DIVISION S-4—SOIL FERTILITY & PLANT NUTRITION

In-Season Nitrogen Status Sensing in Irrigated Cotton: I. Yields and Nitrogen-15 Recovery

Teresita T. Chua, Kevin F. Bronson,* J. D. Booker, J. Wayne Keeling, Arvin R. Mosier,
James P. Bordovsky, Robert J. Lascano, Cary J. Green, and Eduardo Segarra

ABSTRACT

Nitrogen recommendations for Upland cotton (*Gossypium hirsutum* L.) in the western USA are based on spring soil NO_3^-–N tests. In-season monitoring of plant N status is another approach. Our primary objective was to test spectral reflectance and chlorophyll meter measurements as in-season N decision aids for irrigated cotton, and to compare these with soil test-based N management. The secondary objective was to determine the fate of ^{15}N as affected by N management and irrigation modes. Urea ammonium nitrate was applied with low energy precision (LEPA) center-pivot, surface drip, and subsurface drip irrigation. Microplots received 3 atom% ^{15}N. Soil test N application was based on 0- to 60-cm soil NO_3^-–N and 1400 kg lint ha^{-1} expected yield. Thirty-four kilograms of N per hectare was applied when green vegetative index (GVI) or chlorophyll meter readings relative to well-fertilized plots were <0.95. Lint yield responded to N at Lubbock in 2000 and 2001, but not at Ropesville. Nitrogen applied with in-season monitoring in 2000 at both sites was 34 to 101 kg N ha^{-1} less than soil test N application of 134 kg ha^{-1}, with similar yields. In Lubbock, 2001 lint yields were near the expected yield, and in three of four cases, N applications with in-season monitoring equaled soil test N applications of 101 kg ha^{-1}. Nitrogen-15 recovery in plants ranged from 19 to 38%, and was affected by N management in two of three site-years, but not by irrigation. This study indicates that basing N applications on in-season monitoring can reduce N applications in low yielding seasons and match the yield potential in high-yielding seasons.

IRRIGATED UPLAND COTTON is grown on about half of the 1.1 million ha cotton area in the Southern High Plains of Texas (Texas Agricultural Statistics Service, 1998), where water and N are the major constraints of the region (Morrow and Krieg, 1990). The best management practice for center-pivots in the Southern High Plains is low energy precision application (LEPA) where water is delivered to alternate furrows through drop socks that reach the ground (Lyle and Bordovsky, 1981). Furrow-dikes are made in the irrigated "wet" furrows to reduce run-off and further increase water-use efficiency (Lyle and Bordovsky, 1983). Subsurface drip irrigation systems can convey water to the root zone with a greater efficiency than LEPA, and have been increasingly adopted in the Southern High Plains (Bordovsky and Lyle, 1998; Bordovsky, 2001). Due to the limited capacity of irrigation wells in the region that draw from the declining Ogallala aquifer, cotton is deficit irrigated (High Plains Underground Water Conservation District No. 1, 1998). The optimal irrigation amount for cotton production under LEPA-irrigation is about 0.8 base irrigation amount (estimated crop evapotranspiration [ET] minus rain) (Bordovsky and Lyle, 1999). The optimal irrigation frequency for cotton in LEPA-irrigation is 3 d compared with the higher volume and infrequent irrigations of furrow-irrigation (Bordovsky et al., 1992; Bordovsky and Lyle, 1999).

Nutrient management in these irrigation systems has not received as much attention as water management. Nitrogen fertilizer is usually delivered with irrigation water through LEPA or subsurface irrigation systems. Morrow and Krieg (1990) and Bronson et al. (2001) demonstrated that N supply should increase as irrigation capacity increases for cotton in the Southern High Plains. Over-fertilization however, can result in NO_3^-–N buildup in the subsoil, even at high irrigation rates (Bronson et al., 2001). Depth to ground water in the Southern High Plains generally ranges from 30 to 90 m (High Plains Underground Water Conservation District No. 1, 1998) and it is not clear how much subsoil NO_3^-–N from fertilizer leaches to the ground water. However, the NO_3^-–N levels in the irrigation wells south of Lubbock are increasing, such that 20% have NO_3^-–N levels >10 μg mL^{-1} (Hopkins, 1993).

Nitrogen-15 is useful for determining the fate of added N to crop-soil systems, but few ^{15}N balance studies have been conducted in cotton (Torbert and Reeves, 1994; Karlen et al., 1996; Rochester et al., 1997). Recoveries of ^{15}N by cotton crops in these studies have been reported to be low, that is, <50% of added N. Cotton, therefore, may need improved approaches for determining amounts and timing of N fertilizer applications.

Spring soil NO_3^-–N tests have traditionally been the basis for N fertilizer recommendations for cotton in the western USA (Zelinski, 1985; Zhang et al., 1998). Soil

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T.T. Chua, K.F. Bronson, J.D. Booker, J. W. Keeling, J.P. Bordovsky, and R.J. Lascano, Texas A&M Univ. Texas Agricultural Experiment Station, RR 3, Box 219. Lubbock, TX 79403; A.R. Mosier, Soil-Plant Nutrient Res. Unit, USDA-ARS, P.O. Box E, Fort Collins, CO 80522; C.J. Green, Dep. Plant Soil Science, Texas Tech Univ., Lubbock, TX 79409, E. Segarra, Dep. Agric. & Applied Econ., Texas Tech Univ., Lubbock, TX 79409. Received 5 Sept. 2002. *Corresponding author (k-bronson@tamu.edu).

Published in Soil Sci. Soc. Am. J. 67:1428–1438 (2003).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: ANA-MS, automated N analyzer-mass spectrometer; ET, evapotranspiration; GNDVI, green normalized difference vegetative index; GVI, green vegetative index; LEPA, low energy precision application irrigation; LSD, least significant difference NDVI, normalized difference vegetative index; NIR, near infrared; RNDVI, red normalized difference vegetative index; RVI, red vegetative index.

NO_3^-–N measured in late winter or early spring, however, may be leached or denitrified before a crop is planted. Mineralization of organic matter, on the other hand, can increase the supply of N to the next crop. In-season monitoring of plant N status may be a better approach in ensuring that N is applied on an as-needed basis.

The chlorophyll meter provides a quick and nondestructive diagnosis of plant N status and has been widely tested for crops such as rice (*Oryza sativa* L.), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and cotton (Turner and Jund, 1991; Peng et al., 1996, Hussain et al., 2000; Peterson et al., 1993; Varvel et al., 1997, Bijay-Singh et al., 2002; Follett et al., 1992; Wood et al., 1992; Wu et al., 1998; Bronson et al., 2001). Bronson et al. (2001) reported that in-season chlorophyll meter measurements of cotton correlated with petiole NO_3^-–N, leaf N, and lint yield. Wood et al. (1992) observed that chlorophyll meter measurements correlated with cottonseed yield better than petiole NO_3^-–N concentrations. Using the chlorophyll meter as a guide to in-season N fertilization is often based on a sufficiency index, or chlorophyll meter readings divided by the readings of a well-fertilized reference (Varvel et al., 1997; Hussain et al., 2000). In-season N is applied when the sufficiency index <95%. The sufficiency index approach allows the chlorophyll meter to be used in different environments and with different varieties, factors that affect raw chlorophyll meter readings (Peterson et al., 1993).

