Petiole Nitrate Analysis

Petiole nitrate analysis is the most popular plant-tissue assay to ascertain the N status of cotton (Tucker, 1965; Gardner and Tucker, 1967; Miley and Maples, 1988). Its popularity arises from the speed and simplicity of analysis. Because cotton absorbs more nitrate than any other source of N, the petiole nitrate test measures the nitrate levels in xylem vessels in the petiole, estimates the flow of N from the root to the leaf, and indirectly estimates the nitrate levels in the soil solution. Tissue samples for petiole nitrate analysis usually comprise 20–30 petioles from

Table VIII

Typical Cotton Petiole Nitrate Concentrations Reported in the U.S. Cotton Belt

	NO_3, μg/g				
			Arizona[c]		
Growth stage	California Acala[a]	Texas[b]	Acala	DPL 16	Arkansas[d]
First square			15,000	18,000	12,000–28,000
First flower	16,000	16,000	12,000	14,000	8000–24,000
First large boll, midflower	8000	8000	6000–8000	8000–10,000	5000–15,000
First open boll, late flower	2000	2000	4000	4000	2000–6000

[a]Data from MacKenzie *et al.,* 1963.
[b]Data from Longenecker *et al.,* 1964.
[c]Data from Gardner and Tucker, 1967.
[d]Data from Sabbe and Zelinski, 1990.

young, fully expanded main-stem leaves collected from the third or fourth main-stem node from the apex. Nitrogen-deficiency symptoms do not usually appear, nor will growth decline until petiole nitrate levels fall below 2,000 μg/g (Hearn, 1986).

Petiole nitrate analyses cannot determine the total amount of N used by the plant prior to sampling but reflect the amount of nitrate N taken up by the plant from the soil solution. Petiole nitrate levels must be used and interpreted with care, because they vary with cultivar, growth stage, soil type, weather, and insect damage (Table VIII; MacKenzie *et al.,* 1963; Longenecker *et al.,* 1964; Gardner and Tucker, 1967; Baker *et al.,* 1972; Oosterhuis and Morris, 1979). Because water and nitrate uptake occur simultaneously, petiole nitrate samples should be collected when soil moisture or sunlight does not limit leaf gas exchange and transpiration. Zhao (1997) showed that petiole nitrate N in cotton increased by 50% after 1 day of simulated overcast weather (i.e., 60% reduction in incident radiation). Petiole nitrate levels decrease during the growing season, typically decreasing from about 18,000 to 1000 μg/g from early square to maturity (Fig. 8 and Table VIII). These ontogenic changes are associated with declines in root-uptake activity, increased N demand of growing bolls, and lower soil nitrate levels.

In western Texas, Sunderman *et al.* (1979) found that petiole nitrate variation was lowest and yields were best correlated when plants were sampled at flowering. Weekly measurements have been recommended during the important growth stages to reduce the variability associated with petiole nitrate analyses (Maples *et al.,* 1990). Care should be taken to assess and report the crop-water status, growth stage, plant-yield status (i.e., boll load), and efficiency of insect control at the time of sampling (Maples *et al.,* 1990).

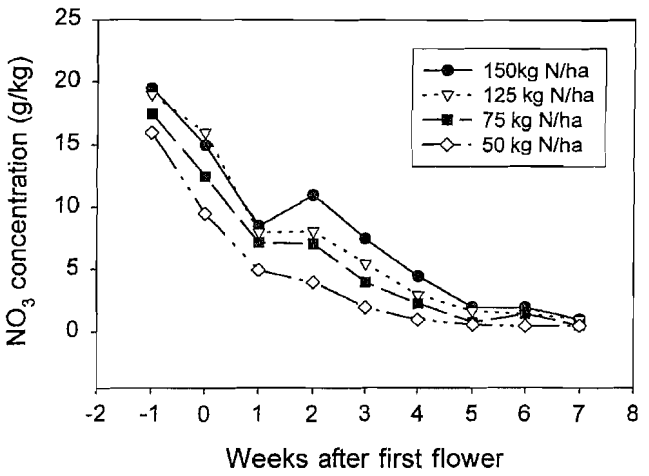

Figure 8 Comparison of four applied-N rates with petiole nitrate (NO_3) concentration at sequential time over the flowering and boll-maturation period of cotton (William Baker, Univ. of Arkansas, pers. comm.).

