Use of Nitrogen Calibration Ramps and Canopy Reflectance on Farmers' Irrigated Cotton Fields

K. F. Bronson*
USDA-ARS
U.S. Arid Land Agric Res Ctr.
21881 N. Cardon Ln.
Maricopa, AZ 85138

T. A. Wheeler
Lubbock Research and Extension Center
Texas AgriLife Research
1102 East FM 1294
Lubbock, TX 79403-6603

C. M. Brown
Lubbock County Office
Texas AgriLife Extension Service
P.O. Box 10536
Lubbock, TX 79408-3536

R. K. Taylor
OSU Stillwater
111 Ag Hall
Biosystems/Agricultural Engineering
Stillwater, OK 74078

P. C. Scharf
University of Missouri
Ag Ext-Plant Sciences
214b Waters Hall
Columbia, MO 65211

E. M. Barnes
Cotton, Inc.
6399 Weston Parkway
Cary, NC 27513

Nitrogen is the main nutrient limiting irrigated cotton (*Gossypium hirsutum* L.) production in the southwestern United States. Canopy spectral reflectance may assess the need for in-season N in irrigated cotton and guide N fertilizer applications. However, calibration of remote sensing indices such as normalized difference vegetative index (NDVI) to the crop's need for N fertilizer is difficult. Well-fertilized reference strips or plots reference NDVI data in the crop area of interest but can result in rank growth and reduced lint yields. Recently, Oklahoma State University developed a calibration procedure of using multiple, sequential, N rate calibration plots, or a ramp approach for wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.). We tested this approach in irrigated cotton fields in Lubbock County, Texas, in 2008 and 2009. The main objective of this research was to test a calibration ramp approach to determining optimum in-season N fertilizer rates in irrigated cotton in West Texas. Near infrared, red, and amber reflectance was measured with active spectroradiometers at 1 m above the canopy. Wide ranges in soil type and irrigation amounts influenced NDVI much more than N fertilizer rate. Normalized difference vegetative index at mid-bloom and at peak bloom were positively related to N fertilizer rate in only one ramp in each year. These two ramp-years also had significant N fertilizer rate response in lint yield. Ramps that did not have mid- or peak bloom NDVI responses to N rate, likewise had no lint yield response to N rate. In both low irrigation- low N input and in high irrigation-high N input farms, in-season NDVI correctly predicted lint yield response to N fertilizer rate.

Abbreviations: aNDVI, amber normalized difference vegetative index; DGPS, differential global positioning system; EONR, economically optimum nitrogen rate; NIR, near infrared; NDVI, normalized difference vegetative index; rNDVI, red normalized difference vegetative index; SDI, subsurface drip irrigation; UAN, urea ammonium nitrate

Improved irrigation technology and cultivar development has led to increased cotton production in the Southern High Plains (SHP) of Texas. Currently about one-third of this region's cotton is in center-pivot irrigation, and nearly 10% in subsurface drip irrigation (SDI) (Colaizzi et al., 2009). Nitrogen fertilizer use efficiency, however is still low (i.e., <50%), especially with ground applications of N in furrow and center-pivot-irrigated fields (Bronson, 2008).

Nitrogen fertilizer recommendations for cotton in the SHP are currently based on associated agronomic N use efficiency factor, a yield goal, and a soil NO_3 credit. In Texas the N use efficiency factor is 0.1 kg N kg lint^{-1} (Lemon et al., 2009) and in Oklahoma it is 0.12 kg N kg lint^{-1} (Zhang et al., 1998). However, there are limitations to this approach. Pre-plant NO_3 availability may change between soil sampling and the mid-season peak N demand period. Planting dates, weather

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*Corresponding author (Kevin.bronson@ars.usda.gov).

conditions and soil N mineralization are unpredictable and the in-season plant development may or may not match the pre-season N fertilizer recommendations. To this end, in-season canopy reflectance has great potential to assess N status and guide in-season N fertilization. This is especially true on the center pivot and SDI systems that allow N fertigation. Petiole-NO_3 analysis is common in the western United States for in-season N assessment of cotton, but it is time-consuming, highly variable and has a several-day turnaround (Bronson et al., 2001).

Several field plot studies in West Texas used canopy reflectance based indices to assess in-season N status of cotton in SDI, and center-pivot fields in the SHP (Li et al., 2001; Chua et al., 2003; Bronson et al., 2003a, 2005, 2011; Yabaji et al., 2009). Reflectance-based N management was tested and resulted in less N fertilizer use than the regional soil test-yield goal based N management, without hurting yields (Chua et al., 2003; Yabaji et al., 2009; Bronson et al., 2011). Previous studies in corn on the use of canopy reflectance to assess in-season N status reported that a well-fertilized reference plot or strip is mandatory to compare reflectance in the area of interest to (Varvel et al., 1997; Solari et al., 2008; Scharf and Lory, 2009;). Typically reflectance data is converted to an index, such as the NDVI. Tucker (1979) proposed NDVI as $(R_{NIR} - R_{red})/(R_{NIR} + R_{red})$, where R_{NIR} and R_{red} are reflectance in near infrared (NIR) and in the red regions, respectively. When the ratio of NDVI in the area or plot to be managed to the NDVI in the well-fertilized area falls below 0.95, this "sufficiency index" indicates N deficiency that an immediate N application can rectify. The sufficiency index was first proposed by Peterson et al. (1993) for use with a chlorophyll meter in corn, but has been used in other crops as well such as rice (Hussain et al., 2000). Previous West Texas cotton studies also used a well-fertilized reference (Chua et al., 2003) and then the regional soil test-yield goal recommendation (Yabaji et al., 2009; Bronson et al., 2011) as the reference in calculating a sufficiency index.

