RESPONSES TO LIMITING NITROGEN UNDER DRIP IRRIGATION: SOIL N, COTTON GROWTH

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Abstract

A joint project of the USDA-ARS and University of CA was conducted over a four year period to assess growth, yield and nitrogen (N) uptake responses of cotton to a range of nitrogen applications under subsurface drip irrigation. This investigation is part of a series of field studies underway to identify potential for better plant responses and reduced groundwater NO_3-N contamination through use of alternative management practices such as frequent, low-dose applications under drip irrigation, split N applications, reduced preplant N and/or lower total N applications Plants were grown under subsurface drip irrigation and irrigated daily to avoid water deficits. Phosphorus, potassium as well as nitrogen fertilizers were injected into the water. Nitrogen treatments were 0, 60, 120 or 180 kg N per hectare (ha) combined with pre-plant applications of 0 or approximately 53 to 56 kg N per ha. Soil NO_3-N levels in the upper 1.2 m of the soil profile were in the 10 to 30 mg $N0_3$-N/kg range in the first and second years of the study. In the third and fourth year, soil N levels were significantly lower, and petiole nitrate-N levels in 120 kg and lower N application treatments were in the borderline deficient or deficient range of University of CA recommendations for cotton. Peak yields (between 1600 and 2100 kg lint per ha) occurred in 120 and 180 kg N treatments, with no difference in yields with applications in excess of 120 kg N per ha except in the 120 kg treatment without pre-emergence supplemental N in the fourth year. Residual soil N levels have significantly influenced the response to amounts of applied N over the three years.

Introduction

The potential impact of nitrogen (N) fertilization practices on nitrate contamination of groundwater is of increasing interest in areas where both municipalities and farmers share groundwater resources. With improved irrigation practices and better knowledge of the relationships between soil water holding capacity, effective root zones and irrigation uniformity, it is possible to reduce potential for deep percolation and loss of soluble nutrients below the root zone. Reductions in nutrient losses can also be achieved through improvements in our understanding of the actual amount of fertilizer N required to achieve yield goals for specific crops.

A number of studies conducted at the USDA-ARS Water Management Research Laboratory in Fresno, CA (Hutmacher et al, 1993, 1994, 1995) have shown that although high crop yields can be achieved with drip irrigation, maintenance of acceptable nutrient availability is critical in achieving high growth rates and favorable yields. Soluble nutrients are more susceptible to losses via deep percolation when plant uptake is separated for a long time from the time of application. In subsurface drip irrigation studies of Bar-Yosef et al (1992) and Hutmacher et al (1993), nitrogen and phosphorus fertilizers were injected continuously, in small amounts per unit time period, with the irrigation water. Such high frequency water and nutrient applications can prevent even minor water or nutrient deficits if appropriately scheduled.

Where harvestable yield is highly correlated with total biomass (such as alfalfa) or where fruit production is highly sensitive to water deficits (some vegetables), avoidance of minor water or nutrient deficits can be beneficial in achieving high yields. In cotton, where a balance between vegetative and reproductive growth is critical in producing and retaining bolls, an irrigation and nutrient management program that minimizes chances of any water or nitrogen deficits may achieve high total dry matter production but may not achieve high lint yields or high water use efficiency (Phene et al, 1992; Hutmacher et al, 1993). Nitrogen applications must be timed appropriately and in moderate amounts to meet crop N requirements and avoid excessive vegetative growth or deep percolation losses. More information is needed regarding crop responses to a range of N applications under high-yielding conditions with more-recently developed varieties to avoid deficient or excess nutrient applications.

This drip irrigation experiment is part of a series of three to five year cooperative projects between USDA-ARS and University of CA with the long-term goal of identifying growth-stage-specific levels of plant and soil nitrogen under specific management practices and their relationships to specific physiological processes, growth and yield limitations.