Remote sensing of spectral reflectance is another option to assess crop N status, and has the additional advantage of sensing crop biomass. Usually, vegetative ratio indices of reflectance at near infrared (NIR)/red reflectance (or green) are calculated. Tucker (1979) proposed the normalized difference vegetative index or NDVI as $(R_{NIR} - R_{red})/(R_{NIR} + R_{red})$, where R_{NIR} and R_{red} are reflectance in the NIR and in the red regions, respectively. The NDVI has been correlated with leaf area index, canopy cover, and chlorophyll concentration in cotton (Thomas and Gausman, 1977; Maas, 1998; Huete and Jackson, 1988).

Recently, research has been conducted on "proximal" sensing of spectral reflectance of crop canopies. Bausch and Duke (1996) measured reflectance of corn under a center pivot at a 10-m height, and found that R_{NIR}/R_{green} (R_{NIR} and R_{Green} are reflectance in the NIR and in the green regions, respectively) related to leaf N. Researchers in Oklahoma developed a ground-based spectroradiometer with upward and downward facing NIR and red sensors directly over the row in wheat. They related N uptake, biomass (Solie et al., 1996; Stone et al., 1996) and yield (Raun et al., 2001) with NDVI. Ma et al. (2001) estimated soybean (*Glycine max* (L.) Merr.) yield with NDVI calculations of in-season measurements of spectral reflectance 2 m above the ground. Li et al. (2001) measured spectral reflectance from 3 m above the ground and reported that NDVI and red vegetative index were positively correlated with cotton biomass, N accumulation, and lint yield. Leaf N was negatively correlated with blue reflectance in the Li et al. (2001) study. Spectral reflectance and the chlorophyll meter therefore may help determine N fertilizer needs in cotton, regardless of soil test NO_3^-–N results.

The objectives of this study were to: (i) determine cotton response to N fertilizer with LEPA, surface drip, and subsurface drip irrigation systems, (ii) test spectral reflectance and chlorophyll meter measurements as in-season N decision aids for irrigated cotton, and compare them with soil test-based N management, and (iii) determine the balance of added ^{15}N in cotton and soil as affected by irrigation system and N management.

MATERIALS AND METHODS

The study was conducted at the Texas A&M University Research and Extension Center near Lubbock, TX (101° 49' W. long., 33° 41' N. lat.) and on a farmer's field near Ropesville, TX (102° 5' W. long., 33° 26' N. lat.). The soil at Lubbock is an Acuff sandy clay loam (fine-loamy, mixed, superactive, thermic Aridic Paleustolls) and the soil at Ropesville is an Amarillo sandy loam (fine-loamy, mixed, superactive, thermic, Aridic Paleustalf). Key physical and chemical properties of the soils are shown in Table 1. The sites were grown with a rye (*Secale cereale* L.) winter cover crop that was terminated with glyphosate (Monsanto Co., St. Louis, MO)[isoprophylamine salt of N-(phosphomonomethyl) glycine] 2 to 3 wk before planting of cotton. The experimental design was a split-plot with three replications. At the Lubbock site, subplots (7.2 m long by eight 1-m rows) were in north-to-south facing rows, and had alternate wet (drip tape-irrigated) and dry furrows. At Ropesville, all subplots (12 to 17 m long by eight 1-m rows) were under center-pivot irrigation. Uneven plot lengths were due to the circular rows. The main plots had two water regimes: surface and subsurface drip at 75% estimated ET replacement for Lubbock; and LEPA at 80 and 105% estimated ET replacement at Ropesville. At Lubbock, irrigation water in both surface and subsurface systems was delivered through drip tape in alternate furrows with emitters spaced at 60 cm. Water was supplied through the surface drip system at 6.4 L h^{-1} every 3 d at 0.05 to 0.07 MPa. In the subsurface (30-cm depth) drip system, water flowed daily at 1.0 L h^{-1} at 0.07 to 0.10 MPa pressure. In the LEPA system at Ropesville, water was supplied to alternate furrows through drop tubes each equipped with a sock that reached the ground (Bordovsky and Lyle, 1998). Water flow at Ropesville was 100 L h^{-1}, and the irrigation frequency was every 3 d. Potential ET was estimated at both sites with a modified Penman-Monteith equation from daily on-site weather data (Lascano and Salisbury, 1993). Cotton crop coefficients, related to development stages, were used to adjust potential ET to estimated

Table 1. Chemical and physical characteristics of soils at study sites in Spring 2000.

Property	Ropesville	Lubbock
Clay, g kg^{-1}†	196	219
Silt, g kg^{-1}†	141	177
Sand, g kg^{-1}†	663	604
Total N, g kg^{-1}†	0.5	0.6
pH (1:1 soil/water)†	8.3	8.1
CEC, $cmol_c$ kg^{-1}†	18	18
K, µg g^{-1}†	285	400
Mehlich 3-P, mg kg^{-1}†	11	29
NO_3–N, kg ha^{-1}‡	48	37
NO_3–N, kg ha^{-1}§	98	96

† 0–15 cm.
‡ 0–60 cm.
§ 0–90 cm.

ET for the ET replacement irrigation treatments (Bordovsky et al., 1992). Irrigation was terminated at 2000 cumulative heat units (base 15°C) or 25% open boll for all three site-years (Hicks et al., 2000).

Twenty-two and 14.6 kg P ha^{-1} was applied just before planting in 2000 and 2001 at Ropesville, and Lubbock, respectively. These P rates were based on Mehlich-3-P kg^{-1} (Table 1) in soil and the recommendations of Zhang et al. (1998). Phosphorus fertilizer was blanket-applied to the entire areas as 148.5 g H_3PO_4-P kg^{-1} with a liquid fertilizer applicator, fitted with spoke injectors. Placement of P was 10 cm from the seed row and 10 cm deep, on one side of the row.

The subplots at both sites had five N management treatments: zero N, soil test-based, chlorophyll meter-based, reflectance-based, and well fertilized. In each subplot, ^{15}N microplots 1.8 m long by two 1-m rows (separated by a wet furrow) were installed. Microplot locations were changed within the subplots between 2000 and 2001. 'Paymaster Round-up Ready 2326' (Delta and Pine Land Co., Scott, MS) cotton was seeded in 1-m beds at rates of 70 000 and 100 000 seed ha^{-1} at Ropesville and Lubbock, respectively. Seeding dates were 6 May 2000 in Ropesville, 25 May 2000 in Lubbock, and 1 May in Lubbock in 2001. Cotton planted at Ropesville on 2 May 2001 was destroyed by hail on 30 May, so only Year 2000 Ropesville results are presented.