E. Total Leaf Nitrogen Assay

Determining total N content of the most recent fully expanded cotton leaves in the upper canopy is probably one of the most reliable methods to ascertain the plant's N status. It is a direct measure of leaf-N status and provides an estimate of N accumulated prior to sampling, given the mobility of N within the plant. As with the petiole test, total leaf N varies with cultivar, growth stage, soil type, and weather and can be influenced by insects (if boll damage is severe). On a dry-weight basis, leaves are usually considered deficient in N if they contain less than 2.5% N, low in N if they contain 2.5–3.0% N, sufficient in N if they contain 3.0–4.5% N, and very high or excessive in N if the N content exceeds 4.5% (Sabbe *et al.,* 1972; and Sabbe and MacKenzie, 1973). However, total leaf-N assays do not have the ease of sampling and handling that petiole sampling have, and the increased cost and time required has discouraged its use and limited its acceptance as a tool in monitoring commercial cotton fields.

F. Nitrate Reductase Activity

Nitrate reductase is the enzyme that catalyzes the first step in reduction of nitrate N to organic forms within the plant, and it is thought to reflect the level of N activity in leaves (Beevers and Hageman, 1969; Lane *et al.,* 1975). In comparing leaf nitrate reductase activity with petiole nitrate concentration, Oosterhuis and

Bate (1983) found that the nitrate reductase assay was a more sensitive and reliable indicator of plant-N status. However, the nitrate reductase assay is too expensive and time consuming to be used routinely for assessing N levels of commercially grown cotton.

G. Chlorophyll Determination

Chlorophyll, an N-rich pigment molecule in leaves, converts light into the chemical energy needed to drive photosynthesis. Scientists have long known that leaf chlorophyll and N content were correlated. However, chlorophyll determination has not been considered practical for commercial plant-N analyses because it requires timely extraction of fresh leaf tissue with volatile organic solvents. The development of the SPAD-502 chlorophyll meter by Minolta Camera Co., Ltd., Japan, has renewed interest in the use of chlorophyll content as an indicator of plant-N status. This hand-held device nondestructively estimates the chlorophyll content of leaves by measuring the difference in light attenuation at 430 and 750 nm. The 430 nm wavelength is the spectral transmittance peak for both chlorophyll *a* and *b,* whereas the 750 nm wavelength is in the near-infrared spectral region where no transmittance occurs.

The chlorophyll meter provides the means to indirectly determine plant-N status without destructive sampling and laboratory analysis. Recent reports by Tracy *et al.* (1992) and Wood *et al.* (1992) were encouraging and confirmed that leaf chlorophyll contents measured with the SPAD-502 and leaf-N contents were correlated for field-grown cotton. However, further research is needed to determine the strengths and limitations of this new technique.

VI. MANAGING COTTON NITROGEN SUPPLY

A. Computer Models

Soil-N analyses and fertilizer tests provide retrospective assessments of the soil and plant-N status, and tissue analyses are instantaneous "snapshots" of the plant-N status. Crop-simulation models are the only tools that simultaneously integrate the interacting soil, plant, and weather factors important in determining soil-N availability and crop demand for estimating current and future N needs. Several crop-simulation models have been developed and documented to assist in N management of cotton. These models include GOSSYM (Baker *et al.,* 1983), OZCOT (A. B. Hearn, pers. comm., CSIRO, Narrabri, NSW, Australia), EPIC (Williams *et al.,* 1989) and ALMANAC (Kiniry *et al.,* 1992). GOSSYM is the most widely used and accepted cotton model (Albers, 1990). Albers (1990) conducted a survey of

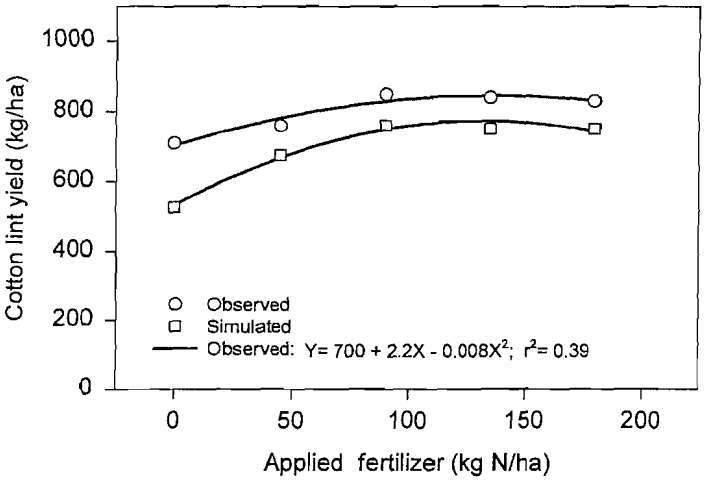

Figure 9 Comparison of GOSSYM-simulated and observed cotton yield in response to applied-N fertilizer (reprinted from Stevens *et al.*, 1996, by permission of the publisher).

