Improving Nitrogen Fertilizer Use Efficiency in Subsurface Drip-Irrigated Cotton in the Desert Southwest

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Declining water availability in the American Southwest continues to generate interest in efficient subsurface drip irrigation (SDI) for cotton (*Gossypium hirsutum* L.) production. Fertigating urea ammonium nitrate (UAN) at low rates with high frequency is an important advantage of SDI. However, N fertilizer management guidelines specific to SDI cotton are lacking. A 3-yr study was conducted on a Casa Grande sandy loam soil in Maricopa, AZ, to test a preplant soil profile NO_3 test algorithm and a canopy reflectance approach to manage in-season N fertilizer for SDI cotton. Treatments included soil test-based N management, reflectance-based N management, and zero-N at 100% evapotranspiration irrigation replacement. A second irrigation level of 70% evapotranspiration replacement included just the soil test-based N and zero-N treatments. The five treatments were replicated three times. Soil test–based N treatments received from 172 to 224 kg N ha^{-1}, and reflectance-based N amounts were 112 to 158 kg N ha^{-1}. Nitrogen recovery efficiency (RE) of UAN-N was high, with 24 fertigations during 6 wk between first square and mid bloom ranging from 58 to 93%. The isotope dilution method estimated similar RE in 2017. Residual post-harvest soil NO_3–N was notable only with 70% irrigation. Lint and seed yields were significantly reduced with the 70% irrigation treatment compared with 100% irrigation. The key result of this study is that reflectance-based N management saved 17 to 112 kg N ha^{-1} without reducing lint yields compared with the soil test–based N treatment.

Abbreviations: AE, agronomic efficiency; DGPS, differential geopositioning system; ET, evapotranspiration; IUE, internal use efficiency; NDRE, normalized difference red edge index; NDVI, normalized difference vegetation index; NUE, nitrogen use efficiency; OSI, overhead sprinkler irrigation; RE, recovery efficiency of nitrogen; SDI, subsurface drip irrigation; SI, surface irrigation; TNU, total nitrogen uptake; TWA, total water applied; UAN, urea ammonium nitrate.

Core Ideas

- **Nitrogen use efficiency is high in subsurface drip-irrigated cotton.**
- **Recovery efficiency was similar with ^{15}N and difference methods.**
- **Reflectance-based N management saved N fertilizer without reducing lint yields.**

Water and nitrogen (N) are, respectively, the first and second limitations to cotton (*Gossypium hirsutum* L.) production in arid lands, such as the southwestern United States (Morrow and Krieg, 1990). With rainfall <200 mm yr^{-1} in the region, all row-cropping is irrigated in the southwestern United States. Drought in the lower Colorado River Basin has been relentless since 2000 (Scanlon et al., 2016). Overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) systems have been steadily installed in central Arizona for the last 10 yr (Bronson et al., 2017). In cotton, deep percolation of irrigation water and NO_3 leaching is significant with surface irrigation systems (SI) but can be reduced with OSI (Bronson et al., 2017).

Nitrogen fertilizer management for cotton production in central Arizona was recently studied for SI and OSI (Bronson et al., 2017). Although lint and seed yields were similar between the two irrigation systems, recovery efficiency of N (RE) was markedly greater with OSI compared with SI. In Texas, RE in cotton increased in the order SI < OSI < SDI (Bronson, 2008). The emissions of nitrous

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oxide (N_2O), a potent greenhouse gas, are greatly reduced with high-frequency N fertigations in SDI cotton compared with two or three split applications of N in SI or OSI cotton (Bronson et al., 2018). Cotton N management studies using SI in arid regions like Australia, California, Texas, and Arizona are numerous (Booker et al., 2007; Hutmacher et al., 2004; Norton and Silvertooth, 2007; Rochester, 2007), but few N management studies have been conducted with SDI (Bronson et al., 2011), especially in Arizona's low desert environment.

Starting in 1985 in California (Zelinski, 1985) and in 1998 in Oklahoma (Zhang et al., 1998, 2017), a pre-plant soil NO_3 test combined with a 0.1 kg N ha^{-1} per kg lint ha^{-1} yield goal was promoted to cotton farmers to support N fertilizer management. Recent studies have developed a pre-plant soil NO_3 test approach for managing N for irrigated cotton in Texas and in Arizona (Bronson et al., 2017; Chua et al., 2003). This approach entailed a 0- to 60-cm soil sample for deficit-irrigated cotton in Texas and a 0- to 90-cm soil test for irrigated cotton in Arizona. This NO_3–N amount in kg N ha^{-1} was subtracted from a N requirement of 0.1 kg N ha^{-1} per kg lint ha^{-1} yield target. Credits were also made for estimated NO_3–N contributions from irrigation water. This approach is currently being used by Texas A&M AgriLife Extension in a Cotton Nitrogen Fertilizer Calculator (http://soiltesting.tamu.edu/cottonNcalc/cottonNcalc.htm). The soil test N management approach has not been evaluated in SDI cotton in Arizona. In Arizona, the plastic SDI tape is typically buried directly beneath the plant row, in contrast to the 2-m centers beneath "wet furrows" approach of the SDI method common in Texas (Bronson et al., 2011). There is a need to evaluate the pre-plant soil NO_3 test approach in deficit irrigation in Arizona for growers who want or need their SDI systems to produce profitable lint yields with limited irrigation water inputs.

The use of canopy spectral reflectance to guide in-season irrigated cotton N management is a relevant research thrust that has been tested in Texas, Arizona, Missouri, and Oklahoma (Arnall et al., 2016; Bronson et al., 2017; Chua et al., 2003; Oliveira et al., 2012; Yabaji et al., 2009). In the approach used in Texas and Arizona, a vegetation index, such as the normalized difference vegetation index (NDVI, a ratio of near infrared and visible canopy reflectance [Tucker, 1979]), in a priori-identified reflectance-based N management plots or field areas is compared with the NDVI obtained from the soil test areas described above. Nitrogen fertilizer rates in the reflectance plots are initially set at 50% of the soil test plots, and N rates are increased when plot averages of $NDVI_{reflectance}$ fall significantly <$NDVI_{soil\ test}$. This reflectance-based N system has been successful in saving N fertilizer without reducing lint yields in OSI and SDI cotton in Texas. This approach has been tested in OSI cotton in Arizona, but not with SDI.

The objectives of this study were (i) to compare lint and seed yields, biomass, N uptake, and N use efficiency (NUE) for soil test–based N fertilizer management with canopy reflectance-based urea ammonium nitrate (UAN)-N management approach in SDI cotton; (ii) to compare lint and seed yields, biomass, N uptake, and NUE for full and deficit irrigation in SDI cotton; and (iii) to construct ^{15}N balances for SDI cotton as affected by UAN-N management for both full and deficit irrigation (2017 and 2018 only).

MATERIALS AND METHODS

A 1.2-ha cotton field study was conducted for 3 yr at the Maricopa Agricultural Center near Maricopa, AZ (33.067 N, 111.97 W, 360 m asl) from 2016 to 2018. The soil is a Casa Grande sandy loam/sandy clay loam (fine-loamy, mixed, superactive, hyperthermic, Typic Natrargid). The surface 30 cm of soil had a pH of 7.9; total N and C of 0.5, and 5.0, g kg^{-1}, respectively; and >400 and 65 mg kg^{-1} of extractable K and P, respectively. These high soil test levels precluded the need for blanket applications of P or K fertilizer (Bronson et al., 2003; Unruh et al., 1993). Pre-plant soil sampling in 2017 and 2018 indicated that soil test P and K remained adequate. The site was fallow for 1 yr prior to the 2016 cotton season. A barley (*Hordeum vulagare* L.) cover crop was planted in early December of 2015 and 2017 and was terminated with glyphosate at the boot stage in the following March (in 2016 and 2018). The existing drip irrigation tape used during the 2016 season was replaced in the winter of 2016 to 2017, so a cover crop was not grown between the first and second seasons of cotton.

