Canopy-Based Normalized Difference Vegetation Index Sensors for Monitoring Cotton Nitrogen Status

Tyson B. Raper, Jac J. Varco,* and Ken J. Hubbard

ABSTRACT

Crop reflectance using ground-based sensors has the potential to provide information on crop N status in real-time. However, the unique physiological and structural characteristics of cotton (Gossypium hirsutum, L.) complicate normalized difference vegetation index (NDVI)-based inferences on cotton N status. Therefore, the objectives of this study were to (i) determine the sensitivity of selected sensors and resulting NDVI measurements to different levels of fertilizer N; (ii) determine relationships between sensors and biophysical measurements; and (iii) compare absolute NDVI readings reported by each sensor. Field trials were conducted during crop years conducted from 2008 through 2010 at Mississippi State, MS. Fertilizer N rates of 0, 45, 90, and 135 kg N ha⁻¹ were applied and replicated four times to establish N-induced growth differences. Sensors used included the Yara N Sensor (Yara International ASA, Oslo, Norway), GreenSeeker (GS) Model 505 Optical Sensor Unit (N'Tech Industries, Inc., Ukiah, CA) and Crop Circle (CC) Model ACS-210 (Holland Scientific, Inc., Lincoln, NE). Sensor readings failed to consistently predict cotton leaf N status before early flowering; however, plant height relationships with NDVIs were strong. Comparison of sensor response curves to fertilizer N resulted in no significant differences in slope values, although consistent, significant differences in y-intercepts were noted beginning at early flowering and continuing through peak flowering. Greater accuracy in the detection of cotton leaf N status may require the utilization of an index which is less responsive to changes in plant height or canopy architecture. Furthermore, the magnitude of canopy reflectance-based NDVI values differed across sensors.

High spatial and temporal variability of soil nitrate (NO₃⁻⁻) in the southeastern United States complicates efficient measurement of in-season cotton N status using conventional sampling and testing methods (Breitenbeck, 1990). Furthermore, a fertilizer N application which fails to match cotton demand can have significant physiological, environmental, and financial implications (Wadleigh, 1944; Maples and Keogh, 1971; Boquet and Breitenbeck, 2000). Dense, efficient in-season field indicators are needed to more accurately and precisely monitor cotton growth and health across spatially variable production fields to assist in variable rate nitrogen applications (VRN).

Visual cotton N deficiencies have been associated with a shift in leaf color from dark green to light green (Nelson, 1949). This contrast in color coupled with many other physiological changes in leaf and plant structure measured through crop reflectance using multi- and hyper-spectral instruments has proven to be a strong indicator of cotton leaf N status (Read et al., 2002; Buscaglia and Varco, 2002; Fridgen and Varco, 2004; Zhao et al., 2005). However, NDVI readings have on occasion been described as insensitive to changes in cotton leaf N status (Li et al., 2001; Bronson et al., 2003, 2005). This may in part be due to the ability of N to translocate from older, lower leaves to meristematic regions or younger leaves in response to N stress, or due to biomass sensitivity of the index. Translocation of N to upper canopy leaves is problematic from a canopy sensing standpoint as these tissues comprise a large portion of canopy reflectance (Maas, 1997). Still, current sensor technology offers a greater level of deficiency detection than the naked eye, from which N deficiencies have often been identified. Extremely dense, instantaneous readings easily acquired by ground-based sensors have already driven successful VRN applications in several other crops (Samborski et al., 2009). Increased nitrogen use efficiency (NUE) and decreased environmental impacts associated with sensor driven VRN in other crops has kept interest in the adoption of this technology for cotton production.