GOSSYM users and found that 76% of farmers who used the model changed their N-management practices.

The estimates of the crop-N utilization, yield, and soil-N availability have been tested with independent field measurements for GOSSYM but not for the other models. Stevens *et al.* (1996) reported that GOSSYM overestimated soil-N availability by 10–30 kg N ha^{-1}, overestimated fertilizer N recovery, and underestimated cotton yield (Fig. 9). However, GOSSYM does not currently simulate MIT processes or ammonia-volatilization losses from soil or plants (Boone *et al.*, 1995), which could explain the overprediction of fertilizer-N recover. EPIC and ALMANAC have the ability to simulate the N MIT processes, leaching, and volatilization from the soil (Williams *et al.*, 1989; Kiniry *et al.*, 1992), but N uptake or the response of cotton yield to N fertilizer has not been validated.

Although crop-simulation models have potential to assist in making fertilizer-N decisions, most have not been validated to determine their accuracy and precision in estimating plant uptake and soil-N availability. Validation studies must be conducted to ensure confidence in the accuracy of the simulated estimates under varied environmental conditions and to identify areas needing improvement.

B. Managing Nitrogen Supply with Crop-Water Use

Basing N fertilization on crop-water use may be another means of balancing the N demand of the crop with supply. It is well established that seasonal evapotranspiration is highly correlated with dry-matter accumulation and yield of cotton

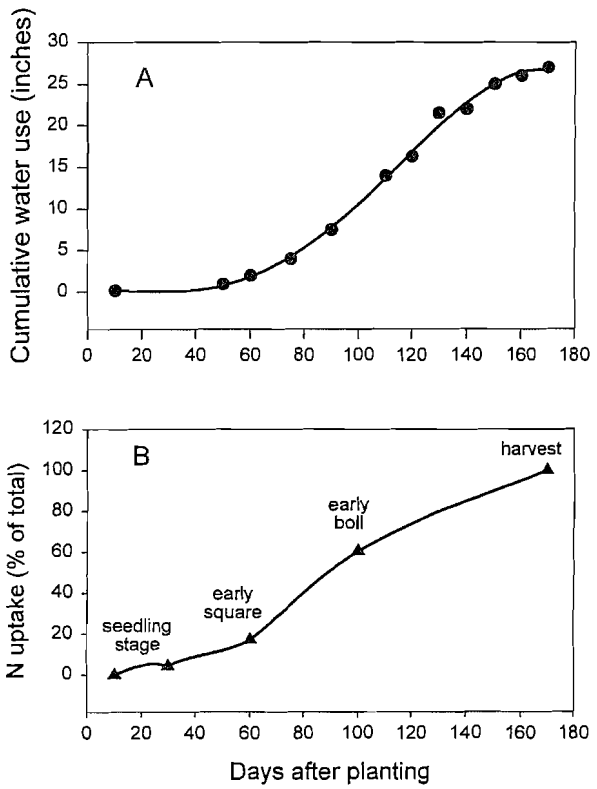

Figure 10 Comparison of cumulative water use (A) (Grimes and El-Zik, 1982) with plant-N uptake (B) (Olson and Bledsoe, 1942) during the growing season.

(Orgaz *et al.*, 1992) and most other field crops. Furthermore, the cumulative crop-water use and N uptake of cotton follows a similar pattern (Fig. 10).

The findings of Morrow and Krieg (1990) from the Texas high plains support this concept. Their data illustrate the curvilinear response of cotton lint yield to water supply and N, but they found a linear decline in the water-use efficiency of lint production with water supply during the fruiting period (Fig. 11). They reported that lint production increased 0.016 kg lint mm^{-1} H_2O for each additional kilogram of N per hectare applied during the fruiting period. Although, their growing season is shorter than most other U.S. cotton-growing regions, sufficient thermal time is available (e.g., 1250 thermal units with a threshold of 15°C) to achieve potential yields of 1000 kg lint ha^{-1}. Because Morrow and Krieg (1990) obtained maximum yield by applying 400 mm water and 100 kg N ha^{-1} during the fruiting