Research in Oklahoma with wheat focused on the use of a "response index" to guide reflectance-based in-season N fertilizer applications (Mullen et al., 2003). The response index was defined as $NDVI_{high\ N\ plot}/NDVI_{zero\text{-}N\ plot}$, and this was related to a response index of grain yield, or $Yield_{high\ N\ plot}/Yield_{zero\text{-}N\ plot}$. To estimate the response index on farmers' fields, the Oklahoma State University researchers moved beyond a single high, well-fertilized reference plot and implemented a "calibration stamp" approach (Raun et al., 2005). The N calibration stamp consisted of a nine m^2 grid with nine, 1-m^2 areas where N fertilizer was sprayed as urea ammonium nitrate near planting at rates of 0 to 112 kg N ha^{-1}. Besides calibrating reflectance indices to assess N fertilizer needs at Feekes 6, the N calibration stamp served as a visual tool for farmers to compare with their N fertilizer practice.

One of the limitations of the calibration stamp was its small size, which made characterizing N response in large fields difficult. To that end, Oklahoma State University researchers next developed a "ramp calibration strip" approach (Raun et al., 2008). Ramp calibration strips consist of 2-m or wider strips of 16 N fertilizer rates (e.g., 0–220 kg N ha^{-1}) in 3 to 6-m steps, applied near planting.

One major assumption in both the N calibration stamp and the N calibration strip approaches is that in-season biomass estimated by NDVI is related to corn or wheat yield. In the indeterminate cotton crop, this is often not the case, as excess water and N can lead to rank top growth, without added lint yield. The high number of N rates, including rates greater than optimum, may mean the ramp calibration strip could be a useful method to calibrate in-season reflectance data in irrigated cotton, especially in large-scale producer fields.

The objectives of this study were to:

1. Establish N fertilizer calibration ramps in farmers' irrigated cotton fields to determine the economically optimum N fertilizer rate (EONR) for lint production on a per-field basis.
2. To use NDVI from canopy reflectance of N fertilizer calibration ramps (same as in objective 1) to estimate in-season N fertilizer requirements, EONR, and lint yield.

MATERIALS AND METHODS

Eleven N fertilizer calibration ramps (each replicated twice, end-to-end) were established shortly after cotton planting in the last 2 wk of May 2008 on three producer fields in Lubbock County, Texas. These included furrow-irrigated, center-pivot, and SDI fields (Table 1). For the pivots and drip systems we tried to locate some fields where the producer does not inject N fertilizer with the irrigation water. In most cases, however, N fertilizer in drip and pivots is injected, but we still tested the utility of the N ramp approach in addition to the farmers' N fertigation program. Only in the zero-N plots of farmer A's ramps in 2008 was no N fertilizer added at all. In May 2009 we repeated the N calibration ramp applications on 11 sites in Lubbock County (same exact locations) and we added a 12th 2009 ramp on farmer D's fields (Table 1). As in 2008, each ramp was duplicated. Planting in 2009 ranged from 2 to 16 May, which is the optimum period for the region.

Soil sampling for extractable NO_3–N from 0 to 90 cm was done in March of 2008 and 2009 in each cooperating producer's field. A Giddings soil-sampling machine (Giddings Inc., Fort Collins, CO) was employed to sample from 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths at four points separated by 50 m across the two duplicate ramps. Two cores were sampled per point and the samples from each depth were combined to form a composite sample. Soil samples were air-dried, extracted with 1 M KCl, and analyzed for NO_3–N with a colorimetric method (Adamsen et al., 1985). Soil core bulk density was used to calculate mass of NO_3–N per area from mass of NO_3–N per kg soil.

Nitrogen fertilizer was applied 2 to 4 wk after planting with a four-row ground applicator, retro-fitted with commercially available variable-rate equipment. This included a Dickey John Land Manager I flow controller (Dickey John Corp., Auburn, IL), a Dickey John servo-valve, a Micro-Trak flow meter (Micro-Trak Systems Inc., Eagle Lake, MN), an Ag-Chem ground speed radar (Ag-Chem Equipment Co., Inc., Minnetonka, MN), and a submeter accurate SATLOC SLX differential global positioning system (DGPS) receiver (SATLOC Inc., Scottsdale, AZ). Site-mate software (Farm Works Software Inc., Hamilton, IN) was used to create a prescription map for each ramp (Fig. 1). Nitrogen calibration ramps consisted of 16 steps of N rates that were 4 m wide by 96 m long strips. Nitrogen fertilizer rates varied sequentially from 22.4 to 179 kg N ha^{-1} in 11.2 kg N ha^{-1} steps. The first step was zero-N rate, and we did not apply an 11.4 kg N ha^{-1} step. The length of each ramp step was 6 m. Duplicate (end-to-end) ramps were applied in each field. Urea ammonium nitrate (320 g N kg^{-1}) fertilizer was knifed-in 10 cm aside of the row of cotton plants (2 true leaf stage) and 10-cm deep. Figure 1 shows examples of the duplicate N calibration ramps on center-pivot and SDI fields of farmer A. The targeted N fertilizer rate in the N calibration ramps and the "as-applied" (as recorded by the flow controller) rates matched well, with an R^2 of 0.96 and a slope of 0.98 for 2008 (Fig. 2). This was a satisfactory result, considering the short, 6-m-long N rate steps. The lack of a better match was due to the short response time of the servo-valve changing rates between ramp steps.