Cotton plant height has been shown to be a good indicator of cotton health, and is often correlated with fertilizer N rates; thus, it may serve as an easily measured proxy indicator of N availability (Oosterhuis et al., 1983; Wallenschleger and Oosterhuis, 1990). Still, several other seasonal parameters such as water (Grimes et al., 1969; Scarsbrook et al., 1959), amount of applied K fertilizer (Bennett et al., 1965; Fridgen and Varco, 2004), and soil type (Gerard and Cowley, 1963) have been shown to influence this parameter. Leaf N response to fertilizer

Abbreviations: CC, Crop Circle; GS, GreenSeeker; NDVI, normalized difference vegetation index; NIR, near infrared; NUE, nitrogen use efficiency; VRN, variable-rate fertilizer N application.
N has been thoroughly described as early as 1944 (Wadleigh, 1944). At first flower, roughly 60% of the total plant N is contained in the leaf blades. Much of this N is translocated to fruiting bodies as bolls begin to develop, but by harvest, 28% is still contained in the leaf blades, making leaf N the second largest N-containing component at maturity (Mullins and Burmester, 1990). Leaf N is considered to be a good indicator of in-season cotton N status (Gerik et al., 1998). The utility of cotton leaf N analysis was most recently demonstrated in a multi-state study (Bell et al., 2003). Strong correlations of a reflectance index to leaf N, from a site-specific N management standpoint, are therefore desirable.

A limited number of studies have examined differences between NDVI sensors. Tremblay et al. (2009) compared NDVI values of the nadir, active GreenSeeker to the passive, off-nadir Yara N-Sensor/Fieldscan in wheat (Triticum aestivum L.) and corn (Zea mays L.). Results indicated the Yara N-Sensor and the GreenSeeker reported similar NDVI values in corn before saturation of the N-Sensor field of view. Also, reported NDVI readings from the GS in wheat were more variable than the Yara N-Sensor readings. The authors suggested noted differences may have been attributed to leaf angle and wind conditions. Furthermore, it was concluded that VRN algorithms developed with one sensor are not generally applicable to other sensor technology (Tremblay et al., 2009).

In a similar study, Sudduth et al. (2010) examined the GreenSeeker, Crop Circle, and TopCon CropSpec (Topcon Precision Agriculture, Mawson Lakes, SA, Australia) against a range of N availability for corn. Readings between the nadir, small-footprint GS and CC were strongly correlated. These two sensors were more sensitive to changes in crop height and were less stable than the CropSpec. Furthermore, the off-nadir, large footprint CropSpec was more strongly correlated to SPAD readings and leaf N content (Sudduth et al., 2010). Other research has also noted advantages of off-nadir angled viewing sensors as compared to nadir sensors (Mistele and Schmidhalter, 2010).

Before on-the-go canopy reflectance sensors can be used effectively to drive VRN applications in cotton, relationships between NDVI derived from differing sensors and biophysical parameters of cotton must be more accurately defined and compared. The objectives of this study were to determine the sensitivity of selected NDVI sensors to varying fertilizer N supply, determine relationships between sensors and biophysical measurements, and to compare absolute NDVI readings from each sensor.

**MATERIALS AND METHODS**

A 0.75 ha trial was conducted at the W.B. Andrews Agricultural Systems Research Center (33°28′13.5″N, 88°45′48.0″W) at Mississippi State, MS, during the 2008–2010 growing seasons. Each of 16 plots consisted of 12 rows at a spacing of 96.5 cm and a length of 38.1 m. Four sublocation points were geo-referenced in each plot with two points located on both Rows 3 and 10. Canopy sensing and plant sampling were conducted within 4.6 m of sublocation points to standardize sensed areas across sensors. An early- to mid-maturity DeltaPine cultivar was planted in each year of the study (DPL 445 BG/RR in 2008 and 2009, DPL 1028 BG/RRflex in 2010) at a rate of 14.1 seeds per m. Sufficiently large beds were present from the 2007 growing season, so no-tillage culture was used in 2008 and 2009. Due to areas of compaction from tire tracks on the beds following cotton stalk shredding in the fall of 2009, the whole area was tilled with an in-row subsoiler equipped with middle busters to make beds. Before planting in 2010, a spike tooth harrow equipped with a rolling chopping blade and a leveling board was used to groom the beds. Insects and weeds were controlled in accordance with guidelines of the Mississippi State Extension Service (Mississippi State University Extension Service, 2008a, 2008b). Furrow irrigation was used on a limited basis, only when visible water stress was observed. These management practices were implemented to assure a healthy crop with N as the primary response factor. Cultural practice dates (Table 1) varied with seasonal growing conditions from year to year. No plant growth hormones were applied to control plant height for any of the years studied.