After emergence, at the two-leaf stage, the soil test-based, chlorophyll meter-based, and reflectance-based plots received 34 kg N ha^{-1}, and the well-fertilized plots received 67 kg N ha^{-1} as urea ammonium nitrate (320 g N kg^{-1}) solution (Tables 2–4). The first N application in all three site-years was dribbled about 10 cm away from the seed row with a one-row push-type liquid applicator, followed immediately by incorporation by hand hoeing. Subsequent applications at Ropesville in 2000 were dribbled onto the bottom of the wet furrow before irrigations. In-season N applications at Lubbock were made during irrigations in the bottom of the wet furrow by repeating syringe injections every 60 cm at each emitter point for both the surface drip tape and the subsurface drip tape. Our intention with all in-season N applications was to simulate fertigation. Since the subsurface irrigation tape was buried at the 30-cm depth, the N solution was applied into funnels in 30-cm-long polyvinyl access tubes at each emitter. The microplots received 3.1 atom% ^{15}N-labeled urea ammonium nitrate at the same rates and times as the corresponding subplots with a repeating syringe.

Table 2. Urea ammonium nitrate-N rates applied at Ropesville 2000.

Treatment	TL†	ES‡	EB§	PB¶	Total
	kg N ha^{-1}				
	80% ET Replacement#				
Well fertilized	67	67	67	0	202
Soil test	34	34	34	34	134
Reflectance	34	0	0	0	34
Chlorophyll meter	34	0	0	0	34
Zero	0	0	0	0	0
	105% ET Replacement				
Well fertilized	67	67	67	0	202
Soil test	34	34	34	34	134
Reflectance	34	0	0	34	67
Chlorophyll meter	34	0	0	0	34
Zero	0	0	0	0	0

† TL, two-leaf.
‡ ES, early squaring.
§ EB, early bloom.
¶ PB, peak bloom.
# ET, evapotranspiration.

Table 3. Urea ammonium nitrate-N rates applied at Lubbock 2000.

Treatment	TL†	ES‡	EB§	PB¶	Total
	kg N ha^{-1}				
	Surface drip				
Well fertilized	67	67	67	0	202
Soil test	34	34	34	34	134
Reflectance	34	0	0	34	67
Chlorophyll meter	34	0	34	0	67
Zero	0	0	0	0	0
	Subsurface drip				
Well fertilized	67	67	67	0	202
Soil test	34	34	34	34	134
Reflectance	34	0	0	0	34
Chlorophyll meter	34	0	34	34	101
Zero	0	0	0	0	0

† TL, two-leaf.
‡ ES, early squaring.
§ EB, early bloom.
¶ PB, peak bloom.

Plant N status was monitored in each subplot at early squaring, early bloom, and peak bloom using a chlorophyll meter and a hand-held multispectral radiometer. Growth stages were established visually when approximately 50% of the plants in the field were at the growth stage of interest. In nearly all cases the growth stages determined in this manner were within a few days of the growth stage suggested by Oosterhuis (1990) based on cumulative heat units (base 15°C). One SPAD 502 chlorophyll meter (Minolta, Inc. Ramsey, NJ) reading was taken from the uppermost, fully expanded leaf of 20 random plants per subplot. One reflectance reading of the plant canopy was taken on each of the four center rows of every subplot using a hand-held spectroradiometer (model MSR16R, CropScan, Inc. Rochester, MN). The radiometer has a sensor that consists of 16 pairs of upward and downward facing interference filters centered at wavelengths: 450, 470, 500, 530, 550, 570, 600, 630, 650, 670, 700, 780, 820, 870, 1600, and 1700 nm. The filters have bandwidths ranging from 6.5 to 17.0 nm. The sensor, which has a 28° field of view, was adjusted to approximately 50 cm above the height determined by sight to be the average plant height in the study on the day of measurement. Reflectance readings were taken with the sensor centered on the row on all subplots between 2 h before solar noon and 20 min before solar noon. Percentage of reflectance was calculated for each waveband as reflected irradiance/incoming irradiance. The following ratio vegetative indices were calculated from the percentage of reflectance (R) data: GVI (R_{NIR}/R_{green}) (Bausch and Duke, 1996), green nor-

Table 4. Urea ammonium nitrate-N rates applied at Lubbock 2001.

Treatment	TL†	ES‡	EB§	PB¶	Total
	kg N ha^{-1}				
	Surface drip				
Well fertilized	67	34	34	0	134
Soil test	34	34	34	0	101
Reflectance	34	0	34	34	101
Chlorophyll meter	34	0	0	34	67
Zero	0	0	0	0	0
	Subsurface drip				
Well fertilized	67	34	34	0	134
Soil test	34	34	34	0	101
Reflectance	34	0	34	34	101
Chlorophyll meter	34	0	34	34	101
Zero	0	0	0	0	0

† TL, two-leaf.
‡ ES, early squaring.
§ EB, early bloom.
¶ PB, peak bloom.

Table 5. Amounts of rain and irrigation water during the growing seasons for the three site years, and irrigation modes.

	Ropesville 2000		Lubbock 2000		Lubbock 2001	
	LEPA†		Surface	Subsurface	Surface	Subsurface
ET Replacement, %‡	80	105	75	75	73	73
Rain, cm§	29.7	29.7	13.1	13.1	7.0	7.0
Irrigation, cm	17.8¶	23.6¶	16.2#	16.2#	27.4††	26.9††
Total, cm	47.5	53.3	29.3	29.3	34.4	33.9

† LEPA is low energy precision application irrigation.
‡ ET is evapotranspiration.
§ May to September, 75-yr average is 32 cm.
¶ 3.1 mg NO_3^-–N L^{-1}.
# 8.4 mg NO_3^-–N L^{-1}.
†† 9.0 mg NO_3^-–N L^{-1}.

malized difference vegetative index (GNDVI) $(R_{NIR} - R_{green})/(R_{NIR} + R_{green})$ (Gitelson et al., 1996), red vegetative index (RVI) (R_{NIR}/R_{red}), (Jordan, 1969) and red normalized difference vegetative index (RNDVI) $(R_{NIR} - R_{red})/(R_{NIR} + R_{red})$ (Tucker, 1979). Twelve possible combinations of each index were calculated using the percentage of reflectance readings at three NIR (780, 820, and 870 nm), and four green (530, 550, 570, and 600 nm) or four red (630, 650, 670, and 700 nm) wavebands.

At the three growth stages that chlorophyll meter and reflectance readings were taken, 1 m of row of aboveground biomass was sampled. Dry weights (60°C) were recorded and leaves were ground to 0.5 mm. A LECO FP-528 Protein N analyzer (LECO Corp., St. Joseph, MI) was used to analyze leaves for N concentration. Biomass and leaf N data were correlated with vegetative indices and chlorophyll meter readings and are reported in a companion manuscript (Bronson et al., 2003).