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 1:657-661 (1997)
National Cotton Council, Memphis TN

Materials and Methods

Cotton (var. "MAXXA") was planted in early to mid-April in each of four years (1993 through 1996). Mepiquat chloride was applied uniformly at a rate of 0.7 to 0.9 L/ha in early to mid-July to all plots with vigor indicating the need for PIX treatments (all plots in 1993, 1994, and all with the exception of no N and 60 kg N/ha treatments in 1995 and 1996). An average of 140 mm of water was applied with sprinklers in all years during the period from 60 days prior to planting through seedling establishment. Sprinklers were kept on the field and irrigations timed to assure successful seedling establishment, after which all sprinklers were removed and the drip irrigation system was used for all subsequent irrigation.

Drip irrigation was with subsurface drip laterals spaced 1.52 m apart in alternate furrows and 40 to 45 cm below the average soil surface. Drip emitters (turbulent-flow, in-line design) were spaced 0.91 m apart along the laterals and had a nominal flow of 2 L/h at 120 to 140 kPa operating pressure. An average of 521 mm (1993), 506 mm (1994), 489 (1995), and 541 (1996) of drip irrigation water was applied to all treatments during the growing seasons.

The subsurface drip system was used in this experiment to deliver precise amounts of nitrogen fertilizer over time and identify plant responses to differing severities and timing of nitrogen deficits. In 1993 and 1994 each plot consisted of 12 rows spaced 0.76 m apart and 9.3 m in length. Due to substantial damage and nutrient leaching caused by a break in an irrigation mainline, the entire experiment was moved to a larger field site in 1995. Row spacing, drip line placement and specifications were the same as prior to 1995, but plot size for 1996 and 1996 changed to 10 rows in width and 28 m length. All N fertilizer treatments were replicated four times in 1993 and 1994 and six times in 1995 and 1996.

Nine fertilizer treatments were imposed in this study, including a control with no N added (T1) and combinations of patterns of N application (linear (treatments T8 and T9) versus growth-stage and uptake rate-dependent (T2 through T7)) (Table 1). Target amounts for N applications following planting were 60 kg N/ha (T2 and T5), 120 kg N/ha (T3 and T6), and 180 kg N/ha (T4, T7, T8, T9). Actual N amounts applied are shown in Table 1. All nitrogen applications were an aqueous solution of calcium ammonium nitrate (CAN-17, 17% N by weight) injected in the irrigation water through the drip system. Treatments T5 through T9 also received supplemental N as a CAN-17 application close to the timing of seedling emergence and after spring soil sampling (Table 1).

N uptake patterns determined in previous studies at the same field site were used to determine the rate and timing of N application in treatments designated as "uptake" application pattern treatments (Fig. 1). If a treatment received 180 kg N/ha in an uptake pattern, the relationship between heat units and N uptake shown in Fig. 1 was used to define N application amounts during each 7-day period. Treatments receiving smaller total applications (60 kg N or 120 kg N/ha) received N applications at 1/3 or 2/3 the rate in the full 180 kg N/ha application treatments during each 7-day period. The approach with treatments T8 and T9 (labelled "linear" in Table 1) was to apply N at the 180 kg N/ha rate during a very compressed time period (quite early in treatment T8 (at growth stage corresponding with 5 through 11 main stem nodes) and during flowering and boll development in T9 (main stem nodes 11 through 17)).

Soil samples were collected after seedling emergence and within 4 weeks post-harvest to a depth of 2.7 to 3 m at 22.5 cm increments to a depth of 90 cm and 30 cm increments to 2.7 m. All samples were analyzed for water content, electrical conductivity, pH, NO_3-N, P, K, Total N and Cl. The orientation for the sampling was under the plant rows, about 35 to 40 cm laterally from a drip line and emitter at each sample location. Petiole samples were collected at 7 to 14 day intervals throughout the season and dried at 50 to 55 C for a minimum of 48 hours prior to grinding and analysis.

Above-ground plant samples were collected three times during the growing season to identify above-ground nutrient uptake based upon the average tissue nutrient concentrations and dry matter sampling of component plant parts. Main stem and sympodial leaves at different positions within the canopy were sampled at intervals through the season and analyzed for gas exchange rates, total-N, chlorophyll levels, and incident photosynthetic photon flux density (PPFD) at different levels within the crop canopy. Plant growth and development were monitored as plant height, node counts, nodes above white bloom, boll counts and position, plant leaf area, and dry matter partitioning.