Treatments consisted of a 50/50 split application of urea–ammonium nitrate (UAN 32%) fertilizer solution for a total N application of 0, 45, 90, and 135 kg ha⁻¹ during the growing season. The first application was made shortly after planting and the side-dress application was made at early squaring. Application dates are listed in Table 1. Fertilizer N was metered through a four-row peristaltic pump unit to ensure an accurate and precise application rate to each row. The applicator was equipped with liquid application knives attached to coulters spaced 23 cm away from one side of each row at a depth of 5 cm. Each fertilizer N rate treatment was replicated four times and treatments were arranged in a randomized complete block design. Nitrogen application rates were chosen to provide a range of available N from deficient through, and exceeding the agronomic optimum.

Plant sampling (Table 1) was conducted to determine leaf N concentration and plant height at each sensing date, total N content at early boll opening, and lint yield. Leaf samples were taken at all sensing dates except pre-squaring due to the small plant size and immaturity of leaf blades at this growth stage. Sampling consisted of four sublocations per plot, with one composite sample taken from each sublocation. Each composite sample consisted of five most recently matured,
fully expanded leaf blades (fifth node from apical meristem) excluding the petiole. To minimize the effects of destructive leaf sampling on subsequent sensing dates, sampling points were moved throughout the growing season between Rows 2, 3, and 4, and 9, 10, and 11 in proximity to each corresponding sublocation point. Leaf samples were oven dried for 48 h at 65°C and ground through a 20 mesh sieve in a Wiley Mill. Leaf N concentrations were determined on duplicate samples of 4 to 6 mg of ground leaf material using a Carlo Erba N/C 1500 dry combustion analyzer (Carlo Erba, Milan, Italy). Duplicate samples exceeding 5% standard error were re-analyzed.

Plant height was measured at each sensing date. Five plant measurements were taken near each of the four marked sublocation points corresponding to sensed (sampled rows) in each plot. Measurements were made from the surface of the soil at the base of the plant to the stem terminal. The five readings were averaged for each sublocation point to correlate to reflectance readings and plant sampling data.

Aboveground whole plant samples from a 1-m length of row were taken from each of the four marked sublocation points at early boll opening, before significant leaf senescence. Senesced plant residue located directly within the 1-m sampling area was also collected, weighed, and analyzed separately. Immediately after whole plant sampling, bolls larger than 1 cm were removed from the plants. Bolls, residue, and whole plants were dried separately at 65°C for 5 d. Seed cotton was removed from dried bolls, acid de-linted, and ground using a coffee bean grinder. Separately, the residue, coarse ground plant cells, resulting in reported mechanically harvested seed cotton weights on a per-plot basis. In total, 152.4 m of row length was harvested from each plot. Lint percentage determined from mechanically harvested seed cotton was multiplied by mechanically harvested seed cotton weights to obtain total N.

Immediately before harvest, 50 boll samples were removed by hand from sensed rows in each plot to determine lint percentage. Cotton in sensed rows was harvested using a two-row automated spindle type picker equipped with baskets and load cells, resulting in reported mechanically harvested seed cotton weights on a per-plot basis. In total, 152.4 m of row length was harvested from each plot. Lint percentage determined from ginning 50 boll samples was multiplied by mechanically harvested seed cotton weight to determine lint yield.