In mid-March of each year, pre-plant soil sampling to a depth of 180 cm for NO_3 and NH_4 was done at four sampling locations in each of the 15 plots on the side of raised planting Bed 5 (within eight beds per plot). The total number of differential geopositioning system (DGPS)-referenced soil sampling points was 60. The soil sampling was repeated after each cotton harvest. A 15- to 22-cm furrow surface irrigation was applied 1 wk before each soil sampling to permit soil sampling below 30 cm in this arid soil environment. Soil was sampled at 0 to 30, 30 to 60, 60 to 90, 90 to 120, 120 to 150, and 150 to 180 cm with a Giddings soil sampling unit (Giddings Machine Co.). Soil samples were oven-dried at 60°C, ground to 1-mm, extracted with 1 M KCl, and analyzed for NH_4 and NO_3 (Adamsen et al., 1985). A soil bulk density of 1.6 g cm^{-3} was assumed for the field site (Post et al., 1988) in converting NO_3–N data to kg ha^{-1} from mg kg^{-1}.

The cotton cultivar 'Deltapine 1549 B2XF' was planted at 12 kg seed ha^{-1} on 12 Apr. 2016, 11 Apr. 2017, and 1 Apr. 2018 into 15-cm high beds in plots that included eight rows (1 m wide, 100 m long). Cotton was planted with strip-tillage in 2016 and 2018 by running 25-cm-wide tine rollers just prior to planting. Plant densities were consistently about 10 plants m^{-1}. After harvest, a root puller operation was followed by a lister to reshape the beds. The five N management and irrigation treatments included a soil test-based N treatment and a zero-N treatment at two irrigation levels, full irrigation, 100% replacement of estimated crop evapotranspiration (ET), and a deficit irrigation with 70% replacement of crop ET (Table 1). A reflectance-based N management treatment was included at the 100% irrigation level only. The experimental design was a randomized block design with three replications, and the same treatment–plot assignments were used for all 3 yr.

Weekly canopy reflectance was measured on the cotton in Rows 4 and 5 of each plot starting 2 wk after emergence with active optical sensors (Crop Circle ACS-470, Holland Scientific Inc.). Sensors were mounted on the front arms of a Hamby high-clearance tractor and adjusted weekly to a height of 1 m above the first plot that had a soil test–based N rate treatment at 100% irrigation. Weekly measurements (n = 11–12) were made until mid-bloom when the plant canopy closed. The Crop Circle ACS-470 sensors had interference band-pass filters centered at 800 nm (20 nm width), 590 nm (10 nm width), and 670 nm (10 nm width). The second sensor in each row had filters at 550 nm (10 nm width), 530 nm (10 nm width), and 730 nm (10 nm width). Weekly calibration just prior to field data acquisition was performed for one sensor at a time connected to the Holland Scientific FieldCAL SC-1. This consisted of "zeroing" the sensors' output while covered with black foam followed by "spanning" the output to 1.0 with sensors 1.3 m above a 1.2 × 1.8 m titanium white-painted piece of plywood. Crop Circle data were logged to a Holland Scientific GeoSCOUT X datalogger. The DGPS was logged with a GPS receiver (Crescent A100, Hemisphere GPS). The normalized difference red edge index (NDRE) (Gitelson and Merzlyak, 1994) was used for the reflectance-based N treatment and was calculated as $(R_{800} - R_{730})/(R_{800} + R_{730})$, where R_{800} and R_{730} are reflectance at 800 and 730 nm, respectively.

The soil test–based treatments at both irrigation levels used a lint yield goal of 2240 kg ha^{-1} and a 224 kg N ha^{-1} N requirement of 0.1 kg N kg^{-1} lint^{-1} (Bronson et al., 2017). The N requirement was increased slightly to 0.1125 kg N kg^{-1} lint^{-1} (252 kg N ha^{-1}) in 2017 and 2018. The application rate of N fertilizer for the soil test treatments was calculated by subtracting from the N requirement the 0- to 90-cm amount of pre-plant soil NO_3–N (mean of soil test–based plots) and the estimated irrigation input of 22 kg N ha^{-1} (estimated 100 cm irrigation of 2 mg L^{-1} NO_3–N water). The soil test treatment at deficit 70% irrigation received the same N fertilizer rate as the soil test 100% irrigation for each year. This allowed treatment comparisons based on irrigation level alone with no confoundment of N fertilizer rate, although we expected a lower lint yield with deficit irrigation. The reflectance-based N treatment was initially fertigated with N at 50% of the soil test-based N daily rate. This treatment's N rate was then increased to match the daily N rate of the soil test treatment when $NDRE_{reflectance}$ became significantly less than $NDRE_{soil\ test}$ at $P < 0.05$.

Urea ammonium nitrate (liquid, 320 g N kg^{-1}) was fertigated in 24 events over a 6-wk period from pin-head square to mid-bloom in the irrigation line of each N-fertilized plot after the disk filters, pressure reducers, and flow meters. Fertigations were performed for each of the N-fertilized plots with a 1.25-L h^{-1} diaphragm pump. In 2016 and 2018, a commercially available UAN fertilizer (320 g N kg^{-1}) was used. In 2017, 180 kg ^{15}N-depleted (0.02 atom% ^{15}N) ammonium nitrate (manufactured at Los Alamos in the 1970s) was made available to us. We made 320 g N kg^{-1} liquid UAN by weighing and mixing in reagent-grade urea (Fisher Scientific) to mimic commercial UAN (i.e., 50% urea-N, 50% ammonium nitrate N).

Drip irrigation "tape" was buried 22 cm deep in 2016. New drip tape was installed in early 2017 at a 28 cm depth for the 2017 and 2018 cotton seasons. Emitter spacing was 60 cm in 2016 and 30 cm in 2017 and 2018. Flow rate per emitter at the operating pressure of 103 kPa was 1.1 Li h^{-1} in 2016 and 0.6 Li h^{-1} in 2017 and 2018. Drip tape was installed in the center of the 1-m-wide, 15-cm-high beds to be near the plant roots. Irrigation water (pH 7.8) was acidified to pH <6.5 to reduce precipitation of $CaCO_3$ and plugging of emitters. Sulfuric acid was injected into the main header line of the SDI system with a pH meter-cum-pump. Surface irrigation (7–14 cm) was applied right after planting in each season to ensure germination and emergence.

The soil water balance over the cotton root zone was calculated daily for the 100% irrigation treatment to determine irrigation requirements and daily soil water depletion. Crop evapotranspiration was estimated by the FAO-56 dual crop coefficient procedures (Allen et al., 1998) using a locally developed basal crop coefficient curve (Hunsaker et al., 2005, 2015). Daily grass-reference ET and meteorological data, including rainfall, were provided by a University of Arizona Meteorological Network (ag.arizona.edu/azmet) weather station located about 100 m from the study site. The 100% irrigation treatment was managed to meet 100% of the ET requirement and maintain soil water depletion at <30%, as determined in the soil water balance. The 70% irrigation treatment was given 70% of the 100% irrigation amount starting in late April of each season. After the germination/emergence irrigations, no irrigation was applied to plots for 2 wk. Afterward, 7-mm irrigations (5-mm in the 70% treatment) commenced at a frequency of twice per week. The frequency was increased to three to four irrigations per week (10-mm irrigations, 7-mm in 70% treatment) at first bloom. Starting at early-mid bloom, daily irrigation requirements for the 100% treatment were ~12 mm d^{-1} (8.4 mm d^{-1} in the 70% treatment). During this period, treatment irrigations were usually applied 7 d wk^{-1} through mid- to late August depending on climate and year. Due to rainfall that met irrigation requirements, daily irrigation was not applied for a few days each season. Cumulative irrigation after crop stand establishment for the 100% treatments was 804, 851, and 809 mm for 2016, 2017, and 2018, respectively (Table 1).