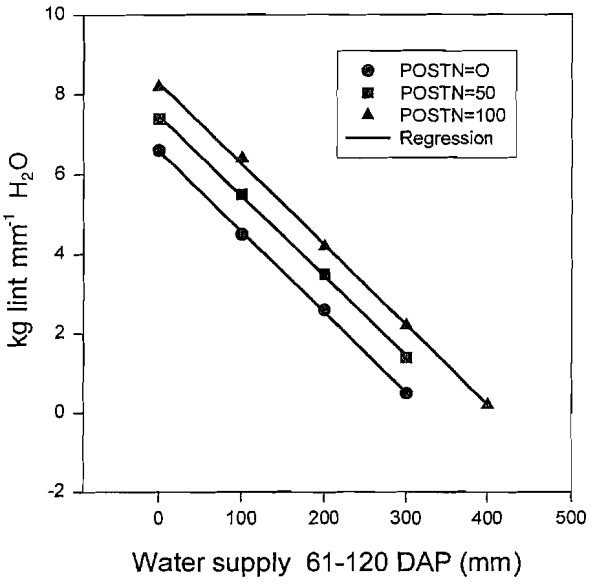

Figure 11 The effect of water supply and N on the water use efficiency of cotton lint production during the critical fruiting period, 61 to 120 days after planting (DAP) (reprinted from Morrow and Krieg, 1990, by permission of the publisher).

period, they concluded a ratio of 0.25 kg N ha^{-1} mm^{-1} H_2O during the fruiting period was necessary to obtain maximum cotton production in their environment.

Earlier, Grimes *et al.* (1969) and Grimes and El-Zik (1982) reported a curvilinear response of cotton lint yield to irrigation and N and found that the water-use efficiency of lint production improved, in some cases, with applied N. Yet, Grimes *et al.* (1969) did not account for the total N supplied to the cop (e.g., the residual soil N supplied to the crop), nor did they consider that cotton growth stages might influence the water–N response as did Morrow and Krieg (1990). Morrow and Krieg's interpretation has merit because it parallels our fundamental understanding of the interaction of water and N on physiological and morphological processes associated with cotton yield. A relationship between N-fertilizer rate and irrigation was also demonstrated by McConnell *et al.* (1989), although this was also related to irrigation method.

Applying N in irrigation water is often the most convenient and cheapest method of fertilization, and technology is rapidly improving for measuring crop-water use and in applying fertilizers through irrigation systems. Perhaps the time has come to more closely examine the concept of managing crop-N supply on the basis of crop-water supply.

VII. SUMMARY

Cotton growth is sensitive to N supply. Physiologically, N uptake and carbon assimilation are so interdependent that neither can operate without detriment to the other. This interdependence transcends the obvious impact on photosynthesis and alters other physiological and morphological processes, including water uptake, leaf expansion, assimilate partitioning, and the duration of morphological periods associated with fruit formation by changing the time to harvest. Optimizing N supply during the fruiting period is critical for promoting vegetative growth (e.g., leaf development), maintaining photosynthetic activity, and maximizing the plant's boll carrying capacity and lint yield.

The mobility and dynamic nature of N in the plant–soil continuum complicate its availability to the crop. Plant uptake must be balanced with soil N and water supply. Most analytical methods for measuring soil- or plant-N status provide antecedent estimates of N uptake or availability, and empirically derived fertilizer tests rely on previous experience to estimate the fertility needs of the crop. Basing N fertilization on crop-water use has potential in irrigated production systems.

Crop-simulation models hold considerable promise for estimating crop-N consumption and future needs. Several models have been developed to simulate N uptake of cotton and to predict future growth and final yield. The accuracy of these models relies, in part, on our knowledge of plant-N requirements. Most models have not been validated for N uptake or must be improved to accurately simulate N recovery and yield.

Both analytical and empirical methods provide valuable information in determining the crop's fertilizer needs, but knowledge of the plant-N requirement and future growth are needed to estimate the fertilizer required for the remainder of the growing season. Bondada *et al.* (1994) showed that boll load had a major influence on plant-N requirements and response to foliar N. Substantial discrepancies exist in published estimates of cotton's N requirement for lint production. Are these discrepancies due to variation in water supply, or are they due to variation in soil N and the mineralization–immobilization turnover; or do they reflect differences in cultivar due to differences in source sink relations (i.e., boll load and leaf area), soil type, or climate? Research is needed to rectify these discrepancies—to accurately determine the plant-N requirement for cotton and to identify the factors responsible for this variation.

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