The canopies of three of the sensors investigated in this study were the Yara N-Sensor, GS Model 505, and CC ACS-210. The Yara N Sensor is a passive multispectral scanner consisting of two diode array spectrometers. Two fiber optic inputs are located on each end of the sensor unit for viewing both left and right of the sensing platform. Optics on both ends feed into one spectrometer. The field of view for each crop-sensing fiber optic input is 12°. All four inputs are directed 64° from nadir and with regards to orientation of each pair, one is centered at 45° and the other at 135° from the direction of travel. The sensor is made to be cab mounted and the field of view encompasses between 50 and 100 m² of crop area depending on the height of the sensor above the crop. The second spectrometer is connected to an irradiance detector which points skyward and is used to correct for variations in light intensity. The commercially produced model reports five user selectable wavelengths between 450 and 900 nm with a bandwidth of ±5 nm. The acquisition interval for the Yara N-Sensor is 1 s.

The GS Model 505 is a pole- or application equipment-mounted active sensor. The active sensor emits near infrared light (NIR) light at 774 nm with a half power bandwidth of roughly 25 nm full width at half-maximum (FWHM) and a red wavelength at 656 nm with a half-power bandwidth of roughly 25 nm FWHM. The system only uses one photodetector and thus alternates intermittently between modulated visible and NIR light sources (Samborski et al., 2009). The vegetation indices available with the GS Model 505 are NDVI, Inverse Ratio Vegetation Index (IRVI), Ratio Vegetation Index (RVI), and Soil Adjusted NDVI (SA-NDVI). Optimal height range for sensing with the unit is between 71 and 112 cm. The sensor has a nadir viewing angle and a field of view which ranges from 52 to 145 cm². The acquisition interval for the GS Model 505 ranges from 20 to 1500 ms.

The CC ACS-210 is a hand-held pole-mounted active sensor available as either Yellow/NIR or Red/NIR. The Red/NIR sensor uses modulated polychromatic light emitting diode (LED) arrays to emit NIR light at 880 nm and a red light at 650 nm. Two detectors measure reflected modulated light; the first detector measures from 400 to 680 nm and the second detector measures from 800 to 1100 nm. The vegetative indices reported by the instrument are NDVI, Wide Dynamic Range Vegetation Index (WDRVI), Simple Ratio Index (SRI), infrared band reflectance (R_NIR), and visible band reflectance (R_VIS). Optimal height range for sensing with the unit is between 51 and 91 cm. The sensor has a nadir viewing angle and a field of view of roughly 36° by 6° from the sensor. The acquisition interval for the ACS-210 ranges from 1 to 20 samples per second.

Canopy reflectance data was acquired at multiple growth stages using all three of the sensors. Sensing dates (Table 1) were based on the growth stages of the crop. Early season sensing occurred at a weekly interval from early squaring to the second week of flowering. Reflectance by each sensor was measured within 2 h of solar noon. The Yara N Sensor was driven down the center of each 12-row plot, simultaneously measuring reflectance from Rows 2 to 4 and 9 to 11. Reflectance at wavelengths of 650 and 840 nm was acquired. Data from the Yara N Sensor was then processed in ArcGIS (ESRI, Redlands, CA) Desktop 10 by only including data within a 4.6 m buffer of the sublocation points located in Rows 3 and 10 (Fig. 1). For handheld sensors, data was collected from 36 m of row per plot (9 m per sublocation) and sensors were held at a height of 90 cm above the plant terminals. The following formula was used to calculate NDVI (Rouse et al., 1974):
Statistical analysis was conducted using JMP, Version 10 (SAS Institute Inc., Cary, NC). Analysis of variance was conducted to determine effects of fertilizer N rate and sensor type on NDVI readings across crop development and years (environments). Pearson correlations were examined between sensors, leaf N, plant height, and fertilizer N rates applied. Regression analysis was used to develop relationships between NDVI sensors and biophysical measurements. Response to fertilizer N was modeled for each sensor at each sampling date in each year and compared to an average model derived from responses of all sensors used in the experiment at that date. Quadratic models were selected only when the models and quadratic terms were significant. Response of NDVI was graphed as a quadratic response to treatment. Resulting models were compared at a significance level of $P = 0.05$. Since all reflectance data was acquired within the same plot area and thus, same plant material sensed, equations examining the relationships between each sensor were also developed by graphing NDVI readings correlated with plant measurements.