The reflectance and chlorophyll meter plots received in-season N of 34 kg ha^{-1} during or shortly before an irrigation when the sufficiency index, relative to the well-fertilized plots was <0.95 (Varvel et al., 1997; Bronson et al., 2001) (Tables 2–4). The sufficiency index using chlorophyll meter readings was determined at each growth stage by dividing the reading of each chlorophyll meter plot by the average (by each irrigation treatment) chlorophyll meter reading of the well-fertilized reference plots (Varvel et al., 1997). Using reflectance readings, the sufficiency index was calculated at each growth stage by dividing the GVI (R_{820}/R_{550}, R is percentage of reflectance at waveband indicated in subscript) of each reflectance plot by the average (by each irrigation treatment) GVI (R_{820}/R_{550}) of the well-fertilized reference plots. The GVI (R_{820}/R_{550}) was chosen instead of RVI because it was positively correlated with leaf N and N rate and was affected by N more frequently and to a greater degree than the RVI at both sites at early squaring in 2000 (Bronson et al., 2003). The decision on what vegetative index to use was made before any in-season N was added to the reflectance plots in 2000 and the GVI chosen (R_{820}/R_{550}) was used for the reflectance plots in 2001 as well.

Total N fertilizer rates applied to soil test plots were calculated from the amount of N needed for an expected yield of 1400 kg lint ha^{-1}, 168 kg N ha^{-1} minus the 0- to 60-cm spring soil NO_3^-–N (Zhang et al., 1998). Nitrogen fertilizer for the soil test plots was applied in 34 kg N ha^{-1} increments after the 34 kg N ha^{-1} application at the two-leaf stage (Tables 2–4). To establish a reference treatment for the reflectance and chlorophyll meter treatments, well-fertilized plots at both sites received 1.5 times the N fertilizer as the soil test plots in 2000 (Tables 2 and 3). At Lubbock in 2001, the well-fertilized treatment received just 1.3 times more N than the soil test plots, due to buildup in residual NO_3^-–N in the well-fertilized plots. The objective of the well-fertilized treatment was to stimulate luxury uptake of N, so that the greenness of the leaf reaches a maximum (Peterson et al., 1993; Hussain et al., 2000). The amount of precipitation and irrigation for the entire growing season for each site-year is shown in Table 5.

Plant Sampling and Analyses

Aboveground biomass was sampled from 60 cm of both rows in each microplot at first open boll (area = 1.25 m^2). Plants were separated into leaves, stems, burrs, lint, and seeds, dried at 65°C and then weighed. Stems and burrs were coarsely ground (1 mm) in a Wiley mill (Arthur C. Thomas Co., Philadelphia, PA) and then ground to 0.25 mm in an ultra centrifugal mill (ZM 100, Retsch GmbH & Co., Haan, Germany). Leaves and seeds were ground directly to 0.25 mm. Lint was neither ground nor analyzed for N as checks indicated that it was <1 g N kg^{-1}. Amounts of finely ground plant material were weighed into Sn capsules so that they contained approximately 150 μg N. Plant samples (capsules) were then analyzed for %N and atom% ^{15}N with an automated Carlo-Erba CN analyzer (CE Instruments, Milan, Italy) that was interfaced to a VG Isomass mass spectrometer (ANA-MS) (VG Isogas, Middlewich, England).

Lint was harvested from four rows (2 m from each row, area = 32 m^2) in each subplot in October of each year. Lint, seed, and burrs were harvested by hand and ginned. Seed and lint weights were recorded.

Soil Sampling and Analyses

Before planting, two soil cores per subplot were sampled to 90 cm in each of the following positions: dry furrow, wet furrow, and seed row. The cores were sectioned into 0 to 15, 15 to 30, 30 to 45, 45 to 60, and 60 to 90 cm. The upper 45-cm soil layers were processed fresh, while the lower depths were air-dried and crushed to pass through a 2-mm sieve. Soils were extracted with 2 *M* KCl (1:10 soil/extract) and analyzed for NH_4^+-N and NO_3^-–N (Adamsen et al., 1985) on a Technicon AutoAnalyzer 2 (Technicon Industrial Systems, Tarrytown, NY).

Soil sampling at harvest involved two arcs of 45-cm deep cores reaching from dry furrow to dry furrow (2 m) in the microplot. Each arc consisted of 10 cores that were sampled using a Giddings soil-sampling machine (Giddings Machine Co., Fort Collins, CO). The probe was lined with plastic tubes to prevent cross-contamination. Cores were sectioned into 0 to 15, 15 to 30, and 30 to 45 cm and pooled by depth. Two soil cores were sampled from the microplot at harvest to 90 cm from each position: dry furrow, wet furrow, and seed row. Soils from these cores were pooled by depth and by position. Similar to the spring soil samples, the upper 45 cm samples were extracted fresh with 2 *M* KCl and the lower depth samples (45–60, and 60–90 cm) were extracted air-dry with 2 *M* KCl.

Atom% ^{15}N analysis of NH_4^+-N + NO_3^-–N was accomplished by diffusing NH_3 from the soil extracts (volume that contained approximately 100 μg N) in the presence of MgO and Devarda's alloy onto acidified glass fiber disks at room temperature for 7 d (Brooks et al., 1989). The fiber disks were then analyzed for atom% ^{15}N and N concentration by ANA-MS. Analysis of the extracts revealed that >98% of the inorganic N was in the NO_3^- form, and that <2% was in the NH_4^+ form. For this reason, we shall refer to extractable N as NO_3^-–N from here on.

Non-extractable ^{15}N in 0- to 15-, and 15- to 30-cm surface soil samples was determined by leaching 2 g of air-dried soil samples with 2 *M* KCl three times, followed by leaching with de-ionized water. The leached soil was then air-dried and ground to 0.25 mm and then analyzed for %N and atom% ^{15}N by ANA-MS. Soil samples taken from below 30 cm were not leached and analyzed for non-extractable N because the N content of these lower depths were less than the detection limit of the ANA-MS. Non-extractable N included fixed NH_4^+ in clay lattices, immobilized N in organic forms, and fine roots <2 mm before grinding.

Percentage of ^{15}N recovery in plant or soil was calculated using the formula of Hauck and Bremner (1976):

$$\% \ ^{15}\text{N Recovered} = 100 \times S \times (c - b)/f \times (a - b)$$

where *S* is the total N in plant part or soil in kilogram per hectare; *a*, *b*, and *c* represent atom% ^{15}N in fertilizer, soil or plant part that did not receive the labeled fertilizer, and soil or plant part that received the labeled fertilizer, respectively; and *f* was the rate of the labeled fertilizer applied in kilograms of N per hectare (kg N ha^{-1}).

Statistical Analyses

The effects of irrigation, N management, and irrigation × N management on first open boll biomass, first open boll N accumulation, lint yields, seed yields, residual soil NO_3^-–N, and ^{15}N sinks and balances were determined using the PROC MIXED procedure in SAS (SAS Institute Inc., 1999) for each site-year. Replicate and replicate × irrigation effects were considered random effects in the split-plot design. Nitrogen management and N management × irrigation were considered fixed effects. Means were separated using Fisher's protected least significant difference (LSD) at the 0.05 probability level (*P*).

Table 6. Lint and seed yields, and biomass and N accumulation at first open boll, as affected by N management.