Table 1. Irrigation amounts and N fertilizer rates applied in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2016–2018.

Nitrogen treatment	Irrigation level†	Irrigation level			Fertilizer rate		
		2016	2017	2018	2016	2017	2018
	% ET		mm			kg N ha^{-1}	
Soil test–based	100	804	851	809	175‡	172§	224§
Reflectance-based	100	804	851	809	158¶	125¶	112¶
Zero	100	804	851	809	0	0	0
Soil test–based	70	582	608	570	175‡	172§	224§
Zero	70	582	608	570	0	0	0

† Does not include surface irrigations right after planting to ensure germination and emergence of 92, 95, and 136 mm for 2016, 2017, and 2018, respectively.

‡ Based on lint yield goal of 2240 kg ha^{-1} and a 224 kg N ha^{-1} N requirement minus 0–90 cm soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 100 cm irrigation of 2 ppm NO_3–N water).

§ Based on lint yield goal of 2240 kg ha^{-1} and a 252 kg N ha^{-1} N requirement minus 0–90 cm soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 100 cm irrigation of 2 ppm NO_3–N water).

¶ Initial N fertigation rate equals 50% soil test–based N treatment. Rate was increased when normalized difference red edge index (NDRE) was statistically significantly (P < 0.05) < soil test-based N treatment NDRE.

Aboveground biomass was sampled from 50-cm lengths of rows five and six in plots at first open boll next to each of the 60 DGPS soil sampling points. Beyond the first open boll growth stage, lower leaves began to senesce. This sampling time was close to when cotton achieved maximum biomass and total N uptake (TNU) (Li et al., 2001). Plants were separated into leaves, stems, burrs, lint, and seeds; dried at 65°C; and weighed. Stems and burrs were coarsely ground (1 mm) in a Wiley mill (Arthur C. Thomas Co.) and then ground to 0.25 mm in an ultra-centrifugal mill (ZM 200, Retsch GmbH & Co.). Leaves and seeds were ground directly to 0.25 mm. Lint was neither ground nor analyzed for N because lint N is negligible at <1 g N kg^{-1} (Bassett et al., 1970; Chua et al., 2003). In 2016, first open boll plant samples were analyzed with a Truspec Leco-Truspec CN analyzer (Leco Corp.). In 2017 and 2018, plant samples were analyzed for % N and atom% ^{15}N with an PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd.).

Seed-lint was harvested from Rows 4 and 5 in a 6-m long section of each plot that centered on the 60 DGPS soil sampling points. Harvests were performed in October of 2016 and 2017 and in November of 2018 with a cotton picker (2155, Case IH). Lint and seed were separated by a gin and weighed.

Post-harvest soil sampling in early December of 2016 and late November of 2018 was identical to the pre-plant soil sampling. In mid-November of 2017, in addition to the 60- to 180-cm soil sampling in 30-cm increments, we sampled the 0- to 30-cm and 30- to 60-cm depths in three positions per DGPS point (top of bed, side of bed, and bottom of bed) to better estimate labeled N in the extractable and non-extractable forms. The top two soil depths were extracted with 1 M KCl without drying to prevent loss of exchangeable NH_4. The soil depths from 60 to 180 (30-cm increments) were sampled only on the side of the bed and were dried at 65°C prior to KCl extraction.

Nitrogen-15 content of the post-harvest KCl soil extracts for NH_4^+–N + NO_3^-–N were prepared for analysis by diffusing NH_3 in 940250-mL Mason jars onto acidified glass fiber disks for 7 d (Brooks et al., 1989). Devardas alloy was added to the extracts to promote reduction of NO_3 to NH_4. To raise the pH for NH_4 to convert to NH_3, MgO was added to the extracts. Fiber disks were analyzed for atom% ^{15}N on a Vario EL Cube elemental analyzer (Elementar Analysensysteme GmbH) interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd.).

Nitrogen-15 content of non-extractable soil N was determined by leaching 1 g soil samples with 1 M KCl three times, followed by three more leachings with nano-pure water. This soil was then air-dried and analyzed for atom% ^{15}N on the same instruments as the fiber disks. Non-extractable soil N includes N immobilized N in organic matter and fine roots (Bronson and Fillery, 1998; Bronson et al., 1991).

Percent recovery of ^{15}N-depleted NH_4NO_3 in plant or soil was calculated as suggested by Hauck and Bremner (1976):

$$\%\,^{15}\text{N-depleted NH}_4\text{NO}_3\text{ recovered} = 100 \times P \times (b-c)/\,f \times (b-a)$$

where P is total N in plant or soil (kg N ha^{-1}); a, b, and c are atom% ^{15}N in fertilizer (0.02), plant or soil from zero-N plots, and plant or soil part received ^{15}N-depleted NH_4NO_3, respectively; and f is the application rate of ^{15}N-depleted NH_4NO_3 (kg N ha^{-1}).

Recovery efficiency (RE) of added N (difference method) was calculated as suggested by Dilz (1988):

$$\text{RE}(\%) = \frac{(\text{TNU in N-fertilized plot} - \text{TNU in 0-N plot}) \times 100}{\text{N fertilizer rate}}$$

where TNU is total N uptake at first open boll.

Agronomic efficiency (AE) was calculated as suggested by Novoa and Loomis (1981):

$$\text{AE} = \frac{\text{Lint yield in N-fertilized plot} - \text{lint yield in 0-N plot}}{\text{N fertilizer rate}}$$

Internal use N efficiency (IUE) was calculated as lint yield divided by TNU (Witt et al., 1999).

Statistical Analysis

The effects of N management and irrigation level on soil NH_4 and NO_3, cotton biomass, NDRE, TNU, RE, IUE, AE, lint, and seed yields were estimated with PROC MIXED by year (SAS Institute Inc., 2013). Nitrogen (and irrigation) management was considered a fixed effect. Replicate and replicate × N (and irrigation) management were considered random effects. Data from the four subsamples per plot were averaged in the PROC MIXED procedure. When the main and interaction F statistics were significant at the $P = 0.05$ level, then the PDIFF option was used to test for differences of least square means at $P = 0.05$ (SAS Institute Inc., 2013).

RESULTS

Initial soil profile NO_3 for the soil test 100% irrigation plots was low in March 2016 and 2018 (i.e., at the start of the growing seasons) at 28 and 3 kg NO_3–N ha^{-1} for the 0- to 90-cm soil, respectively (Table 2). At the start of 2017, which was the year without a cover crop, this value was 60 kg N ha^{-1}. Nitrogen fertilizer rates for the soil test (100 and 70% irrigation) treatments were 175, 172, and 225 kg N ha^{-1} for 2016, 2017, 2018, respectively, which were all within 1% of our calculated target N rates (Table 1).

Residual soil profile NO_3–N after harvest for the 3 yr is shown in Table 2. In December 2016, profile NO_3–N was similar across all treatments, with high values of 38 and 31 kg NO_3–N ha^{-1} for the 0- to 90-cm and the 90- to 180-cm soils, respectively (Table 2). In December 2017 and in November 2018, soil test 70% irrigation had the greatest NO_3–N concentrations in the 0- to 90-cm soil profile and had the greatest NO_3–N concentrations in 90- to 180-cm soil layers in 2018 (Table 2). Soil profile NO_3–N was similar in the reflectance plots to both irrigation levels of zero-N plots.

Post-establishment irrigation for the 100% treatment began in late April for all seasons and ceased in late August for 2016 and 2017 and mid-August in 2018. Cumulative irrigation to-

Table 2. Pre-plant and post-harvest soil NO_3–N as affected by N management and irrigation level in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2016–2018.