Plots were machine harvested in late-October or early-November of each year with a modified commercial spindle picker and seedcotton yields were determined on two rows per plot. Yields were corrected for moisture content and gin percentage. Gin turnout was determined at the USDA-ARS Cotton Laboratory in Shafter, CA.

Results and Discussion

Prior crops grown in the field used in 1993 and 1994 was one year of cotton (grown without fertilizer) following four years of alfalfa. Prior crops in field used in 1995 were four years of cotton, the first three receiving a uniform 177 (1991), 192 (1992) and 187 kg N ha^{-1} (1993) as Calcium Ammonium Nitrate (CAN-17) through the drip system, and no applied N across the entire field in 1994. This information on pre-existing conditions is important in interpreting differences in responses to applied N during the four years of the study.

Crop Water Use, Plant Water Status

Calculated crop evapotranspiration (ET_c, including measured soil water depletion) averaged 735 mm (1993), 706 mm (1994), and 749 mm (1995), and ranged from a low of 591 mm in the no nitrogen treatment (1995) to over 780 mm in the high nitrogen treatments (T7 in 1995) (data not shown). Soil water balance data analyses for 1996 were incomplete at the time this report was prepared, so 1996 ET_c values are not reported. Leaf water potential (LWP) and infrared thermometer / CWSI measurements indicated no moderate water deficits in any treatments and no treatment differences in plant water status in 1993 and 1994 (data not shown). LWP values did not fall below -1.7 MPa nor did CWSI values exceed 0.17 in treatments until after the second week in August either year. During late-July through August in 1995 and mid-July through August in 1996, however, CWSI values in no N (T1) and low N (T2) treatments were significantly higher than other treatments (ranging from 0.12 to 0.28 CWSI and -1.84 to -2.26 MPa LWP; data not shown). Increases in CWSI values were positively correlated with reductions in leaf conductance but were also in part a reflection of large reductions in leaf area and plant height occurring in no N and low N treatments (data not shown).

In both 1993 and 1994, leaf conductance was not significantly affected by N treatments except in the no N control in 1994 (data not shown). Prior studies done by Radin et al (1985) in Arizona suggest that severe N deficits result in reduced leaf conductance (similar to a water deficit response), but petiole NO_3-N levels in those Arizona studies were significantly lower than in the no N and low N treatments in 1993 and 1994 of the current study. Petiole NO_3-N levels in the T1 and T2 treatments in 1995 and 1996, however, were much closer to those reported by Radin et al (1985). During late July and August of the 1996 season, with much lower prevailing petiole NO_3-N levels than in 1993 or 1994, the no N (T1) and low N (T2) treatments exhibited 26 and 17% lower conductance than the average of all remaining treatments. Leaf age was much more a determinant of leaf conductance, with the highest and most variable conductance in the youngest leaves (third node from the top of the plant) and lowest in the older leaves at the eighth or ninth node from the top.

Petiole Nutrient Status

In 1993 (data not shown) and 1994 (Fig. 2), petiole NO_3-N in all but the 0 N and 60 kg N/ha treatments (T1, T2) without pre-emergence N application remained within University of CA recommended levels throughout the growing season. Even the 0 N and 60 kg treatments were close to the lower end of the “sufficient” range in 1993 and 1994. In 1995 (Fig. 2) and 1996 (data not shown), lower prevailing soil residual NO_3-N levels prevailed in all plots, resulting in less soil N available to make up for low applied N. In 1995 (Fig. 2) and 1996 (data not shown), petiole NO_3-N levels even in the 120 kg N/ha treatment (without pre-emergence supplemental N) fell below the “sufficient” level (Univ. of CA) beginning in late and mid-July, respectively, and continuing through August.

All PO_4-P and K petiole concentrations were consistently within University of CA recommended levels for each growth stage in all treatments. The only significant interactions between petiole PO_4-P or K levels and the N treatments was for treatement T4 (high N application without pre-emergence application) in 1993 and 1994. No other interactions were noted in 1995 or 1996.