Table 1. 2008 and 2009 Nitrogen calibration ramp descriptions: soil type, variety, and irrigation type.

Ramp no.	Farmer	Soil type	Cultivar	Irrigation
1	A	Portales clay loam (Aridic Calciustoll)	FM 9180	Center-pivot
2	A	Portales clay loam	FM 9180	Subsurface drip
3	A	Acuff loam (Aridic Paleustoll)	FM 9180	Center-pivot
4	A	Olton clay loam (Aridic Paleustoll)	FM 9180	Center-pivot
5	A	Amarillo sandy loam (Aridic Paleustalf)	FM 9058	Furrow
6	A	Amarillo fine sandy loam	FM 9058	Furrow
7	B	Estacado clay loam (Aridic Paleustoll)	FM 9180	Center-pivot
8	C	Pullman clay loam (Torrertic Paleustoll)	FM 989	Subsurface drip
9	C	Pullman clay loam	FM 9063	Subsurface drip
10	C	Pullman clay loam	MG 3538	Furrow
11	C	Pullman clay loam	FM 9180	Subsurface drip
12†	D	Estacado loam and Olton clay loam	FM 9180	Subsurface drip

† Note: Ramp 12 was in 2009 only.

Canopy reflectance was measured at mid- and peak bloom stages (late July or ~60 d after planting, and mid-August or about 90 d after planting, respectively) using the active spectroradiometers Crop Circle ACS-210 (Holland Scientific Inc., Lincoln, NE) and a GreenSeeker spectroradiometer (NTech Industries, Ukiah, CA). The radiometers were connected to the SATLOC SLX DGPS via a HP IPAQ Pocket PC H3835 and held at 1 m above the canopy as the operator walked the length of each ramp. Ten readings from each spectroradiometer were taken every second, but these were averaged to the second to match the DGPS acquisition rate. The Crop Circle's and GreenSeeker's NIR light sources are at 880 and 770 nm, respectively. The visible light source in the Crop Circle is at 590 nm (amber) and the GreenSeeker's visible light source is at 660 nm (red). Red NDVI (rNDVI) and amber NDVI (aNDVI) were calculated as:

$$(R_{NIR} - R_{red\ or\ amber})/(R_{NIR} + R_{red\ or\ amber})$$

where R_{red} and R_{amber} are reflectance in red and the amber regions, respectively.

Cotton was entirely managed by the farmers. This included occasional early season glyphosate applications for weed control, but no growth regulators or insecticides were applied.

Cotton was harvested in October of both years with a John Deere 7445 cotton stripper, fitted with a burr extractor, SATLOC SLX DGPS, and an Agriplan AG700 cotton yield monitor (AGRIplan, Stow, MA). One grab sample was taken at random from each ramp for ginning.

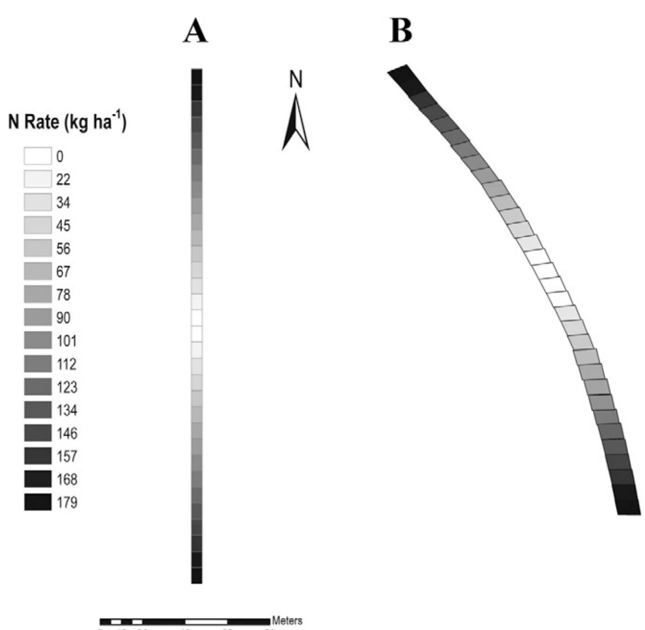

Fig. 1. Examples of prescription maps for N calibration ramps, Lubbock County, Texas, 2008. (A) Ramp 2 in subsurface drip-irrigated field of farmer A and (B) ramp 3 in center-pivot-irrigated field of farmer A.