		2016				2017				2018			
		Pre-plant		Post-harvest		Pre-plant		Post-harvest		Pre-plant		Post-harvest	
Nitrogen treatment	Irrigation level	0–90 cm	90–180 cm	0–90 cm	90–180 cm	0–90 cm	90–180 cm	0–90 cm	90–180 cm	0–90 cm	90–180 cm	0–90 cm	90–180 cm
		kg N ha^{-1}											
Soil test–based	100	28a†	33a	38a	20a	60a	2a	23b	19b	3a	7b	32b	22a
Reflectance-based	100	24a	63a	13a	14a	38ab	37a	17b	6c	2a	7b	3c	6a
Zero	100	33a	97a	29a	28a	36ab	9a	17b	7c	2a	4b	11bc	7a
Soil test–based	70	20a	53a	25a	31a	58a	20a	53a	36a	3a	19a	75a	15a
Zero	70	22a	61a	25a	14a	32b	24a	13b	3c	1.7a	5b	10bc	5a
SE		7.4	31	7	6	8.5	17	5	4	0.5a	2	7.7	6

† Means in a column followed by the same letter are not significantly different at $P = 0.05$ by Fisher's protected LSD test.

tals for these periods (Table 1) do not include in-season rainfall amounts, which were 34, 51, and 74 mm in 2016, 2017, and 2018, respectively. Much of the rain in 2018 (51 mm) occurred in mid-August; thus, irrigation was not needed during the second half of August in 2018. The total water applied (TWA), including rainfall, to the 100% irrigation treatments after establishment compared with the estimated cumulative ET for the same periods in each year is as follows: 2016, TWA = 838 mm and ET = 907 mm; 2017, TWA = 902 and ET = 929; 2018, TWA = 883 and ET = 879. In 2016, cumulative estimated ET exceeded the 100% treatment TWA by about 8% compared with very few differences between ET and TWA in 2017 and 2018. When irrigation was ceased in August of each year, estimated soil water depletion for the 100% irrigation treatments from the water balance was 34, 9, and 14%, for 2016, 2017, and 2018, respectively. The total water applied for the 70% treatments (Table 1; irrigation amounts plus rainfall) were 74, 73, and 73% of the TWA for the 100% treatments in 2016, 2017, and 2018, respectively.

The NDRE for the 100% irrigation in the zero-N plots dropped significantly below 100% irrigation soil test plots rapidly at the first square growth stage in all 3 yr (Fig. 1). This rapid onset of N deficiency occurred 7, 15, and 12 d after commencement of the 6-wk fertigation period for 2016, 2017, and 2018, respectively. Monitoring for the onset of N deficiency in the reflectance plots indicated that NDRE for these plots with 100% irrigation fell significantly below NDRE in the soil test 100% irrigation plots on Day of Year 159 (2 wk before first bloom), 164 (first bloom), and 176 (mid-bloom) for 2016, 2017, and 2018, respectively. This was 13 and 29 d after the start of fertigation for 2016 and 2017, respectively. At these dates, N fertigation rates in the reflectance plots were increased to match the daily rates provided to the soil test plots. In 2018, on the other hand, the reflectance plots did not become N deficient until 54 d after start of fertigation, which was 12 d after the end of the fertigation period. Nitrogen rates were therefore not adjusted in 2018. Savings of N fertilizer for the reflectance plots compared with the soil test plots at 100% irrigation were 17, 47, and 112 kg N ha^{-1} for 2016, 2017, and 2018, respectively (Table 1).

Biomass yields for soil test 100% irrigation ranged from 12.4 to 14.9 Mg ha^{-1}, with the highest being in 2016 and the lowest in 2018 (Tables 3–5). Biomass decreased in the order: soil test 100% irrigation > reflectance plots 100% irrigation > soil test 70% irrigation > zero-N plots, regardless of irrigation level.

Total N uptake in the soil test 100% irrigation plots ranged from 202 to 222 kg N ha^{-1} among the 3 yr (Tables 3–5). Nitrogen uptake for the reflectance plots was less than TNU in soil test 100% irrigation plots in 2016 and 2018 (Tables 3 and 5). Reflectance plot TNU was similar to soil test 70% irrigation TNU in 2016 and 2017 (Tables 3 and 4). In 2018, TNU decreased in the order: soil test 100% irrigation > soil test 70% irrigation > reflectance plots (Table 5). Recovery efficiency of N fertilizer (by difference method) was very high in the soil test 100% irrigation plots (range, 81–92%) (Tables 2–4). Reflectance based N recovery efficiency (by difference) was 93 to 91% in 2017 and 2018 (Tables 3 and 4) but was only 67% in 2016 (Table 2). The soil test 70% irrigation plots had N recovery efficiency by the difference method of 58 to 60% for the 3 yr (Tables 3–5).

Recovery efficiency by the isotope dilution method in 2017 showed very good agreement with the difference method for soil test 100% irrigation and the reflectance plots (Table 4). There was a discrepancy between the two RE methods for the soil test 70% irrigation treatment. Table 6 shows the balance of applied ^{15}N-depleted ammonium nitrate in plant and soil in 2017. Recovery in the surface soil in non-extractable, organic forms was very low at 3 to 5%. Residual labeled-N in inorganic N was higher in the soil test 70% treatment than in the two 100% irrigation treatments at 11% recovery. The total balance of ^{14}N recovery was very high at 98 to 102% in the soil test and reflectance plots at 100% irrigation and was 92% for soil test 70% irrigation (Table 6).

Residual recovery by 2018 cotton of ^{14}N added in 2017 ranged from 2.7 to 3.1% (Table 5). Soil test cotton at 70% irrigation had lower recovery. The barley cover crop, which was terminated in late February 2018, recovered 0.5 to 1.1% of ^{14}N added in 2017, with the greatest recovery in the soil test 70% irrigation plots (Table 5).

Lint and seed yields responded strongly to added N fertilizer relative to the zero-N plots in all 3 yr (Tables 3–5). The N response was significantly less in the soil test 70% irrigation plots with yields 82 to 85% of the soil test 100% irrigation in 2016 and 2018 and 64% in 2017. Zero-N plot yields were greater with

100% irrigation than 70% irrigation in 2016, but these two treatments were similar in 2017 and 2018. Reflectance plot lint yields were statistically similar to the lint yields of the soil test 100% irrigation plots in all 3 yr, despite lower N fertilizer rates. Seed yields, on the other hand, were significantly reduced with reflectance management, compared with soil test 100% irrigation in one of three years (2018).