Treatment	Ropesville 2000	Lubbock 2000	Lubbock 2001
	Lint Yield, kg ha^{-1}		
Well fertilized	682	1060	1485
Soil Test	705	1068	1429
Reflectance	687	1026	1344
Chlorophyll meter	623	1033	1395
Zero	707	887	1163
LSD ($P = 0.05$)	NS	90	138
	Seed Yield, kg ha^{-1}		
Well fertilized	1283	1803	2438
Soil Test	1259	1786	2352
Reflectance	1219	1663	2221
Chlorophyll meter	1115	1721	2288
Zero	1267	1476	1920
LSD ($P = 0.05$)	NS	152	220
	Biomass, kg ha^{-1}		
Well fertilized	4303	5692	5971
Soil Test	3769	5451	6181
Reflectance	4109	4679	5411
Chlorophyll meter	3704	5172	5497
Zero	3007	4249	4234
LSD ($P = 0.05$)	NS	762	872
	N Accumulation, kg ha^{-1}		
Well fertilized	78	104	122
Soil Test	69	94	123
Reflectance	70	76	102
Chlorophyll meter	59	87	102
Zero	50	68	71
LSD ($P = 0.05$)	16	13	19

RESULTS

Nitrogen Rates Applied

In 2000, the soil test-based N management received 134 kg N ha^{-1} at both sites, calculated as described above (Table 2 and 3). The soil test N application was reduced to 101 kg N ha^{-1} at Lubbock in 2001 (Table 4), because of the buildup in spring NO_3^-–N in the upper 60 cm soil in that treatment to 66 kg N ha^{-1} (data not shown). Among the three site-years, reflectance and chlorophyll meter treatments did not call for in-season N until early or peak bloom stage (Tables 2, 3, and 4). There were several cases within irrigation treatments where there were differences in the amounts of N applied between the reflectance and chlorophyll meter treatments. Thirty four to 100 kg ha^{-1} less N fertilizer was applied to the in-season monitoring (chlorophyll meter and reflectance) treatments compared with the soil test plots in 2000 at Ropesville and Lubbock. In 2001 at Lubbock, three of the four in-season monitoring by irrigation combinations demanded the same amount of N as the soil test treatments. Among the three site-years of the study, less N was applied with the chlorophyll meter and reflectance treatments than with the soil test plots in nine of 12 cases (i.e., in-season monitoring-irrigation site-year combinations).

Lint and Seed Yields

In both years at Lubbock, irrigation mode did not affect lint or seed yields. Similarly, at Ropesville, irrigation level did not affect lint or seed yields. There was no N management × irrigation interaction. Lint and seed yields for the three site-years are therefore presented averaged across irrigation treatments (Table 6). Lint yield had a strong positive correlation with seed yield in all site-years ($r = 0.97$ to 0.98). For this reason, only lint yields will be discussed for the remainder of this manuscript.

Lint yields at Ropesville were low (average 681 kg ha^{-1}) and did not respond to N (Table 6). A strong rain and windstorm 2 wk after planting resulted in a reduced stand and damaged seedlings from blowing sand, which resulted in slow early growth. However, the remaining plant population of 12 plants linear m^{-1} (50 000 plants ha^{-1}) was still near the optimum population according to local plant population studies (Franklin et al., 2000). Root-knot nematode (*Meloidogyne inconita*) may have contributed to slow early growth as well, because the density in soil was greater than the damaging level of 1000 eggs 500 cm^{-3} suggested by Wheeler et al., (1999). Low soil test P (11 mg Mehlich 3-P kg^{-1}, Table 1) may have also limited growth, despite P fertilization, as early squaring leaf P was below the critical level of 3 g P kg^{-1} (data not shown) (Plank, 1979; Jones et al., 1991). High insect pressure at Ropesville for 2 wk in August 2000 probably contributed to low yields. Leaf area was reduced about 10% by cabbage loopers (*Trichoplusia ni*, Hubner), and developing squares and bolls were damaged beet army worms (*Spodoptera exigua*, Hubner). However, the economic threshold of 5600 small beet army worm larvae ha^{-1} was only briefly exceeded, and for the Southern High Plains there is no published economic threshold for cabbage loopers (Muegge et al., 2001).

Nitrogen-fertilized treatments resulted in greater lint yields than the zero-N plots in 2000 and 2001 at Lubbock (Table 6). All N-fertilized treatments in Lubbock were statistically similar in 2000. Only in Lubbock 2001 was the expected yield of 1400 kg lint ha^{-1} met in the N-treated plots. The finding that the in-season monitoring treatments were similar to the soil test treatment is notable, especially since less N was applied in all four N treatment-irrigation combinations in 2000, and in one of the four combinations in 2001. The observation that N applications in 2001 equaled the soil test N treatments are reasonable given the potential for high yields that occurred that year in Lubbock. Although there was light insect pressure (cabbage loopers and beet army worms) in Lubbock in 2000 (but less than in Ropesville), the growing season in Lubbock in 2001 after early squaring was free of insect pressures. There was early *Thrips* sp. pressure in Lubbock, 2001 that slowed growth up to early squaring. Final plant populations were 63 000 and 72 000 plant ha^{-1} for Lubbock in 2000 and 2001, respectively.

Water input at Ropesville was greatest among the three site-years (Table 5). However, most of a 15-mm rain storm that occurred 2 wk after seeding likely ran off the 2% slope field at Ropesville because of the short time period in which the rain fell. Seasonal water input at Lubbock in 2001 was slightly greater than 2000, and the proportion as irrigation was much larger in 2001. The slope at Lubbock is 0.2%, and runoff of rain there is rare.

Biomass and Nitrogen Accumulation at First Open Boll

Irrigation level or mode had no effect on first open boll biomass among the three site-years. Similar to the trend of lint and seed yields, biomass responded to N in both years at Lubbock but not at Ropesville (Table 6). No N management × irrigation interaction was observed. Within each site year, biomass was similar among the N-fertilized treatments. The ratio of lint to biomass ranged from 0.16 to 0.27 and was similar to reports from California (Bassett et al., 1970) and Alabama (Mullins and Burmester, 1990).

Nitrogen accumulation in cotton is probably near the maximum for the season at first open boll, when leaf shedding begins (Halevy, 1976; Li et al., 2001). Generally, N accumulation reflected lint yields. However, N fertilizer response in N accumulation was observed in all three site-years (Table 6). At Lubbock in 2000, N accumulation was similar between the soil test plots and the chlorophyll meter management. Reflectance plot N accumulation, however, was lower than the soil test plot N accumulation. Greater N accumulation was observed in the soil test treatments than in the chlorophyll meter or reflectance treatments at Lubbock, 2001, despite 101 kg N ha^{-1} being applied to three of four of these N treatment-irrigation mode combinations. This reflects the greater amounts of preplant 0- to 60-cm extractable NO_3^-–N in soil test plots (66 kg N ha^{-1}) compared the chlorophyll meter (47 kg N ha^{-1}) and reflectance plots (27 kg N ha^{-1}) (data not shown).