Crop Growth

Under conditions in 1995, the more severe deficit N application treatments (0 kg and 60 kg N/ha) resulted in large reductions in plant growth parameters (plant height, total dry matter, leaf area, node number) (data not shown). Plants in treatment T1 (no applied N) were significantly shorter than all other treatments by early-July in 1995 and 1996, while the low N treatments (T2, T5) were significantly shorter than higher N application treatments by mid-July (data not shown). Individual leaf expansion rates, the number of main stem nodes and the extension of sympodial branches were only significantly reduced in treatments T1, T2, with these parameters generally reduced by between 8% and 19%. Nodes above white bloom (as an indicator of plant maturity and vegetative cutout) indicated a significantly more rapid progression toward cutout only in treatment T1 in 1995 and T1 and T2 in 1996.

In early to mid-August of 1995 and 1996 (data not shown) and mid-September, leaf area index and total above-ground plant dry matter were significantly lower in treatments T1, T2 and T5 (no N and low N treatments, respectively) when compared with all other treatments, indicating a significant reduction in overall growth with no or low N treatments. These reductions in growth parameters averaged in excess of 30 percent in 1995 while they were generally less than 15 percent in earlier years. Within any level of within-season N application, there were no significant differences in growth responses to pre-plant N versus no pre-plant N in 1993 and 1994. In 1995 and 1996, mid-August total dry matter averaged 12 and 15 percent higher, respectively, in treatment T5 when compared with T2 (data not shown).

Net photosynthetic rates (data not shown) and main stem leaf N concentrations (Fig. 3) were similarly reduced in no or low N treatments when residual soil N was largely depleted (1995, Fig. 4) when compared with values in the initial year of the study (1993, Fig. 4). Total N content of the most recent, fully-expanded leaves (expressed as percent N on a dry weight basis) was significantly lower in the treatment T1 (no N fertilizer) plants than in other treatments as early as day 198 (mid-July) (Figure 3). In comparison, leaf total N in treatment T2 (60 kg N ha-1 rate) was not significantly lower than in higher N treatments until mid- to late-August. Mid- to late-season reductions in leaf total N in treatment T1 and T2 are correlated with reductions in late-season leaf photosynthetic rates (data not shown), and were severe enough to reduce soluble protein and restrict photosynthetic rates in 1995 and 1996.

Soil Nitrate

Petiole NO_3-N levels were consistently and strongly influenced by soil NO_3-N levels in treatments receiving applied N of 120 kg N/ha or less. Due to the fact that different levels of soil NO_3-N prevailed during different years of the study (indication in Fig. 4), it is not realistic to assess crop response only to applied N. The reduction in soil N as NO_3-N during the emergence through post-harvest period can be used to indicate much of the use of available soil N across different treatments (Fig. 5).

It is recognized there are other forms of N and transformations potentially occuring during each year. However, the soil at the research site is a mineral soil with low organic matter and the irrigation amounts and delivery method resulted in little or no leaching below the root zone. Under these conditions, changes in soil NO_3-N can be a useful approximation of soil N use. Reductions in soil NO_3-N during the growing season accounted for as much as 140 to 150 kg N/ha in the no N treatment in 1993, with lower amounts supplied from soil N depletion in higher N application treatments (Fig. 5) or in later years of the study when lower soil N levels prevailed. Combining amounts of applied N plus changes in soil profile NO_3-N results in total crop N use ranging from less than 90 kg N/ha in no N treatments in 1995 to over 270 kg N/ha in high N treatments with supplemental post-emergence fertilization in 1993 (Fig. 5).

Yield

Peak lint yields were generally obtained with 120 or 180 kg N/ha in within-season applications across all years of the study (Fig. 6). Addition of supplemental N at emergence did not significantly influence yield in 1993 through 1995 except in treatment 60-P (60 kg N/ha within-season plus 53 kg N/ha at emergence) when compared 60 kg N/ha alone (Fig. 6). In 1996, with emergence-time soil NO_3-N levels down to 5 to 12 mg N/kg soil in the upper 1 m of profile, a trend toward a response to supplemental emergence-time applications was observed even at the 120 kg N/ha level. In 1993 through 1995, the treatment receiving the 180 kg N/ha in the mid-season (linear application, treatment 180-L11) had significantly lower yields than in other treatments receiving the same total N (Fig. 6). Application of the 180 kg N/ha in the early season linear application pattern treatment (180-L5) did not result in lower yields except in 1996.