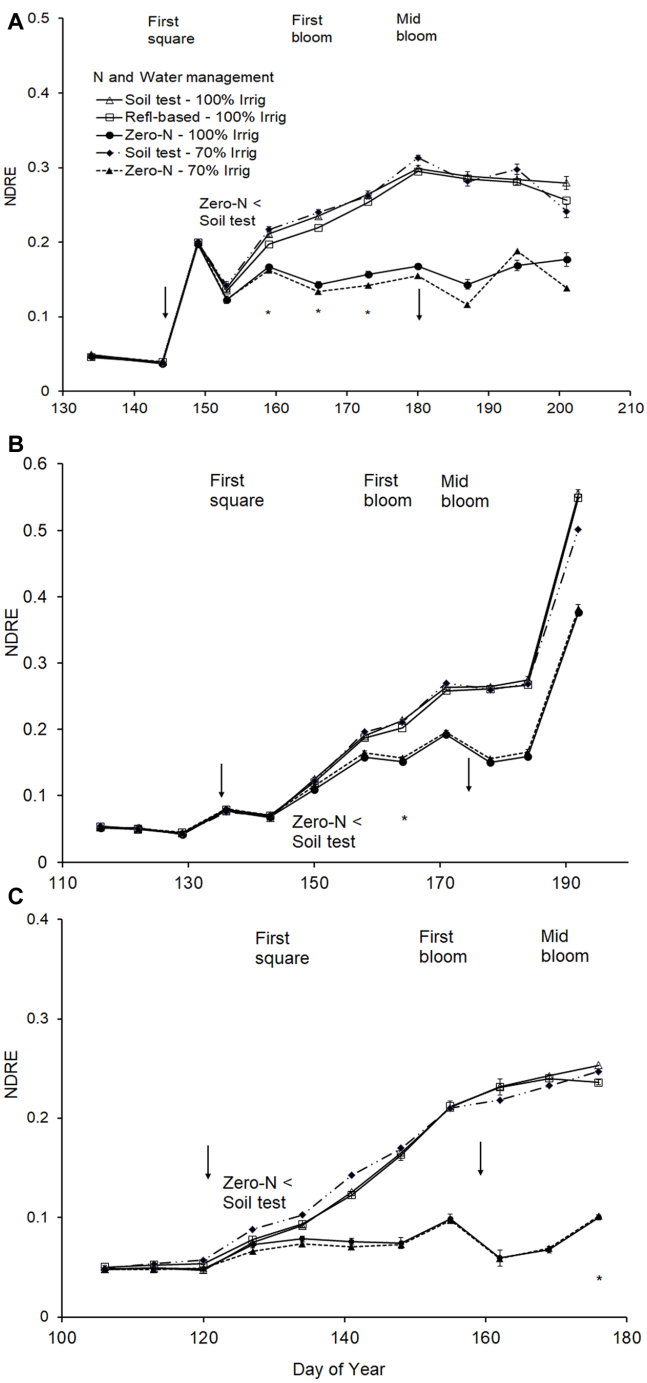

Fig. 1. Normalized difference red edge index (NDRE) as affected by N fertilizer and irrigation management in subsurface drip irrigated cotton, Maricopa, AZ, in (A) 2016, (B) 2017, and (C) 2018. Downward arrows indicate start and end of 6-wk N fertigations. *Normalized difference red edge index of reflectance-based N 100% irrigation plots are significantly < NDRE in soil test–based N 100% irrigation plots at *P* < 0.05. Standard error bars are shown for each date.

Agronomic NUE was higher with the reflectance plots than soil test 100% irrigation plots in 2017 and 2018 (Tables 3–5). In 2017, the soil test 70% irrigation plots had lower AE than soil test 100% irrigation, whereas in 2016 and 2018 they were similar. Internal N use efficiency was greater for the two zero-N treatments than in the N-fertilized plots in 2016 and 2018 (Tables 3–5). In 2017, IUE with the reflectance plots was similar to the zero-N plots. In 2018, IUE was greater with the reflectance plots than with the soil test 100% irrigation plots (Table 5). Internal NUE trended upward from 2016 to 2018 for all treatments.

DISCUSSION

Nitrogen fertilizer rates for the soil test treatments were similar for 2016 and 2017. Very low soil NO_3 in the spring of 2018 led to a higher rate of 224 kg N ha^{-1}. We made a small adjustment to the soil test algorithm due to lower than expected leaf N concentrations at first open boll in 2016. The N requirement of 0.1 kg N kg^{-1} lint^{-1} was increased to 0.1125 for 2017 and 2018. Specifically, leaf N in the reflectance-based 100% irrigation at first open boll was 3.0% N, whereas in the SI and OSI studies it was 3.5 to 4.0% N for similar soil test treatments (Bronson et al., 2017).

The NDRE data for 2016 and 2017 showed greater in-season variation than in 2018. The first early-season "spike" in 2016 coincided with the first 43°C air temperatures of the season. The end-of-season variability across treatments in 2016 and 2017 is harder to explain but may be related to the sensitivity of NDRE, with near-infrared and red edge wavebands being closer together than visible and near-infrared wavebands that result in smoother seasonal NDVI trends reported by Bronson et al. (2017). The dates when NDRE showed N deficiency in the zero-N plots was between first square and first bloom in 2016 to 2017 but preceded first square in 2018. Reflectance-plot N deficiency from NDRE data appeared later each of the 3 yr: mid-square in 2016, first bloom in 2017, and past mid-bloom in 2018. The reason for this is not clear, especially considering that 2018 had the highest yields. Several newer active optical sensors available have near-infrared, red, and red edge wavebands, such as the Holland Scientific RapidSCAN CS-45 and CropCircle ACS-430 and the AgLeader OptRx Crop Sensor. The TOPCON CropSpec has near-infrared and red edge wavebands, so all of these sensors can be used to calculate NDRE.

Lint yields were markedly lower than expected in 2016; this result was in contrast to similar studies at this site with SI and OSI (Bronson et al., 2017). Several days of severe heat stress (i.e., air temperatures of 48°C) at the early squaring stage resulted in small squares dropping. Furthermore, the 100% irrigated cotton in 2016 had less TWA during the growing season than in other years, whereas estimated cumulative ET was higher in 2016 than in 2018. Seasonal TWA that was 8% less than estimated ET in 2016 might also explain the lower lint yield in that year compared with 2017 and 2018, when TWA and ET differences were negligible. Lint and seed yields for 100% irrigation soil test increased in the order 2016 < 2017 < 2018. On the other hand, reductions in lint and seed yield for the 70% treatment were more severe in

Table 3. Lint yield, seed yield, N uptake, and N use efficiency (NUE) as affected by N management and irrigation level in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2016.

Nitrogen treatment	Irrigation level	Fertilizer rate	Biomass yield	Lint yield	Seed yield	Total N uptake	Recovery efficiency, difference method	NUE Agronomic	NUE Internal
	mm	kg N ha^{-1}	——— kg ha^{-1} ———			kg N ha^{-1}	%	— kg lint kg N^{-1} —	
Soil test–based	804	175	14,904a†	1473a	1914a	202a	81a	3.5a	7.4b
Reflectance-based	804	158	13,133b	1532a	1972a	166b	67a	4.2a	9.4b
Zero	804	0	6310d	885c	1117c	61c	–	–	15.0a
Soil test–based	582	175	9966c	1233b	1561b	151b	59b	3.2a	8.2b
Zero	582	0	5831d	694d	826d	49c	–	–	14.4a
SE			644	63	61	8.3	5.9	0.4	1.2

† Means in a column followed by the same letter are not significantly different at $P = 0.05$ by Fisher's protected LSD test.

2017 than in ther other years. Because estimated ET demand was large in 2017, plants in the 70% irrigation treatment were probably under greater water stress relative to the 100% treatment and relative to plants in the 70% treatments in 2016 and 2018. Biomass yields, on the other hand, decreased among years in the order 2016 > 2017 > 2018 The biomass yields of 12.4 to 14.9 Mg ha^{-1} for the soil test 100% irrigation were markedly higher than the 9.8 and 10.5 Mg ha^{-1} for similar N treatments for SI and OSI in Maricopa, AZ (Bronson et al., 2017). Obviously, the SDI system was efficient in producing cotton biomass. At this same site, Hunsaker and Elshikha (2017) and Hunsaker et al. (2019) reported nearly double the biomass of guayule (*Parthenium argentatum*) on SDI compared with similar irrigation rates on an adjacent SI field. However, it is well known that biomass is not necessarily correlated with yield in cotton (Oosterhuis, 1990). Increased lint and seed yields in 2018 is due to several factors. Cotton was planted earlier in 2018, and the temperatures were cooler than average during the first 7 wk after planting. These favorable growing conditions likely contributed to the relatively high lint and seed yields of the soil test 70% irrigation treatment in 2018; these conditions also correlate to less water demand on the deficit-irrigated cotton during this time compared with the more extreme early-season temperature conditions that occurred in 2016 and 2017.