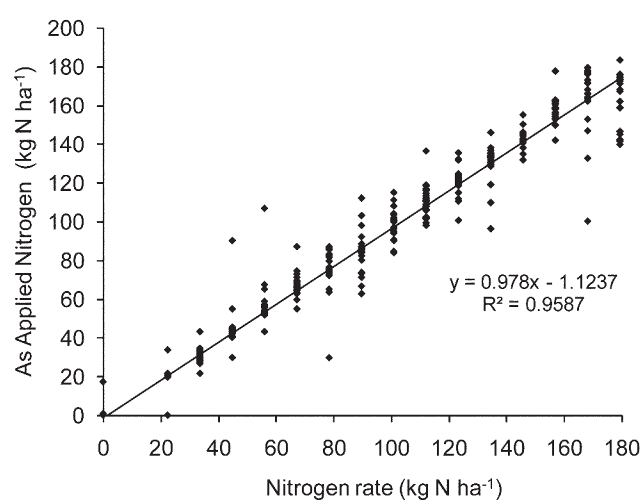

Fig. 2. As-applied N fertilizer vs. target N rates in 11 N calibration ramps, Lubbock County, Texas, 2008.

Statistical Analysis

Single lint percentage turnout of the seed cotton was determined from the ginned grab sample and used to convert seed cotton to lint for each ramp. A "spatial joining" of the yield data and the as-applied N fertilizer data was performed with ArcMap 9.2 (ESRI, 2006). Analysis of variance was performed for each ramp-year for the lint yield and NDVI data using PROC MIXED (SAS Institute, 2008). Replicate (two) was considered a random effect, and N rate was fixed. If the *F* test in the ANOVA for N rate was significant at the $P < 0.05$ level, then PROC REG was used to regress lint yield on N rate using a quadratic model. We also used PROC REG to regress NDVI vs. lint yield and NDVI vs. N rate for each growth stage-year combination (i.e., pooled across all ramps). The EONR was calculated by setting the first derivative of the quadratic regression model of lint yield vs. N rate to a N fertilizer to cotton lint price ratio of 0.91 (\$1.1 kg N^{-1}/\$ 1.21 kg $lint^{-1}$) and solved for N rate (Cerrato and Blackmer, 1990). We also estimated optimum N rate for maximum NDVI by setting the first derivative of quadratic regressions of aNDVI and rNDVI vs. N rate to zero, and solving for N rate.

RESULTS

Farmers' Practice, Lint Yields, and Lint Yield Response to Nitrogen Fertilizer

2008

Pre-plant soil profile NO_3 (0–60 cm) ranged from 34 to 103 kg N ha^{-1} (Table 2). Farmers A and B did not apply N fertilizer in 2008, due to the record high prices of fertilizer that year. Farmer C on the other hand, applied 187 to 219 kg N ha^{-1} in 2009, mostly though fertigation (Table 2). All farmer N fertilizer applications on ramps in 2008 and 2009, used urea ammonium nitrate (320 g N kg^{-1}). All pre-plant N fertilizer was knifed-in the side of the 0.8- to 1-m wide beds, as was in-season N applications to the furrow-irrigated fields. All in-season N fertilizer applied to SDI and center-pivot fields was fertigated, that is, injected with irrigation water.

Irrigation amounts were much greater with farmer C than farmer A or B. Visually, cotton in the ramps in Farmer C's fields was large and green due to the high irrigation and N fertilization. Farmer A's plant height was much shorter than the plants in farmer C's fields (No plant height measurements were made). Farmer B's mid-season plant growth was intermediate to that of farmers A and C.

Thirty-nine centimeters of in-season rain in 2008 resulted in good yields in most ramps, even in Farmer A's ramps that received no N and little irrigation (Table 2). Lint yields among the ramps in 2008 reflected the N and irrigation inputs, as well as pre-plant soil NO_3 (Table 2). With the exception of ramp 10, which was in a furrow-irrigated field that received far less water than the other fields, lint yields on farmer C's fields were very high, ranging from 1410 to 2591 kg ha^{-1} (Table 2). Farmer A's yields were variable, with the highest-yielding ramp being ramp 4 (on a center-pivot), which had 103 kg pre-plant soil NO_3–N ha^{-1}. Farmer B's lint yield on center-pivot ramp 7 in 2008 was 1661 kg lint ha^{-1}, which may have been due in part to 92 kg pre-plant soil NO_3–N (Table 2).

Lint yields in 2008 showed very large, low to high variation within each ramp-N fertilizer rate among the 11 ramps (Fig. 3A). The lower yields across N rates reflected the lower irrigation inputs, poorer soils, and lower farmer N fertilizer inputs from, for example, farmer A's fields. In 2008, lint yields responded significantly ($P < 0.05$) to N rate in ramp 1 only. This was one of farmer A's center-pivot fields that received no N fertilizer and only 13 cm of irrigation (Table 2). Soil type was apparently an important factor in controlling yields. The Estacado soil type on ramp 1 is a SHP soil that has low water holding capacity and generally produces less cotton than Amarillo soils (Bronson et. al., 2003b).