The ratio of lint yield to N accumulation was 11.1, 12.1, and 13.6 kg lint kg plant N^{-1} for Ropesville, 2000, Lubbock, 2000, and Lubbock, 2001, respectively, and reflected the decreasing insect pressure for the three site-years. These internal N use efficiencies (Witt et al., 1999) compare well with the 12 kg lint kg plant N^{-1} reported by Constable and Rochester (1988) in Australia. Lower N utilization efficiencies of 5, 6.7, 7.4, 8.3, and 10 kg lint kg plant N^{-1} were cited by Mullins and Burmester (1990) in Alabama, Unruh and Silvertooth (1996) in Arizona, Basset et al. (1970) in California, Boquet and Breitenbeck (2000) in Louisiana, and Halevy (1976) in Israel, respectively. Relatively high physiological (internal) N use efficiency in Southern High Plains cotton may be a result of breeding for low plant height as well as the deficit irrigation.

Harvest indices (seed plus lint/open boll biomass) for the three site-year were 0.52, 0.54, and 0.67 for Ropesville, 2000, Lubbock, 2000, and Lubbock, 2001, respectively. The two sites in 2000 had statistically similar harvest indices despite the non-N related factors that reduced growth and yields at Ropesville. Cotton harvest indices reported in other regions include 0.34 by Halevy (1976) in Israel, 0.32 by Boquet and Breitenbeck (2000) in Louisiana, and 0.33 to 0.52 by Mullins and Burmester (1990) in Alabama. However, those studies cited substantially greater biomass production (12 000 kg ha^{-1} in Israel and Louisiana, and 6900 to 7900 kg ha^{-1} in Alabama) than we report here in our studies in the Southern High Plains.

Residual Soil Nitrate

Irrigation level at Ropesville had no effect on soil profile NO_3^-–N at harvest. The effect of irrigation mode on residual NO_3^-–N by depth at Lubbock was inconsistent (data not shown). In Lubbock 2000, the subsurface drip resulted in higher residual NO_3^-–N than surface drip at the 15- to 30-cm depth. Conversely, the surface drip had higher residual nitrate than subsurface drip at the 30- to 45-cm depth. These trends however were not observed in 2001.

Residual soil profile NO_3^-–N at harvest in all site-years was strongly affected by N management (Table 7). Buildup in soil profile NO_3^-–N at Ropesville in the soil test treatment above that of the in-season monitoring plots confirms that the 134 kg N ha^{-1} rate was excessive for the growing conditions of that crop. At Lubbock in 2000, the in-season monitoring treatments had similar profile NO_3^-–N to the soil test plots. The 90-cm soil profile at Lubbock 2001 contained less NO_3^-–N with the

Table 7. Soil extractable NO_3^-–N at harvest of cotton, as affected by N management.

Treatment	Ropesville 2000	Lubbock 2000	Lubbock 2001
	kg ha^{-1}		
		0–60 cm	
Well fertilized	182	159	111
Soil test	119	91	98
Reflectance	43	65	77
Chlorophyll meter	46	80	77
Zero	36	44	37
LSD ($P = 0.05$)	24	28	25
		0–90 cm	
Well fertilized	243	202	132
Soil test	170	127	115
Reflectance	103	105	86
Chlorophyll meter	90	107	83
Zero	66	74	46
LSD ($P = 0.05$)	29	38	24

chlorophyll meter and reflectance plots than soil test plots, but the 60-cm NO_3^-–N profiles were similar. Bronson et al. (2001) also reported that residual 0- to 90-cm soil profile NO_3^-–N was positively related to N fertilizer rate at the Lubbock site with 75% ET surface drip irrigation.

Mineralization of N from residues and soil organic matter probably affected soil NO_3^-–N during the season. Nitrate-N additions in irrigation water at Lubbock were significant as well, especially in 2001 (23 kg NO_3^-–N ha^{-1}, calculated from Table 5). Bronson et al. (2001) estimated that the Acuff soil at the Lubbock site mineralizes about 50 kg N ha^{-1} per growing season of irrigated cotton. Examining the 90-cm profile NO_3^-–N levels in the zero-N plots of our study gives similar estimates. Starting with Spring 2000 NO_3^-–N at Lubbock (96 kg N ha^{-1}, Table 1) and subtracting the NO_3^-–N level at harvest in the zero-N plots (74 kg N ha^{-1}, Table 7) gives 22 kg N ha^{-1}. Adding this number to the N accumulation of 68 kg N ha^{-1} in zero-N plots (Table 6) and subtracting irrigation water N of 13 kg N ha^{-1} (calculated from Table 5) gives an estimated net mineralization of 33 kg N ha^{-1}. Repeating this calculation for Lubbock, 2001 with the spring 0- to 90-cm soil profile NO_3^-–N level in zero-N plots of 43 kg N ha^{-1} results in net mineralization of 51 kg N ha^{-1}. The same estimation procedure for the Ropesville 2000 data yields 12 kg N ha^{-1} of net mineralization.

Nitrogen-15 Balance

Plant ^{15}N recoveries ranged from 19 to 38% among the three site-year (Table 8). These values are within the range of plant ^{15}N recoveries previously reported for cotton by Torbert and Reeves (1994) in Alabama, Karlen et al. (1996) in South Carolina, and Rochester et al. (1997) in Australia. There was no effect of irrigation or irrigation × N management on ^{15}N recovery in plant among the three site-years. At Ropesville in 2000, recovery of ^{15}N in plants was significantly less with the well fertilized and soil test plots than with the reflectance and chlorophyll meter plots. The trend was similar in Lubbock, 2000, except that ^{15}N plant recovery was similar between the soil test and reflectance plots. There was no effect of N management on plant ^{15}N recovery in Lubbock, 2001.

Soil extractable $^{15}NO_3^-$–N in the 0- to 60-cm layers was not affected by irrigation level at Ropesville. However, in the 60- to 90-cm layer, greater recovery of $^{15}NO_3^-$–N was found with the 105% ET irrigation level (0.7% recovery) than the 80% ET irrigation (0.3% recovery) for the well-fertilized and reflectance treatments (data not shown). At Lubbock, there was an irrigation effect on recovery of extractable $^{15}NO_3^-$–N but it was inconsistent between the two years (Fig. 1). In 2000, ^{15}N recovery as extractable N in the 15- to 30-cm soil was higher with subsurface than surface drip irrigation, but in the 30- to 45-cm soil, it was higher with surface drip than subsurface drip irrigation (Fig. 1a). However, irrigation had no effect on ^{15}N recovery for the entire 90-cm soil profile (Table 8). In 2001, subsurface drip had greater extractable $^{15}NO_3^-$–N than surface drip in the 0-to 15-cm surface layer only (Fig. 1b). Recovery of extractable $^{15}NO_3^-$–N was negligible (i.e., <1% recovery) below 60 cm in all three site-years. Little water movement below 60 cm is to be expected at 75 and 80% ET deficit irrigation levels.

Table 8. Nitrogen-15 balance in plant and soil as affected by N management.