Acknowledgements

We are grateful for the financial assistance to this project provided by Cotton Incorporated and the California Department of Food and Agriculture. We gratefully acknowledge the assistance of staff field assistants J. Covarrubias, J. Jimenez, and other staff at the USDA-ARS Water Management Research Laboratory in Fresno, CA for all their efforts in installation, operation and analysis in this project. The assistance of the staff of the University of CA West Side Research and Extension Center and Mark Keeley and other staff of the University of CA Cooperative Extension in Shafter, CA and the USDA-ARS Cotton Research Station in Shafter in operating, installing the project and in harvesting are sincerely appreciated.

References

Bar-Yosef, B., C.J. Phene, B. Sagiv, T. Markovitch, I. Levkovitch. 1992. Positive response in field crop yields to subsurface drip irrigation and fertilization via the water. Hassadeh. 2519(5):102-115.

Bassett, D.M., W.D. Anderson, C.H. E. Werkhoven. 1970. Dry matter production and nutrient uptake in irrigated cotton (Gossypium hirsutum). Agron. J. 62:299-303.

Hodges, S.C. 1991. Nutrient uptake by cotton: A review. Proc., Beltwide Cotton Conf., 2:938-940.

Hutmacher, R.B., C.J. Phene, K.R. Davis, T.A. Kerby. 1993. Acala and Pima cotton responses to subsurface drip irrigation: Water use, plant water relations and yield. Proc., Beltwide Cotton Conf., 2:1221-1224.

Hutmacher, R.B., C.J. Phene, K.R. Davis, M.S. Peters, T.J. Pflaum, S.S. Vail, C.A. Hawk, A.D. Bravo, D. Clark, D.A. Ballard, N. Hudson, T.A. Kerby, M.A. Keeley. 1995. Nitrogen uptake of Acala and Pima cotton under high-yield, drip irrigated conditions. Proc., Beltwide Cotton Conf. 2:1295-1300.

Phene, C.J., R.B. Hutmacher, K.R. Davis. 1992. Subsurface drip irrigation: cotton does not need to be a high water user. Proc. Beltwide Cotton Conf. 1:489-493.

Radin, J.W., J.R. Mauney, G. Guinn. 1985. Effects of N fertility on plant water relations and stomatal responses to water stress in irrigated cotton. Crop Sci. 25:110-114.

Table 1. Treatment designations, pre-plant nitrogen applications, and total nitrogen applications made through the drip irrigation system during the growing season in 1993, 1994, 1995 and 1996 drip irrigation-nitrogen study at the University of CA West Side Research and Extension Center near Five Points, CA.

Nitrogen treatment number	Pre-emergence applied N (kg N ha-1)				Post-emergence total nitrogen applied via drip system (kg N ha-1)				Pattern of within-season N applic.
	1993	1994	1995	1996	1993	1994	1995	1996	
T1	0	0	0	0	0	0	0	0	none
T2	0	0	0	0	60	67	60	62	uptake
T3	0	0	0	0	120	134	120	124	uptake
T4	0	0	0	0	180	192	180	183	uptake
T5	56	53	57	56	60	67	60	60	uptake
T6	56	53	57	56	120	134	120	122	uptake
T7	56	53	57	56	180	192	180	181	uptake
T8	56	53	57	56	180	180	180	182	L5[a]
T9	56	53	57	56	180	192	180	185	L11[a]

[a] L5 = all nitrogen applied at a constant rate during a period from appearance of main stem node # 5 through node # 11

[a] L11 = all nitrogen applied at a constant rate during a period from appearance of main stem node # 11 through node #17

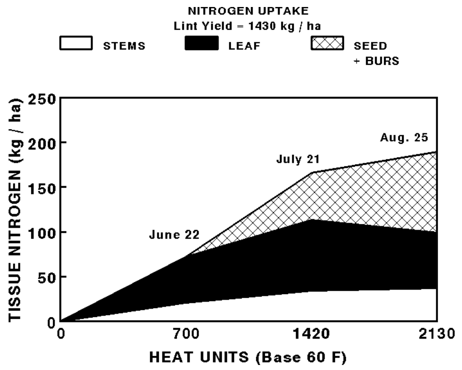

Figure 1. Total above-ground accumulated plant N in leaf, stem and reproductive tissue versus heat units (base 60F) for crop with lint yield of 1430 kg / ha at the West Side Research and Extension Center grown under subsurface drip irrigation.