The Pullman soils of farmer C have higher organic matter, CEC, and water holding capacity than Estacado or Amarillo

Table 2. 2008 Nitrogen calibration ramp: pre-plant soil nitrate, farmer N management, and average lint yields.

Ramp no.	Farmer	Soil NO_3–N (0–60 cm)	Pre-plant N applied	In-season N fertigation	Pre-plant and in-season irrigation	Mid-bloom aNDVI	Mid-bloom rNDVI	Peak bloom aNDVI	Peak bloom rNDVI	Average lint yield
		——kg N ha^{-1}——			cm	—— *F* test for N rate——				kg ha^{-1}
1	A	76	0	0	13.2	*	**	**	**	1219**
2	A	76	0	0	18	ns†	ns	ns	ns	978
3	A	56	0	0	14.5	ns	ns	ns	ns	nd‡
4	A	103	0	0	14.5	ns	ns	ns	ns	1528
5	A	65	0	0	13.7	ns	ns	ns	ns	1056
6	A	67	0	0	13.7	ns	ns	ns	ns	620
7	B	92	24	0	20.3	ns	ns	ns	ns	1661
8	C	62	25	162	61.2	ns	ns	ns	ns	2591
9	C	62	34	185	71.3	ns	ns	ns	ns	2180
10	C	83	34	185	19.5	ns	ns	ns	ns	1174
11	C	34	34	185	61.7	ns	ns	ns	ns	1410

* Significant N fertilizer rate response at $P < 0.05$.

** Significant N fertilizer rate response at $P < 0.01$.

† ns is not significant at $P = 0.05$.

‡ nd is no data.

soils. Soil test nitrate N (0– 60 cm) averaged 65, and 60 kg NO_3–N ha^{-1} in farmer A and farmer B's fields, respectively.

2009

Soil test nitrate N (0-60 cm) was slightly reduced in spring 2009 compared to spring 2008, with the exception of ramp 10 (Table 3). Farmer A irrigated slightly more, and farmer C slightly less than in 2008. In-season rain was only 6.1 cm in 2009, and this resulted in lower yields than in 2008 in farmer A, B, and C's ramps. Similar to 2008, the furrow-irrigated fields were watered less and yielded less than the center-pivot and drip-irrigated fields. Farmer A applied more N fertilizer than in 2008 and farmer C applied less. Lint yield responded to N fertilizer rate in 2009 only on the new, farmer D ramp 12 in SDI (Table 3, Fig. 3B). Wide low to high variation in lint yields in 2009 were similar to that of 2008.

In-season Normalized Difference Vegetative Index and Nitrogen Fertilizer Rate

At mid-bloom in 2008, aNDVI and rNDVI showed little response to N rate, with the exception of a weak response of rNDVI in ramp 1 (Fig. 4). Peak bloom in 2008 showed both aNDVI and rNDVI responding to N rate in ramp 1 in a similar manner (data not shown). There was large variability in NDVI among the ramp-N step combinations with NDVI ranging from 0.25 to 0.85 at mid-bloom. This reflected that same kind of variation in lint yields among soil types, and farmer inputs.

Mid-bloom NDVI in 2009 exhibited the same large variability observed in 2008, and an N rate response was observed only on farmer D's SDI ramp 12 (data not shown). At peak bloom in 2009 ramp 12 again showed significant N rate response (data not shown) with R^2 values of 0.88 and 0.82 for aNDVI and rNDVI, respectively. Amber-NDVI appeared to be more responsive to the lower N fertilizer rates at peak bloom, with a steeper linear response (data not shown). It was surprising that few ramps in 2009 had NDVI responses to N rate. We expected more ramps with NDVI responding to N rate, since pre-plant soil NO_3 was lower than in 2008.

In-season Normalized Difference Vegetative Index and Lint Yield

In contrast to the weak NDVI-N fertilizer rate relationships, significant regressions were observed for mid-bloom aNDVI, and rNDVI and lint yield as well as peak bloom NDVI and lint yield across all ramps in both 2008 (R^2s of 0.59–0.68, Fig. 5) and in 2009 (R^2s of 0.42–0.50, Fig. 6). Greater R^2 values in the wetter year of 2008 suggest better ability of NDVI to estimate yields in wet years. Strong NDVI-yield and weak NDVI-N rate correlations indicate that N was a minor factor affecting lint yields in these farmers' fields, compared to the varying soil types and irrigation amounts discussed earlier. Bronson et al. (2003a) also reported good correlation between peak-season NDVI from canopy reflectance and lint yield. Similar to that work, the R^2s improved between mid- and peak bloom. Figure 6 indicates that