Treatment	Plant	Extractable-NO_3^-–N (0–90 cm)	Nonextractable-N (0–30 cm)	Total
	% Recovery			
		Ropesville 2000		
Well fertilized	18.9	43.5	11.8	74.1
Soil Test	23.7	30.0	13.8	67.4
Reflectance	33.0	8.2	12.1	53.2
Chlorophyll meter	38.2	8.1	12.4	58.6
LSD ($P = 0.05$)	6.7	9.8	NS†	10.9
		Lubbock 2000		
Well fertilized	19.2	44.6	7.3	71.1
Soil Test	21.8	22.7	5.8	50.3
Reflectance	27.3	21.9	9.8	58.9
Chlorophyll meter	28.3	30.9	9.0	68.2
LSD ($P = 0.05$)	5.8	NS	NS	NS
		Lubbock 2001		
Average	30.5	26.1	9.8	66.4
LSD ($P = 0.05$)	NS	NS	NS	NS

† Not significant.

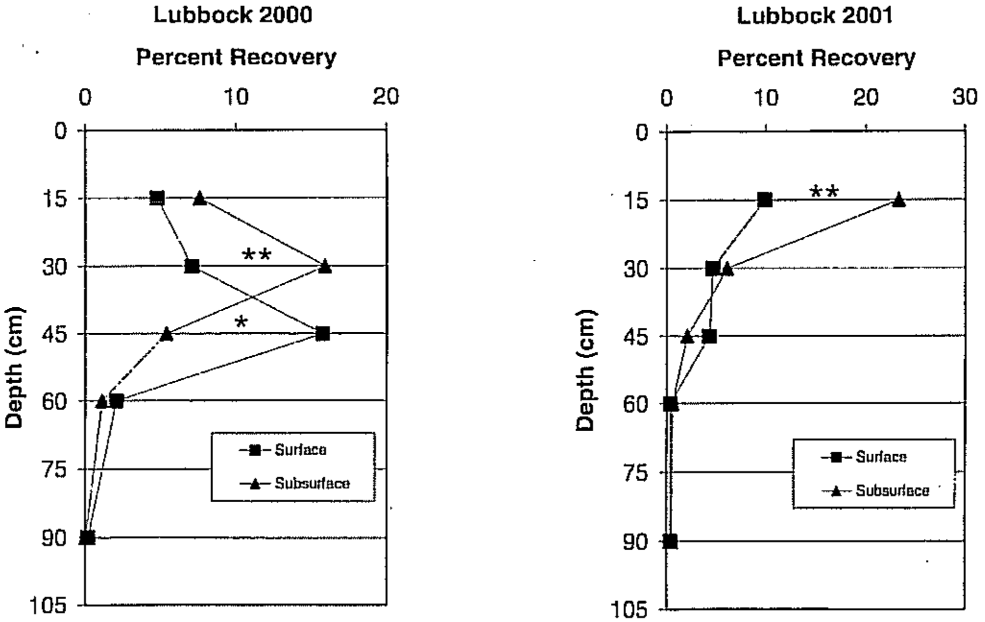

Fig. 1. Soil extractable $^{15}NO_3^-$–N at harvest of cotton, as affected by irrigation mode, Lubbock 2000 and Lubbock 2001 (* and ** are significantly different at $P = 0.05$ and 0.01, respectively).

Only in Ropesville, 2000 was there an effect of N management on extractable $^{15}NO_3^-$–N (Table 8). Recovery of extractable ^{15}N in soil decreased in the following order: well-fertilized plots > soil test plots > reflectance and chlorophyll meter plots.

The nonextractable ^{15}N represents the $^{15}NH_4^+$–N held within the clay lattice (Drury and Beauchamp, 1991; Thompson and Blackmer, 1993), N immobilized in organic forms (Balabane and Balesdent, 1992; Balabane, 1996), and fine roots. Nitrogen-15 recovery for this pool ranged from 5.8 to 13.8% (Table 8). There was no effect of irrigation mode or level on nonextractable ^{15}N. Nitrogen treatment differences in nonextractable ^{15}N were not present in any site-year.

Total recovery of ^{15}N in plant and soil or ^{15}N balance (Table 8) among the three site-years had a similar range (50–75% recovery), although Lubbock, 2001 had less variation (mean 66% recovery). These values were in the range of other reports (Torbert and Reeves, 1994; Karlen et al., 1996; Rochester et al., 1997).

DISCUSSION

Water use efficiencies, or lint produced per centimeter of water input, are difficult to compare for the irrigation treatments due to the varying N additions. By restricting the comparisons to the soil test treatments it can be concluded that the subsurface drip with daily irrigation had similar water-use efficiency (i.e., similar yields with equal water input) to the surface drip on a 3-d cycle. However, subsurface drip systems normally do not have the option of being switched to a 2- or 3-d cycle, because of the limits of the system to deliver the required water in shorter time periods. Our results were in contrast to the work of Bordovsky and Lyle (1998) who reported greater lint yields with daily subsurface irrigation than with LEPA on a 3-d interval. Surface-applied irrigation is susceptible to evaporative losses, which the subsurface-applied water is not. The lack of a lint yield response to irrigation level at Ropesville 2000 was probably because of other growth factors besides water (e.g., wind stress, insect damage, P deficiency) that limited yield.

The in-season monitoring approaches tested in this study led to reduced N application rates compared with the spring soil test NO_3^-–N guidelines in most cases. The N savings appeared to be related to the growing conditions and final lint yields of the crop. In the weather- and insect-stressed season at Ropesville 2000, for example, the lowest yields among the three site-years were obtained, and the greatest N savings with the chlorophyll meter and reflectance-based N management were realized. However, since no N response was observed at Ropesville 2000, any in-season N addition was too much. By this standard, three of the four in-season monitoring treatments at Ropesville 2000 "correctly" called for no in-season N additions (Table 2). Hunt et al. (1998) reported reduced N applications with the use of the GOSSYM/COMAX model to determine the need for in-season N in subsurface-irrigated cotton in South Carolina. Lint yields were similar with the GOSSYM/COMAX approach compared to five equal splits of N. Stone et al. (1996) reported N fertilizer savings of 32 and 57 kg N ha^{-1} with variable-rate N fertilization based on spectral reflectance compared to fixed topdress N rates in wheat in Oklahoma.

The lack of differences in biomass or lint yields between the well-fertilized and the zero-N plots clearly indicate that N was not limiting yields at Ropesville. Lint yields at Lubbock in 2000 were intermediate between the lower Ropesville yields and the higher Lubbock 2001 yields. Nitrogen fertilizer response at Lubbock 2000 was perhaps related to the insect pressure that was at less than economical threshold levels. It was surprising that the harvest indices were similar between Ropesville and Lubbock in 2000, considering the insect pressure at Ropesville.