Lint yields in all 3 yr were not statistically different with reflectance-based N management compared with the soil test–based N. This again confirms the robustness of the "save N fertilizer without hurting lint yields" philosophy of the reflectance-based approach that was previously tested for SI and OSI in Arizona and with OSI and SDI in Texas (Bronson et al., 2011; Chua et al., 2003; Yabaji et al., 2009). However, in 2018, seed yields were reduced with reflectance management compared with soil test management. The consequences of this, however, are limited because the price of lint is several-fold higher than the price of cotton seed.

The ^{15}N isotope results of the 2017 season are very unique. First, ^{15}N isotope studies are rare these days, especially in cotton. Of great note is the use of fertigating the labeled N-fertilizer into plots (100 m-long, 8 m wide) that are far larger than the microplots normally used for labeled-N studies (Chua et al., 2003; Fritschi et al., 2004; Karlen et al., 1996; MacDonald et al., 2017; Rochester et al., 1997; Torbert and Reeves, 1994). The close agreement observed in RE by the isotope and difference methods and the high RE values are unusual in the literature. More typically, isotope substitution and added N interaction with soil organic matter (Jenkinson et al., 1985) results in lower RE estimates compared with the difference method (Chua et al., 2003; Fritschi et al., 2004; Rao et al., 1991). Our result can probably be explained by the very high number of low-dose N fertigations over a 6-wk period, where most ^{15}N studies used one, two, or at most three N applications. Consistent with this explanation is the very low amount of labeled-N recovery in non-extractable soil (i.e., <5% applied N), indicating that there was little opportunity for N fertilizer to interact with soil organic matter. MacDonald et al. (2017) reported that 27% of applied ^{15}N added to cotton was immobilized by harvest, where 180 of a season total amount of 230 kg N ha^{-1} was applied at planting. The total recovery of labeled N of 98 to 102% in the 100% irrigation treatments strongly indicates little to no significant losses of fertilizer N to leaching or denitrification. The SDI system with a high frequency of N fertigations is clearly extremely efficient in delivering N to cotton.

The residual study in 2018 of labeled N applied in 2017 was unremarkable. The agronomically insignificant uptake of residual labeled-N by cotton in 2018 (applied in 2017) of 2.7 to

Table 4. Lint yield, seed yield, N uptake, and N use efficiency (NUE) as affected by N management and irrigation level in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2017.

Nitrogen treatment	Irrigation level	Fertilizer rate	Biomass yield	Lint yield	Seed yield	Total N uptake	Recovery efficiency: Difference method	Recovery efficiency: ^{15}N method	NUE: Agronomic	NUE: Internal
	Mm	kg N ha^{-1}	—— kg ha^{-1} ——		— kg N ha^{-1} —		——— % ———		— kg lint kg N^{-1} —	
Soil test–based	851	172	13,467a†	1780a	2252a	222a	92a	94a	6.5b	8.5ab
Reflectance-based	851	125	12,347ab	1855a	2319a	179a	93a	91a	9.5a	10.6a
Zero	851	0	4622c	665c	828c	63b	–	–	–	10.7a
Soil test–based	608	172	10,284b	1136b	1414b	179a	60a	76a	2.4c	6.5b
Zero	608	0	5959c	719c	869c	76b	–	–	–	9.5a
SE			922	67	96	15	12	8.4	0.5	0.7

† Means in a column followed by the same letter are not significantly different at $P = 0.05$ by Fisher's protected LSD test.

Table 5. Lint yield, seed yield, N uptake, and N use efficiency (NUE) as affected by N management and irrigation level in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2018.

Nitrogen treatment	Irrigation level	Fertilizer rate	Biomass yield	Lint yield	Seed yield	Total N uptake	Recovery efficiency: Difference method	Recovery efficiency: ^{15}N method†	Recovery efficiency: ^{15}N method‡	NUE: Agronomic	NUE: Internal
	mm	kg N ha^{-1}	kg ha^{-1}			kg N ha^{-1}	%			kg lint kg N^{-1}	
Soil test–based	809	224	12,384a§	2200a	2772a	215a	82a	3.0a	0.6b	7.2b	10.3c
Reflectance-based	809	112	11,499b	2061ab	2576b	133c	91a	3.1a	0.5b	13.3a	15.6b
Zero	809	0	3114d	586c	726c	32d	–	–	–	–	18.6a
Soil test–based	570	224	9356c	1857b	2349b	159b	58b	2.7b	1.1a	5.7b	11.9 c
Zero	570	0	2970d	584c	730c	30d	–	–	–	–	20. a
SE			452	77	105	7.4	6.1	0.15	0.06	0.7	1.0

† Recovery efficiency of labeled ammonium nitrate applied in 2017 by 2018 cotton.

‡ Recovery efficiency of labeled ammonium nitrate applied in 2017 by 2018 barley cover crop.

§ Means in a column followed by the same letter are not significantly different at *P* = 0.05 by Fisher's protected LSD test.

3.1% was in the range of other residual studies of labeled-N in the second season (Blackmer and Sanchez, 1988; Bronson et al., 1991; Karlen et al., 1996).

Internal NUE were similar to those observed with SI and OSI in the Bronson et al. (2017) study, with the zero-N plots producing the greatest IUE. The SI/OSI study was with cotton cultivar DP 1044, and the widely planted cultivar DP 1549 used in the current study (released in 2015) did not perform noticeably differently. However, given the greater biomass yields and N uptakes with SDI, the challenge remains to improve management so that lint and seed yields are increased (i.e., boost IUE). The early (1 April) planting of 2018 may have contributed to greater IUE that year because fruiting occurred during cooler temperatures, resulting in good fruit retention. Rochester (2011) examined IUEs in a range of irrigated cotton studies and farmers' fields in Australia. He concluded that an IUE of 12.5 kg lint kg N^{-1} corresponded to the optimum N rate and an N uptake in researchers' studies of 213 kg N ha^{-1}. Applying this IUE threshold to our studies, there were few treatments with IUE >12.5 kg lint kg N^{-1}, except the zero-N plots in 2016 and 2018 and the reflectance plots in 2018. The reduced seed yield in 2018 with reflectance-based N management compared with soil test 100% irrigation and the high IUE of 15.6 kg lint kg N^{-1} indicate N deficiency. The observation of N deficiency in the reflectance plots in 2018 in the NDRE data, after the 6-wk N fertigation period with an associated reduction in seed yield, suggests that an 8-wk N fertigation period starting at first square may be more appropriate to long-season cotton of the low US desert. Internal NUE may have been higher with a longer fertigation period as well. In the Texas High Plains, Yabaji et al. (2009) reported that lint yields of SDI cotton were similar with an N fertigation period of 5 wk starting from first square to midbloom compared with a prolonged 7-wk period to mid bloom, but the growing season in western Texas is shorter than in the low desert of Arizona.

Greater residual soil NO_3–N for all years in the 70% deficit irrigation treatments is to be expected because plant biomass and lint yields were water limited. The soil test N rate was closer to optimal for the 100% irrigation level and therefore resulted in relatively little residual soil NO_3 in 2016 and in 2017. This is in contrast to the SI and OSI studies, where after 2 yr soil NO_3 accumulated in the soil test treatment (Bronson et al., 2017). The low soil profile NO_3 in reflectance plots that were similar to the zero-N plots indicates that the reflectance N rates did not exceed the cotton plants' requirements. Greater post-harvest soil NO_3 with soil test N rate in 2018 suggests that the 212 kg N ha^{-1} rate was more than needed. Bronson et al. (2001) similarly observed greater post-cotton harvest residual soil NO_3–N levels as irrigation rates were decreased and/or as N fertilizer rates increased in semiarid western Texas. Increased residual soil profile NO_3–N in the deeper depths of >120 cm was likely affected by the need to surface-irrigate with 15 to 22 cm to soil sample. These pre-soil sampling irrigations probably moved soil NO_3 downward 30 cm or more, giving the appearance of more leaching than likely occurring with irrigations during the growing season. We do not have data on how deep the cotton roots grew in the 3-yr study. Hons and McMichael (1986) reported that in Texas it can be as deep as 1.8 m. In our SDI study, it is likely that most of the cotton roots were in the 0- to 90-cm soil layers (Plaut et al., 1996).