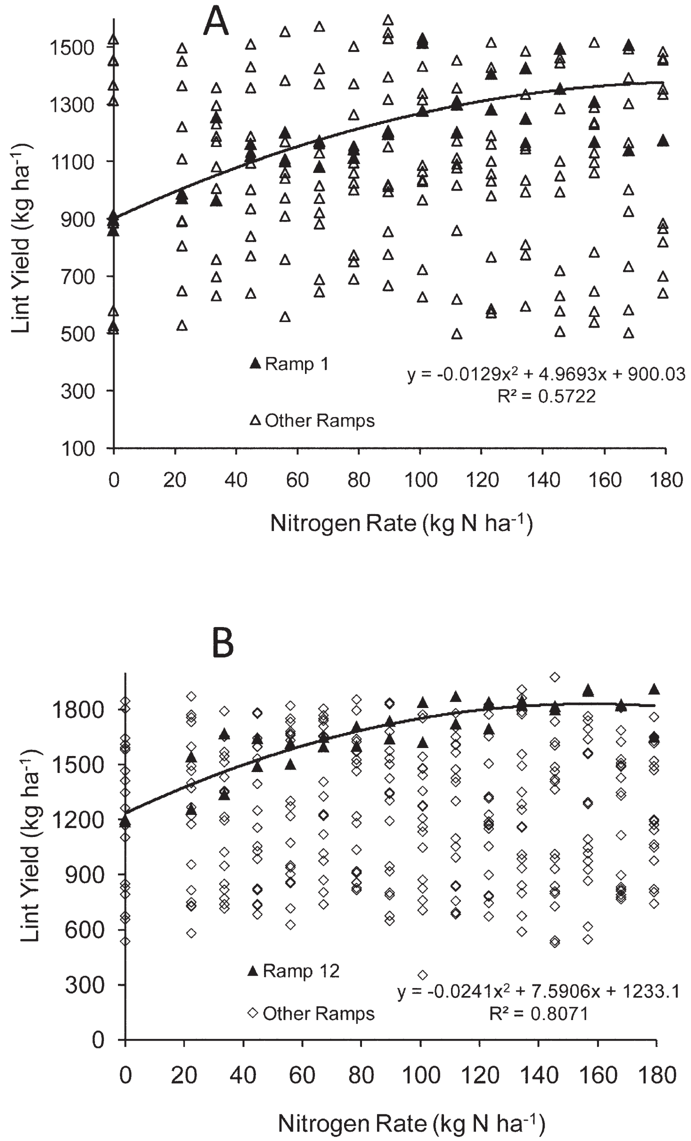

Fig. 3. Lint yield vs. calibration ramp N fertilizer rate, Lubbock County, Texas, (A) 2008 and (B) 2009.

NDVI did not increase appreciably between mid-bloom and peak bloom in 2009, as was observed in the high rainfall season of 2008 (Fig. 5). This reflected a slower rate of biomass development in the low rainfall season of 2009.

DISCUSSION

Lint yield was largely unresponsive to N fertilizer rate among the 23 ramp-year combinations (Tables 2 and 3). The exceptions were a center-pivot ramp (1) in 2008 and a SDI ramp (12) in 2009. Other researchers have reported the difficulty of measuring N fertilizer response at large- scale farmer fields or in landscape-scale researcher fields (Bronson et al., 2006; Scharf et al., 2006). Lack of N fertilizer rate response was surprising, given the relatively low pre-plant soil NO_3 levels in both years. Hutmacher et al. (2004) reported that furrow-irrigated cotton in California responded to N fertilizer if 0 to 60 cm soil NO_3–N was <70 kg N ha^{-1} (9 of 17 sites). Furthermore with irrigated cotton, recovery efficiency of N fertilizer decreases by irriga-

Table 3. 2009 Nitrogen calibration ramp: pre-plant soil nitrate, farmer N management, and average lint yields.

Ramp no.	Farmer	Soil NO_3–N (0–60 cm)	Pre-plant N applied	In-season N fertigation	Pre-plant and in-season irrigation	Mid bloom aNDVI	Mid bloom rNDVI	Peak bloom aNDVI	Peak bloom rNDVI	Average Lint yield
		———	kg N ha^{-1}	———	cm	———	*F* test for N rate		———	kg ha^{-1}
1	A	34	22	45	20.3	ns†	ns	ns	ns	nd‡
2	A	31	0	45	25.4	ns	ns	ns	ns	1254
3	A	20	22	45	20.3	ns	ns	ns	ns	nd
4	A	56	22	45	20.3	ns	ns	ns	ns	1146
5	A	27	0	67	10.1	ns	ns	ns	ns	771
6	A	40	0	67	10.1	ns	ns	ns	ns	762
7	B	35	22	45	20.3	ns	ns	ns	ns	1399
8	C	43	29	112	35.6	ns	ns	ns	ns	1597
9	C	32	29	112	43.2	ns	ns	ns	ns	1701
10	C	96	0	112	15.2	ns	ns	ns	ns	952
11	C	27	29	112	43.2	ns	ns	ns	ns	1620
12	D	21	63	58	43.2	**	**	**	**	1668**

** Significant N fertilizer rate response at $P < 0.01$.
† ns is not significant at $P = 0.05$.
‡ nd is no data.

tion system in the order SDI > center-pivot > furrow irrigation (Bronson, 2008). Super-imposing the N calibration ramp on the farmers' existing N management practice as recommended by Raun et al. (2008) needs to be reconsidered.