Our results in Lubbock 2001 demonstrate that when cotton yield potential is high, in-season spectral reflectance or chlorophyll meter monitoring sufficiency indices were <0.95, indicating need of additional N compared with the 2000 sites (Bronson et al., 2003). When insect pressure was non-existent after early squaring in 2001, and the 1400 kg lint ha^{-1} expected yield was reached, the total amounts of N applied to the in-season monitoring treatments equaled the soil test treatment of 101 kg N ha^{-1} in three of four in-season monitoring-irrigation treatment combinations (Table 4). The 23 kg N ha^{-1} addition with irrigation water at Lubbock 2001 and the apparent 51 kg net N mineralization can help explain the greater yields in the zero-N plots compared with 2000. The similar N accumulation of the zero-N plots at Lubbock between the two years however (Table 6), indicates the importance of an insect-free reproductive growth stage in improved physiological efficiency and N response in 2001.

The reflectance and chlorophyll meter approaches themselves resulted in similar amounts of N being applied (±34 kg N ha^{-1}) in 11 of 12 in-season monitoring-irrigation site-year combinations (Tables 2–4). The one exception was at Lubbock 2000 in the subsurface drip treatment, when 34 and 101 kg N ha were applied to the reflectance and chlorophyll meter plots, respectively.

There were few differences (four of 18 cases) among all calculated green and red vegetative indices in the prescribed decisions regarding in-season N applications for the reflectance plots at early squaring, early bloom, and peak bloom (Bronson et al., 2003). However, the green-based vegetative indices correlated more often with leaf N concentration and leaf N accumulation than did the red-based indices (Bronson et al., 2003).

The 0.95 sufficiency level appeared to be a reasonable critical level. However in looking at the normalized difference vegetative indices, either GNDVI or RNDVI, the sufficiency indices of the reflectance treatments were rarely <0.95. Correlation was 0.99 between normalized vegetation indices and the simple ratio indices using reflectance from the same two wavebands. It appears that the normalized indices can be used in calculating sufficiency indices, but that the critical level with GNDVI or RNDVI is greater. When the sufficiency index calculated from GVI or RVI was near 0.95, the GNDVI or the RNDVI was 0.97 or 0.98. Our companion paper (Bronson et al., 2003) presents data and more details on how the various vegetative indices we calculated relate to leaf N and biomass, and includes more data on sufficiency indices calculated with reflectance from different combinations of wavebands.

It is notable that in two of the three site-years (Ropesville 2000 and Lubbock 2001), residual profile (0–90 cm) NO_3^-–N was less with in-season monitoring treatments than the soil test plots (Table 7). This was explained previously for Ropesville 2000 to over-fertilization of the soil test treatments. In Lubbock 2001, however, N applied with the reflectance plots (and chlorophyll meter plots in subsurface drip) equaled the 101 kg N ha^{-1} rate of the soil test plots. Reduced residual NO_3^-–N therefore, can likely be attributed to differences in timing of N applications, which was linked to N status monitoring in the case of the reflectance and subsurface drip chlorophyll meter treatments.

The large recoveries of extractable inorganic ^{15}N in the well-fertilized and soil test plots in Ropesville 2000 indicate over-fertilization (Table 8). Ropesville 2000 was the only site-year that had a reduction in residual $^{15}NO_3^-$–N recovery with the chlorophyll meter and reflectance plots, relative to the soil test plots. This again indicates over-fertilization of the soil test plots for the low-yielding conditions of that site-year. Although residual $^{15}NO_3^-$ at harvest among the three site-year was not significant below 60 cm, the 0- to 60-cm profile of $^{15}NO_3^-$ is susceptible to leaching during fallow period rains.

The fate of the 25 to 50% of ^{15}N not accounted for in plant or soil is not clear (Table 8). Since basal ^{15}N was incorporated, and in-season ^{15}N was applied either with or right before irrigation, it is not likely that $^{15}NH_3$ volatilization from soil was significant. As stated above, leaching of ^{15}N below 60 cm was negligible. Denitrification in wet zones of the upper 30 cm soil therefore appears to be the strongest possibility as a loss pathway (Thompson et al., 2000). Comparing the extractable-NO_3^-–N levels in subsurface drip irrigation with surface drip and LEPA does not give clear indications about the extent of denitrification. Another possibility in addition to denitrification is that NH_3 was lost through the cotton plants during the blooming and fruiting stages. This has been reported for wheat (Bashir et al., 1997), rice (Norman et al., 1992), and soybean (Stutte et al., 1979), but we are unaware of any such reports in cotton.

The plant recovery efficiency of added ^{15}N in this study was relatively low compared with studies with other upland crops such as wheat (Olson and Swallow, 1984; Bashir et al., 1997), or corn (Sanchez and Blackmer, 1988; Walters and Malzer, 1990). To further examine plant recovery of added N, we also calculated plant N fertilizer recovery efficiency by the difference method as:

$$\text{(N accumulation in N-fertilized plots} - \text{N accumulation in zero-N plots)/N rate}$$

In 2000, the difference recovery efficiencies were similar to those calculated by ^{15}N (14–40% for Ropesville, 16–23% for Lubbock). At Lubbock 2001, difference recovery efficiencies (32–51%) were generally greater than ^{15}N plant recoveries. Among the three site-years, the difference recovery estimates were much more variable than the ^{15}N plant recoveries, and there were no irrigation or N management treatment effects.

Nitrogen-15 plant recovery was greater with both in-season monitoring treatments at Ropesville and with the chlorophyll meter at Lubbock 2000 compared with the soil test treatment. Raun et al. (2002) also reported enhanced N recovery efficiency in wheat with in-season N applications based on proximal sensing of spectral reflectance. The reason why this trend was not observed in 2001 at Lubbock is not clear.

Future research is needed to try to improve cotton plant recovery efficiency of added N. Timing of N application is one possible management area that could be modified. Restricting N additions to the period of rapid cotton growth, that is, between early squaring and peak bloom, may result in greater recovery efficiency than what we reported in this study. In subsurface irrigation systems, N can be added in small quantities (e.g., <1 kg N ha^{-1}) daily. Setting up research with various N timing and rate treatments requires separate injection stations for every treatment. We were limited in doing true fertigation in this study because of the ^{15}N microplots. Another researchable issue for management of N in irrigated cotton in the Southern High Plains is the depth of the spring soil NO_3^-–N test. It is possible that a 0- to 90-cm soil sample may predict N fertilizer response better than the 0- to 60-cm sample Western states are currently using.

SUMMARY

This study demonstrated the potential of proximal reflectance measurements and chlorophyll meter readings as indicators of need for in-season N in irrigated cotton. In growing conditions that limited yield potential and N fertilizer response, N applications, and residual soil NO_3^-–N with in-season monitoring were less than with N fertilization based on spring soil NO_3^-–N tests. Nitrogen applications were similar between the N management approaches in high-yielding environments. Irrigation mode had no effect on lint yields or ^{15}N recovery in plants. Research on increasing the low recovery efficiency of fertilizer N by cotton is needed. Candidate strategies may include avoiding N applications near planting, and splitting in-season N application into smaller doses.

ACKNOWLEDGMENTS

The authors thank David Keeling for allowing this study on his field at Ropesville. We also thank Jimmy Mabry for his capable field assistance. This study was funded by USDA-CSREES-NRI Competitive Grant 99-35102-8526.

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