RESULTS

Plant height response to fertilizer N rate was strong late in the 2008 and 2010 growing seasons and throughout the 2009 growing season, but early in 2008 and 2010 response was frequently very weak (Fig. 2). A quadratic response was noted at peak flowering in 2009 and 2010, but the trend was generally linear with a low small slope early in the growing season. Response of plant height to changes across growth periods and years were very consistent, with maximum plant height shifting from year to year depending on crop year. Plant height increased as each growing season progressed, however, separation of fertilizer N rates was often not evident until sampling dates late in the growing season. Plant height response to fertilizer N rates early in 2008 and 2010 suggests this parameter was not a strong indicator of cotton N status in this study. Plant height may possibly serve as a proxy measurement for N availability, but LAI is also strongly influenced and has direct effects on NDVI measurements (Eitel et al., 2009; Li et al., 2001). Although plant height is influenced by available N, cotton's architecture is characterized by vegetative and reproductive branching.

Leaf N response to fertilizer N rate was strong at almost every sensing date, including those very early in the growing season (Fig. 3). This response was frequently quadratic. Absolute leaf N values across growth periods and years were inconsistent; however, most likely due to changing growing conditions (rainfall, temperatures, tillage systems, etc.), cultivars, and source- sink- relationships influencing crop development. Although these inconsistent shifts greatly complicated full-season modeling, differences between fertilizer N rates were noted.
at all sampling dates. These relatively large separations suggest leaf N is a good indicator of cotton N status.

Total N uptake, as measured at early boll-opening stage, increased with fertilizer N rate in all years (Fig. 4A). All models of total N uptake were significant ($p \leq 0.05$). The response was linear in 2008 and 2009, indicating that increases in fertilizer N rate proportionately increased total N uptake. Total N uptake in 2010 was best described by a quadratic model with maximum N uptake found at 103 kg ha$^{-1}$. The quadratic trend in 2010 may have been the result of water stress limiting crop recovery of N at the highest rate, while cultivar and tillage differences compared to 2008 and 2009 may have been contributing factors as well.

Observed lint yield response to applied fertilizer N was quadratic in all 3 yr due to a decline in yield at 135 kg N ha$^{-1}$ (Fig. 4B). Frequent, heavy rainfall and wind late in the 2009 growing season greatly reduced yields by knocking locks from open bolls and hard-locking many bolls which remained. Weather conditions during this period were drastic enough to promote vivipary of cotton seed in open bolls. Still, yield trends were similar to the 2008 and 2010 crop years (Fig. 4B).

Initial ANOVA of reflectance measurements indicated significant interactions between sensor and year, sensor and week, and sensor and treatment (Table 2). As a result, ANOVA was conducted and reported for each growth stage in each year (Table 3). Fertilizer N rate effects on NDVI were significant at all growth stages in all years. Sensor effects on NDVI tended to only be significant late in the growing season. The fertilizer N rate and sensor interaction term was only significant during the second week of flowering in 2009 and at peak flowering in 2010. Significant interactions late in the growing season may be explained by differences in sensing angles or changes in plant architecture.

Pearson correlations ($r$) of sensor NDVI values with leaf N and plant height were variable, but trends were still evident (Table 4). Correlations of NDVI with all variables generally increased in strength from pre-squaring to peak flowering. Before early flowering, correlations between NDVI and plant height were always greater than correlations between NDVI and leaf N. After early flowering, this trend weakened slightly, as NDVI readings were noted to be more sensitive to leaf N than plant height in 5 of the 27 observations. However, it was apparent that NDVI readings were much more sensitive to plant height than leaf N. Overall, NDVI was strongly related to plant height which suggests LAI would be as well. Although NDVI may not be as strong of an indicator of leaf N status, it is a good proxy biomass indicator and implies total N content also.
Differences between sensor sensitivities to leaf N, plant height, and total N content were also variable, but again trends were noted. The Yara N Sensor most frequently had the strongest relationship with leaf N (11 of 16 observations), plant height (12 of 18 observations), and total N content (13 of 18 observations). The GS 505 followed in terms of frequency and strength of correlation to leaf N (3 of 16 observations), plant height (5 of 18 observations), and total N content (4 of 18 observations). The CC ACS-210 had the lowest frequency and strength of correlation of the three sensors to leaf N (2 out of 16 observations), plant height (1 out of 18 observations), and total N (1 out of 18 observations).