Red NDVI and aNDVI at mid- and peak bloom showed wide variation, presumably due to spatial variation in plant biomass and N status, largely unrelated to the N fertilizer rates applied in the ramps. Bronson et al. (2011) reported that both aNDVI and rNDVI were strongly correlated to cotton leaf N at mid-bloom and only weakly related to cotton biomass. The quadratic relationships among aNDVI, rNDVI and lint yield were similar. Differences in the magnitudes of the aNDVI and

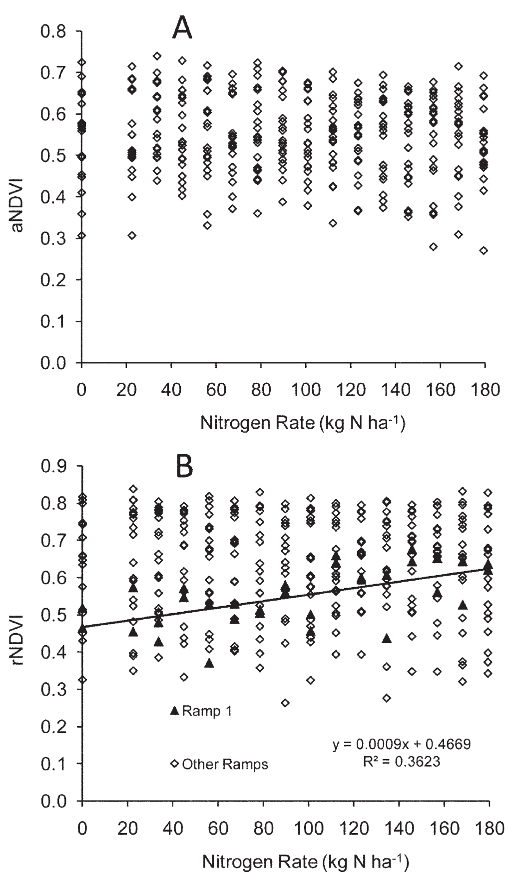

Fig. 4. (A) Amber normalized difference vegetative index (aNDVI) and (B) red normalized difference vegetative index (rNDVI) vs. N fertilizer rate at mid-bloom, Lubbock County, Texas, 2008.

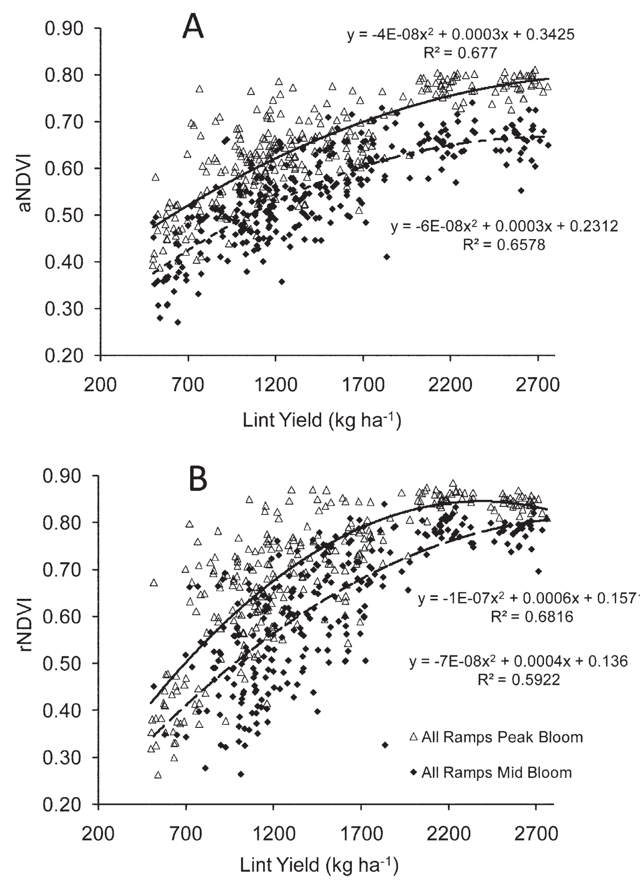

Fig. 5. (A) Amber normalized difference vegetative index (aNDVI) and (B) red normalized difference vegetative index (rNDVI) vs. lint yield at mid and peak bloom for 11 ramps, Lubbock County, Texas, 2008.

rNDVI are due to the differing wavelengths and the field of view (Bronson et al., 2011). There was a trend of the rNDVI to plateau at high yields. The aNDVI did not show this trend. This may be due to saturation of the rNDVI in large, green plant canopies, while a green NDVI (Gitelson et al., 1996) or aNDVI does not saturate (Bronson et al., 2011).

In-season NDVI response to N fertilizer rate mirrored lint yield response to N rate in all 23 ramp-year combinations. With the exception of the three furrow-irrigated fields, the farmers had the ability to fertigate N fertilizer during or after the mid- to peak bloom reflectance sampling period. The results indicate that if the farmers had used in-season NDVI to guide subsequent N fertilization, the reflectance data correctly called for no additional N in all cases but ramp 1 in 2008 and ramp 12 in 2009. The significant NDVI N rate responses in those two ramps could have been used as indicators to continue N fertigations for additional lint yield. Farmer A, therefore, would have benefited from applying/fertigating additional N in the ramp 1 center-pivot field in 2008. Farmer D correctly injected additional N (58 kg N ha^{-1}) between mid- and peak bloom to SDI ramp 12 in 2009. The apparent predictions of lint yield response to in-season N fertilizer with mid- to peak bloom NDVI was despite the N calibration ramps being super-imposed on the farmers practice, and the wide range of irrigation and N fertilizer inputs among the farmers.