Table 6. Balance of ^{15}N-depleted ammonium nitrate in cotton plant and in soil as affected by N management and irrigation level in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2017.

Nitrogen treatment	Irrigation level	Fertilizer rate †	Plant recovery of ^{14}N	Recovery ^{14}N in non-extractable soil (0–30 cm)	Recovery $^{14}NH_4$ + $^{14}NO_3$–N in KCl-extractable soil (0–180 cm)	Total ^{14}N recovery
	mm	kg N ha^{-1}	%			
Soil test-based	851	86	94a‡	3.8a	4.8b	102a
Reflectance-based	851	63	91a	3.3a	3.6b	98a
Soil test-based	608	86	76a	4.9a	11.4a	92a
SE			8.2	0.8	1.8	7.9

† Represents 50% of total N fertilizer rate, other 50% was unlabeled urea-N.

‡ Means in a column followed by the same letter are not significantly different at *P* = 0.05 by Fisher's protected LSD test.

Overall, the very high recovery of fertigated N in this SDI cotton study compared with similar OSI and SI studies indicates little loss of fertilizer N to leaching or denitrification. More research is needed to evaluate IUE in this system because, although biomass and TNU were markedly greater than the comparable SI and OSI studies, lint and seed yields were not. Reflectance-based N management starting with 50% of a soil test–based algorithm continues to show great promise in saving N fertilizer. However, in long-season cotton the length of the fertigation period needs careful consideration.

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REFERENCES

Adamsen, F.J., D.S. Bigelow, and G.R. Scott. 1985. Automated methods for ammonium, nitrate, and nitrite in 2 M KCl-phenylmercuric acetate extracts of soil. Commun. Soil Sci. Plant Anal. 16:883–898. doi:10.1080/00103628509367651

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage paper no. 56. FAO, Rome, Italy.

Arnall, D.B., M.J.M. Abit, R.K. Taylor, and W.R. Raun. 2016. Development of an NDVI-based nitrogen rate calculator for cotton. Crop Sci. 56:3263–3271. doi:10.2135/cropsci2016.01.0049

Bassett, D.M., W.D. Anderson, and C.H.E. Werkhoven. 1970. Dry matter production and nutrient uptake in irrigated cotton (*Gossypium hirsutum*). Agron. J. 62:299–303. doi:10.2134/agronj1970.00021962006200020037x

Blackmer, A.M., and C.A. Sanchez. 1988. Response of corn to nitrogen-15-labeled anhydrous ammonia with and without nitrapyrin in Iowa. Agron. J. 80:95–102. doi:10.2134/agronj1988.00021962008000010022x

Booker, J.D., K.F. Bronson, C.L. Trostle, J.W. Keeling, and A. Malapati. 2007. Nitrogen and phosphorus fertilizer and residual response in cotton-sorghum and cotton-cotton sequences. Agron. J. 99:607–613. doi:10.2134/agronj2006.0124

Bronson, K.F. 2008. Nitrogen use efficiency varies with irrigation system. Better Crops Plant Food 92:20–22.

Bronson, K.F., and I.R.P. Fillery. 1998. Fate of nitrogen-15 labelled urea applied to wheat on a water-logged texture-contrast soil. Nut Cyc. Agro-Ecosystems 51(2):175–183.

Bronson, K.F., D.J. Hunsaker, J. Mon, P. Andrade-Sanchez, J.W. White, M.M. Conley, K.R. Thorp, E. Bautista, and E.M. Barnes. 2017. Improving nitrogen fertilizer use efficiency in surface- and overhead sprinkler-irrigated cotton in the Desert Southwest. Soil Sci. Soc. Am. J. 81:1401–1412. doi:10.2136/sssaj2017.07.0225

Bronson, K.F., D.J. Hunsaker, C.F. Williams, K.R. Thorp, E.M. Barnes, S.M. Rockholt, S.J. Del Grosso, R.T. Ventera, and E.M. Barnes. 2018. Nitrogen management affects nitrous oxide emissions under varying cotton irrigation system in the desert Southwest, USA. J. Environ. Qual. 47:70–78. doi:10.2134/jeq2017.10.0389

Bronson, K.F., J.W. Keeling, J.D. Booker, T.T. Chua, T.A. Wheeler, R.K. Boman, and R.J. Lascano. 2003. Influence of phosphorus fertilizer, landscape position and soil series on cotton lint yield. Agron. J. 95:949–957. doi:10.2134/agronj2003.9490

Bronson, K.F., A. Malapati, P.C. Scharf, and R.L. Nichols. 2011. Canopy reflectance-based nitrogen management strategies for subsurface drip irrigated cotton in the Texas High Plains. Agron. J. 103:422–430. doi:10.2134/agronj2010.0161

Bronson, K.F., A.B. Onken, J.W. Keeling, J.D. Booker, and H.A. Torbert. 2001. Nitrogen response in cotton as affected by tillage system and irrigation level. Soil Sci. Soc. Am. J. 65:1153–1163. doi:10.2136/sssaj2001.6541153x

Bronson, K.F., J.T. Touchton, R.D. Hauck, and K.R. Kelley. 1991. Nitrogen-15 recovery in winter wheat as affected by application timing and dicyandiamide. Soil Sci. Soc. Am. J. 55:130–135. doi:10.2136/sssaj1991.03615995005500010023x

Brooks, P.D., J.M. Stark, B.B. McInteer, and T. Preston. 1989. Diffusion methods to prepare soil extracts for automated nitrogen-15 analysis. Soil Sci. Soc. Am. J. 53:1707–1711. doi:10.2136/sssaj1989.03615995005300060016x

Chua, T.T., K.F. Bronson, J.D. Booker, J.W. Keeling, A.R. Mosier, J.P. Bordovsky, R.J. Lascano, C.J. Green, and E. Segarra. 2003. In-season nitrogen status sensing in irrigated cotton: I. Yield and nitrogen recovery. Soil Sci. Soc. Am. J. 67:1428–1438. doi:10.2136/sssaj2003.1428

Dilz, K. 1988. Efficiency of uptake and utilization of fertilizer nitrogen by plants. In: D.S. Jenkinson and K.A. Smith, editors, Nitrogen efficiency in agricultural soils. Elsevier Applied Science, London, UK. p. 1–26.