Slopes of individually derived sensor prediction models did not differ from the overall pooled slopes for either linear or quadratic variables at any growth stages in any years (Tables 5–7). However, consistent, significant differences between y intercepts were observed by early flowering. By the second week of flowering, y intercepts of the N Sensor were significantly lower than the overall combined model in all 3 yr. These trends continued through to peak flowering.

Relationships between sensors were defined by comparing corresponding sensor NDVIs acquired, while sensing the same plant material. Corresponding NDVIs from 2008 to 2010 were analyzed to determine relationships between sensor pairs. Regression analysis resulted in very strong coefficients of determination ranging from 0.94 to 0.96. All models were quadratic and significant (p < 0.05) (Fig. 5A–5C).

The CC ACS-210 and N Sensor relationships with the GS Model 505 were similar (Fig. 5A and 5C). Both the CC ACS-210 and Yara N Sensor tended to be less sensitive to NDVI shifting factors than the GS Model 505 at low NDVI readings. As the CC ACS-210 and N Sensor NDVI readings reached 0.6, however, the GS Model 505 became less sensitive than the two other sensors. Thus, the GS Model 505 was more sensitive early in the growing season, but tended to saturate, while the CC ACS-210 and N Sensor were more sensitive late in the growing season.

### Table 2. Analysis of variance results examining response of normalized difference vegetation index (NDVI) readings to sensor type and fertilizer N rate across growth stages and years.

<table>
<thead>
<tr>
<th>Source</th>
<th>NPARM</th>
<th>DF</th>
<th>Sum of squares</th>
<th>F ratio</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2</td>
<td>2</td>
<td>0.694503</td>
<td>162.185</td>
<td>&lt;0.0001***</td>
</tr>
<tr>
<td>Block</td>
<td>3</td>
<td>3</td>
<td>0.171513</td>
<td>26.7018</td>
<td>&lt;0.0001***</td>
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<tr>
<td>Growth stage</td>
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<td>6</td>
<td>20.411964</td>
<td>1588.913</td>
<td>&lt;0.0001***</td>
</tr>
<tr>
<td>Fertilizer N rate</td>
<td>3</td>
<td>3</td>
<td>0.46682</td>
<td>72.6767</td>
<td>&lt;0.0001***</td>
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<tr>
<td>Sensor</td>
<td>2</td>
<td>2</td>
<td>0.01759</td>
<td>4.0063</td>
<td>0.0185**</td>
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<td>Sensor × year</td>
<td>4</td>
<td>4</td>
<td>0.053788</td>
<td>6.2805</td>
<td>&lt;0.0001***</td>
</tr>
<tr>
<td>Sensor × growth stage</td>
<td>12</td>
<td>12</td>
<td>0.440851</td>
<td>17.1584</td>
<td>&lt;0.0001***</td>
</tr>
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<td>Sensor × fertilizer N rate</td>
<td>6</td>
<td>6</td>
<td>0.003967</td>
<td>0.3088</td>
<td>0.9325</td>
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** Significant at 0.01.
*** Significant at 0.0001.