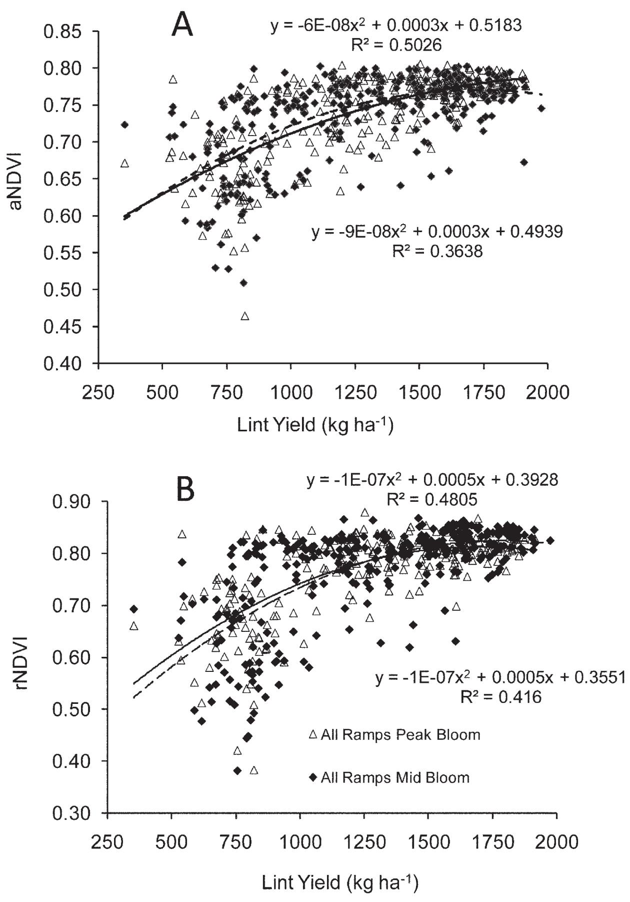

Fig. 6. (A) Amber normalized difference vegetative index (aNDVI) and (B) red normalized difference vegetative index (rNDVI) vs. lint yield at mid and peak bloom for 12 ramps, Lubbock County, Texas, 2009.

We also calculated EONR for lint yield data and optimum N rate for NDVI in the two-ramp years where significant N fertilizer rate response was observed. Amber NDVI at peak bloom in ramp 1 in 2008 had an optimum N rate of 150 kg N ha^{-1} (data not shown). This N rate was well below the EONR of 192 kg N ha^{-1} calculated for ramp 1 lint yield in Fig. 3A. The Texas A&M University recommendation for ramp 1 in 2008 was just 64 kg N ha^{-1}. This was calculated by multiplying the 0.1 kg N kg $lint^{-1}$ efficiency factor (Lemon et al., 2009) by grower A's 1400 kg lint ha^{-1} yield goal (140 kg N ha^{-1}) and subtracting 76 kg NO_3–N ha^{-1} in the 0- to 60-cm pre-plant soil (Table 2). For SDI ramp 12 in 2009, optimum N rate for aNDVI was 130 and 143 kg N ha^{-1} at mid- and peak bloom, respectively (data not shown). Red NDVI optimum N rate (150 kg N ha^{-1}) for both mid- and peak bloom, (data not shown) corresponded very well with EONR for lint yield in the SDI ramp 12 in 2009, which was 156 kg N ha^{-1} (Fig. 3B). These N rates are also very similar to the Texas A&M recommendation of 147 kg N ha^{-1}. This university N recommendation used grower D's 1680 kg lint ha^{-1} yield goal and 21 kg NO_3–N ha^{-1} in pre-plant soil test (Table 3). This last result confirms the potential for rNDVI to estimate N fertilizer needs for SDI irrigated cotton at mid-bloom. Although we report relationships between NDVI and N rate at peak bloom (and with peak bloom NDVI and lint yield), peak bloom is too late to apply N in the SHP to cotton. Yabaji et al. (2009) reported that N fertigation as late as peak bloom did not benefit cotton yields and that the N application window ended at mid-bloom.

Implementing the ramp calibration concept to farmers fields needs further testing. Extrapolating the data from a narrow (i.e., 4-m wide) ramp to the entire farmer's field is not ideal. The length of two end-to-end ramp sets of 192 m is an advantage for extrapolation to the entire field. Perhaps calibration ramps should not be duplicated end-to-end, but be separated by a large distance in order to better represent the fields, which in this study ranged from 20 to 50 ha in size.

Although this study focused on N management, the strong relationships between NDVI and lint yield implies some crop management uses of canopy reflectance besides N fertilizer. These potentially include in-season applications of growth regulators and end-of-season harvest aids (Porter et al., 2011).

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