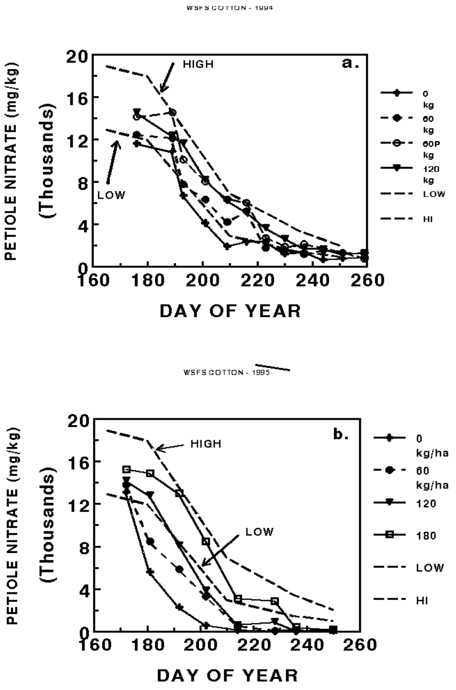

Figure 2. Petiole NO_3-N levels in uppermost fully-expanded main stem leaves of cotton in: (a) 0, 60 kg N/ha, 60 kg N/ha plus pre-emergence fertilizer, and 120 kg N/ha treatments in 1994; and (b) 0, 60, 120, and 180 kg N/ha treatments in 1995. Upper and lower heavy dashed lines indicate high and low recommended values for sufficient petiole nitrate levels according to University of CA.

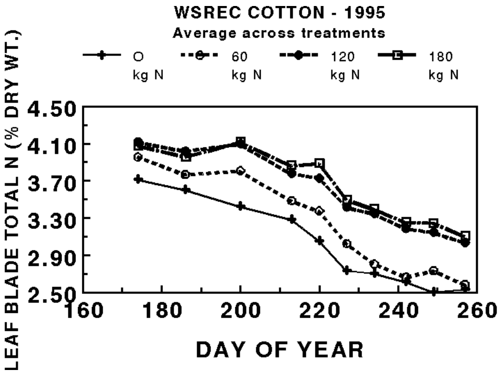

Figure 3. Leaf blade average total nitrogen (N) concentration as a function of nitrogen application treatment and day of year in 1995. Concentrations shown are for uppermost, fully-expanded main stem leaves.

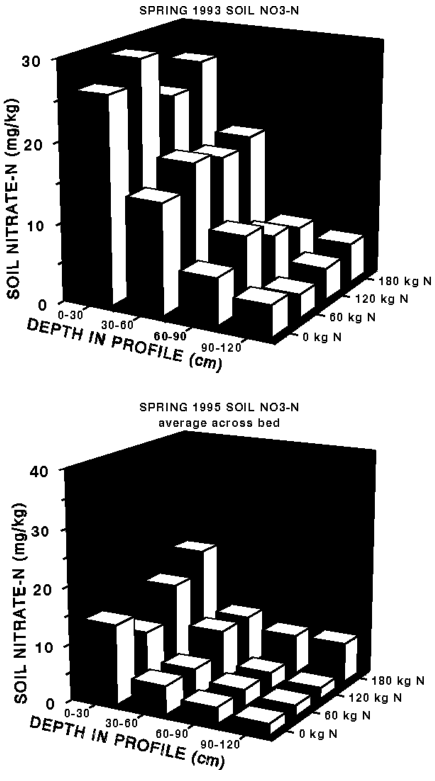

Figure 4. Soil NO_3-N in saturation extracts as a function of nitrogen application treatment and depth in soil profile prior to emergence in Spring of 1993 and prior to emergence in Spring, 1995.