### Table 3. Analysis of variance results examining response of normalized difference vegetation index (NDVI) readings to sensor type and fertilizer N rate, at each growth stage from 2008 to 2010.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Pre-squaring</th>
<th>Early squaring</th>
<th>Second wk† squaring</th>
<th>Third wk squaring</th>
<th>Early flowering</th>
<th>Second wk flowering</th>
<th>Peak flowering</th>
</tr>
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<tbody>
<tr>
<td>2008</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>ns‡</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>N rate</td>
<td>*</td>
<td>=</td>
<td>***</td>
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<td>***</td>
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<td>***</td>
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<tr>
<td>Sensor</td>
<td>=</td>
<td>ns</td>
<td>***</td>
<td>ns</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>N rate × sensor</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
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<td>Block</td>
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<td>***</td>
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<td>ns</td>
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<td>N rate</td>
<td>***</td>
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<td>Sensor</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>N rate × sensor</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
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<td>2010</td>
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<td>N rate × sensor</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
<td></td>
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</tbody>
</table>

* Significant at 0.05.
** Significant at 0.01.
*** Significant at 0.0001.
† Representing week.
‡ ns, not significant.
Table 4. Pearson correlations (r) of the Crop Circle ACS-210 (CC), GreenSeeker Model 505 (GS), and Yara N Sensor (Yara) to leaf N, plant height, and total N content at early boll opening.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
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<tbody>
<tr>
<td></td>
<td>Pre-squaring</td>
<td>Early squaring</td>
<td>Second week of squaring</td>
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<tr>
<td>Leaf N</td>
<td>Plant height</td>
<td>Total N</td>
<td>Leaf N</td>
</tr>
<tr>
<td>CC‡</td>
<td>–</td>
<td>0.7368</td>
<td>0.4744†</td>
</tr>
<tr>
<td>GS</td>
<td>–</td>
<td>0.8161†</td>
<td>0.4231</td>
</tr>
<tr>
<td>Yara</td>
<td>–</td>
<td>0.6036</td>
<td>0.1801</td>
</tr>
</tbody>
</table>

† Identifies the greatest observed correlation value of the variable of interest for that given growth stage.

Table 5. Estimated model parameters of the Crop Circle ACS-210 (CC), GreenSeeker Model 505 (GS), and Yara N Sensor (Yara) to fertilizer N rate at pre-squaring, early squaring, and second week of squaring for the 2008–2010 growing seasons.

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
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<tbody>
<tr>
<td></td>
<td>CC</td>
<td>GS</td>
<td>Yara</td>
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<tr>
<td>Intercept</td>
<td>0.333323</td>
<td>0.320407</td>
<td>0.364215</td>
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<td>Linear</td>
<td>0.000265</td>
<td>–0.00012</td>
<td>–0.00025</td>
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<tr>
<td>Quadratic</td>
<td>1.181×10⁻⁷</td>
<td>3.059×10⁻⁶</td>
<td>2.55×10⁻⁶</td>
</tr>
</tbody>
</table>

** Significant at p ≤ 0.05.

† Represents coefficient of determination for combined model, which includes readings from all three normalized difference vegetation index sensors.
Table 6. Estimated model parameters of the Crop Circle ACS-210 (CC), GreenSeeker Model 505 (GS) and Yara N Sensor (Yara) to fertilizer N rate during third week of squaring, early flowering, and third week of flowering for the 2008–2010 growing seasons.

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Model parameter</th>
<th>Third week of squaring</th>
<th>Early flowering</th>
<th>Third week of flowering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>GS</td>
<td>Yara</td>
<td>CC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>–</td>
<td>0.475†</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>0.649765</td>
<td>0.647265</td>
<td>0.698787</td>
</tr>
<tr>
<td></td>
<td>Linear</td>
<td>0.000481</td>
<td>0.00186</td>
<td>0.00116</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>–6.95×10⁻⁷</td>
<td>–0.00001</td>
<td>–3.65×10⁻⁶</td>
</tr>
<tr>
<td>2009</td>
<td>–</td>
<td>0.40†</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>0.645887</td>
<td>0.630823</td>
<td>0.632880</td>
</tr>
<tr>
<td></td>
<td>Linear</td>
<td>0.000984</td>
<td>0.001501</td>
<td>0.002009</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>–4.05×10⁻⁶</td>
<td>–5.54×10⁻⁶</td>
<td>–7.16×10⁻⁶</td>
</tr>
<tr>
<td>2010</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Linear</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

† Represents coefficient of determination for combined model, which includes readings from all three normalized difference vegetation index sensors. ** Significant at p ≤ 0.05.