Fritschi, F.B., B.A. Roberts, D.W. Rains, R.T. Travis, and R.B. Hutmacher. 2004. Fate of nitrogen-15 applied to irrigated acala and pima cotton. Agron. J. 96:646–655. doi:10.2134/agronj2004.0646

Gitelson, A.A., and M.N. Merzlyak. 1994. Quantitative estimation of chlorophyll using reflectance spectra. J. Photochem. Photobiol. 22:247–252. doi:10.1016/1011-1344(93)06963-4

Hauck, R.D., and J.M. Bremner. 1976. Use of tracer for soil and fertilizer nitrogen research. Adv. Agron. 28:219–266. doi:10.1016/S0065-2113(08)60556-8

Hons, F.M., and B.L. McMichael. 1986. Planting pattern effects on yield, water use and root growth of cotton. Field Crops Res. 13:147–158. doi:10.1016/0378-4290(86)90017-1

Hunsaker, D.J., E.M. Barnes, T.R. Clarke, G.J. Fitzgerald, and P.J. Pinter, Jr. 2005. Cotton irrigation scheduling using remotely sensed and FAO-56 basal crop coefficients. Trans. ASAE 48:1395–1407. doi:10.13031/2013.19197

Hunsaker, D.J., D. El-Shikha, and K.F. Bronson. 2019. High guayule rubber production with subsurface drip irrigation in the USA Desert Southwest. Agric. Water Prod. 220:1–12. doi:10.1016/j.agwat.2019.04.016

Hunsaker, D.J., and D.M. Elshikha. 2017. Surface irrigation management for guayule rubber production in the US desert southwest. Agric. Water Manage. 185:43–57. doi:10.1016/j.agwat.2017.01.015

Hunsaker, D.J., A.N. French, P.M. Waller, E. Bautista, K.R. Thorp, and K.F. Bronson. 2015. Comparison of traditional and ET-based irrigation scheduling of surface-irrigated cotton in the arid southwestern USA. Agric. Water Manage. 159:209–224. doi:10.1016/j.agwat.2015.06.016

Hutmacher, R.B., R.L. Travis, D.W. Rains, R.N. Vargas, B.A. Roberts, B.L. Weir, S.D. Wright, D.S. Munk, B.H. Marsh, M.P. Keeley, F.B. Fritschi, D.J. Munier, R.L. Nichols, and R. Delgado. 2004. Response of recent acala cotton varieties to variable nitrogen rates in the San Joaquin valley of California. Agron. J. 96:48–62. doi:10.2134/agronj2004.0048

Jenkinson, D.S., R.H. Fox, and J.H. Raynor. 1985. Interaction between fertilizer nitrogen and soil nitrogen: The so-called priming effect. J. Soil Sci. 36:425–444. doi:10.1111/j.1365-2389.1985.tb00348.x

Karlen, D.L., P.G. Hunt, and T.A. Matheney. 1996. Fertilizer 15Nitrogen recovery by corn, wheat, and cotton grown with and without pre-plant tillage on a Norfolk loamy sand. Crop Sci. Soc. Am. J. 36:975–981.

Li, H., R.J. Lascano, J. Booker, T. Wilson, and K.F. Bronson. 2001. State-space description of cotton lint yield variability in a heterogeneous soil on a landscape-scale. Soil Tillage Res. 58(3-3):245–258.

MacDonald, B.C.T., Y.F. Chang, A. Nadelko, S. Tuomi, and M. Glover. 2017. Tracking fertilizer and soil nitrogen in irrigated cotton: Uptake, losses and the soil N stock. Soil Res. 55:264–272. doi:10.1071/SR16167

Morrow, M.R., and D.R. Krieg. 1990. Cotton management strategies for a short growing season environment: Water-nitrogen considerations. Agron. J. 82:52–56. doi:10.2134/agronj1990.00021962008200010011x

Norton, E.R., and J.C. Silvertooth. 2007. Evaluation of added nitrogen interaction effects on recovery efficiency in irrigated cotton. Soil Sci. 172:983–991. doi:10.1097/ss.0b013e318158bbf3

Novoa, R., and R.S. Loomis. 1981. Nitrogen and plant production. Plant Soil 58:177–204. doi:10.1007/BF02180053

Oliveira, L.F., P.C. Scharf, E.D. Vories, S.T. Drummond, D. Dunn, W.G. Stevens, K.F. Bronson, N.R. Benson, V.C. Hubbard, and A.S. Jones. 2012. Calibrating canopy reflectance sensors to predict optimal mid-season nitrogen rate for cotton. Soil Sci. Soc. Am. J. 77:173–183. doi:10.2136/sssaj2012.0154

Oosterhuis, D.M. 1990. Growth and development of a cotton plant. In: W.N. Wiley and D.M. Oosterhuis, editors, Nitrogen nutrition in cotton: Practical issues. ASA, CSSA, and SSSA, Madison, WI. p. 1–24.

Plaut, Z., A. Carmi, and A. Grava. 1996. Cotton root and shoot responses to subsurface drip irrigation and partial wetting of the upper soil profile. Irrig. Sci. 16:107–113. doi:10.1007/BF02215618

Post, D.F., C. Mack, P.D. Camp, and A.S. Sulliman. 1988. Mapping and characterization of the soils on the University of Arizona Maricopa Agricultural Center. Hydrol. Water Res. Arizona Southwest 18:49–60.

Rao, A.C.S., J.L. Smith, R.I. Papendick, and J.F. Parr. 1991. Influence of added nitrogen interactions in estimating recovery efficiency of labeled nitrogen. Soil Sci. Soc. Am. J. 55:1616–1621. doi:10.2136/sssaj1991.03615995005500060019x

Rochester, I.J. 2007. Nutrient uptake and export from an Australian cotton field. Nutr. Cycling Agroecosyst. 77:213–223. doi:10.1007/s10705-006-9058-2

Rochester, I.J. 2011. Assessing internal crop nitrogen use efficiency in high-yielding irrigated cotton. Nutr. Cycl. Agroecosyst. 90:147–156. doi:10.1007/s10705-010-9418-9

Rochester, I.J., G.A. Constable, and P.G. Saffigna. 1997. Retention of cotton stubble enhances N fertilizer recovery and lint yield of irrigated cotton. Soil Tillage Res. 41:75–86. doi:10.1016/S0167-1987(96)01081-1

SAS Institute Inc. 2013. The SAS system for Windows version 9.3. SAS Inst., Cary, NC.

Scanlon, B.R., Z. Zhang, R.C. Reedy, D.R. Pool, H. Save, D. Long, J. Chen, D.M. Wolock, B.D. Conway, and D. Winester. 2016. Hydrologic implications of GRACE satellite data in the Colorado River Basin. Water Resour. Res. 51:9891–9903. doi:10.1002/2015WR018090

Torbert, H.A., and D.W. Reeves. 1994. Fertilizer requirements for cotton production as affected by tillage and traffic. Soil Sci. Soc. Am. J. 58:1416–1423. doi:10.2136/sssaj1994.03615995005800050020x

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127–150. doi:10.1016/0034-4257(79)90013-0

Unruh, B.L., J.C. Silvertooth, L.J. Clark, J. Nelson, and J.E. Malcuit. 1993. Upland and pima cotton response to soil and foliar potassium at three Arizona locations. Report no. 370094, Series P_94. College of Agriculture, Univ. of Arizona, Tucson.

Witt, C., A. Dobermann, S. Abdulrachman, H.C. Gines, W. Guangho, R. Nagarajan, S. Satawatanont, T.T. Son, P.S. Tan, L.V. Tiem, G.C. Simbahan, and D.C. Olk. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63:113–138. doi:10.1016/S0378-4290(99)00031-3

Yabaji, R., J.W. Nusz, K.F. Bronson, A. Malapati, J.D. Booker, R.L. Nichols, and T.L. Thompson. 2009. Nitrogen management for subsurface drip irrigated cotton: Ammonium thiosufalte, timing, and canopy reflectance. Soil Sci. Soc. Am. J. 73:589–597. doi:10.2136/sssaj2008.0138

Zelinski, L.J. 1985. Development of a soil nitrogen test for cotton. In: 1985 Proc. Beltwide Cotton Prod. Res. Conf. National Cotton Council of America, Memphis, TN. p. 304–305.

Zhang, H., G. Johnson, B. Raun, N. Basta, and J. Hattey. 1998. OSU Soil test interpretations. Oklahoma Cooperative Extension Service Fact Sheet No. 2225. Oklahoma State Univ., Stillwater.

Zhang, H., B. Raun, and B. Arnall. 2017. OSU Soil test interpretations. Oklahoma Cooperative Extension Service. PSS-2225. Oklahoma State Univ., Stillwater.