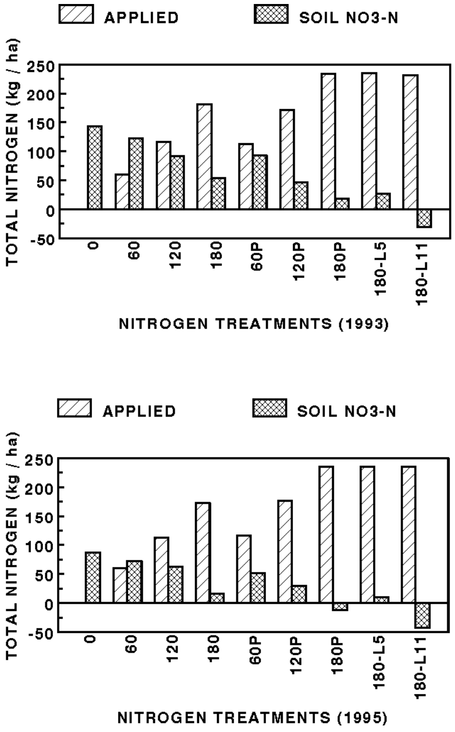

Figure 5.Total nitrogen potentially available to plants (calculated as applied fertilizer N plus the change in soil NO_3-N in the upper 3 m of the soil profile during the period from emergence through post-harvest in 1993 and 1995.

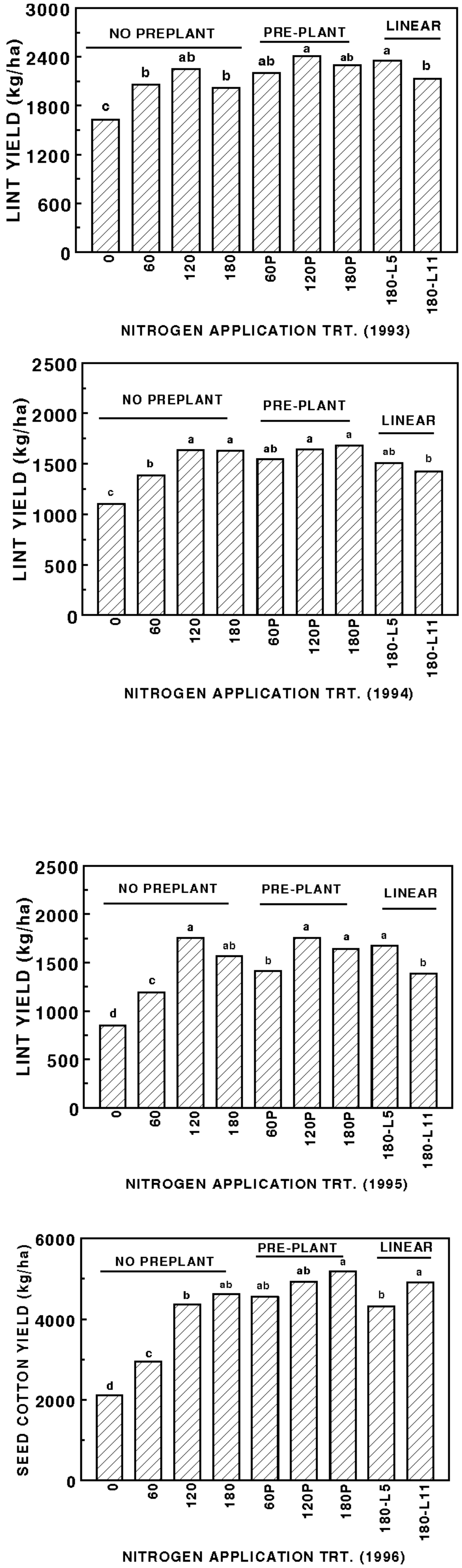

Figure 6.Lint yield (1993, 1994, 1995) and seedcotton yield (1996) as a function of nitrogen fertilizer application treatment at the West Side Research and Extension Center near Five Points, CA.