Table 7. Estimated model parameters of the Crop Circle ACS-210 (CC), GreenSeeker Model 505 (GS) and Yara N Sensor (Yara) to fertilizer N rate during peak flowering for the 2008–2010 growing seasons.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Model parameter</th>
<th>CC</th>
<th>GS</th>
<th>Yara</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>R²</td>
<td>–</td>
<td>0.91†</td>
<td>–</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.729731**</td>
<td>0.792208</td>
<td>0.841501**</td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.001107</td>
<td>0.000766</td>
<td>0.000897</td>
<td></td>
</tr>
<tr>
<td>Quadratic</td>
<td>–5.28×10⁻⁶</td>
<td>–4.11×10⁻⁶</td>
<td>–5.03×10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>R²</td>
<td>–</td>
<td>0.92†</td>
<td>–</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.784572**</td>
<td>0.865600</td>
<td>0.886867**</td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.001052</td>
<td>0.000816</td>
<td>0.000862</td>
<td></td>
</tr>
<tr>
<td>Quadratic</td>
<td>–5.81×10⁻⁶</td>
<td>–5.82×10⁻⁶</td>
<td>–4.41×10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>R²</td>
<td>–</td>
<td>0.96†</td>
<td>–</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.760435**</td>
<td>0.802031</td>
<td>0.869335**</td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.001590</td>
<td>0.000653</td>
<td>0.001149</td>
<td></td>
</tr>
<tr>
<td>Quadratic</td>
<td>–8.72×10⁻⁶</td>
<td>–3.64×10⁻⁶</td>
<td>–6.23×10⁻⁶</td>
<td></td>
</tr>
</tbody>
</table>

† Represents coefficient of determination for combined model, which includes readings from all three normalized difference vegetation index sensors. ** Significant at p ≤ 0.05.

Few studies have defined relationships between sensor-derived NDVI and cotton N status, but most are in agreement with results from this study. Bronson et al. (2003) noted moderate correlations of NDVIs measured at early squaring, early flowering, and peak flowering from a handheld passive spectroradiometer (Model MSR16R, CropScan, Inc., Rochester, MN) with leaf N and biomass. Similarities in results include the general increase in correlations between reflectance and cotton N status measurements as the growing season progressed. Further research by Bronson et al. (2005) found very poor correlations of early squaring NDVIs from a handheld passive spectroradiometer and the GS with leaf N, biomass, lint yield, and fertilizer N rate; however, significant differences were noted between the control and treatments which received fertilizer N. These results are also similar to results noted in this study, as early season differences were typically significant between control and fertilizer N rate treatments, but not between specific fertilizer N rates. A plausible explanation for the weak response of NDVI to changes in N status may be the observed sensitivity of the index to changes in plant height, a parameter which failed to correlate strongly to fertilizer N rate. At the canopy level, NDVI is reportedly more sensitive to leaf area index (LAI) than it is to chlorophyll content (Daughtry et al., 2000; Eitel et al., 2008, 2009). Results do indicate however, the ability of NDVI to detect biomass N content. Subsequently, results suggest an index more sensitive to leaf N and less sensitive to plant height will be most useful in determining early season cotton leaf N status.

Several research efforts have found very poor correlations between fertilizer N rate and sensor-derived NDVIs due to a lack of significant fertilizer N rate response (Li et al., 2001; Plant et al., 2000). In this study, fertilizer N rate response was significant at almost every sensing and sampling date for leaf N and frequently significant for plant height after early flowering. Between fertilizer N rate treatments, but not between specific fertilizer N rates. A plausible explanation for the weak response of NDVI to changes in N status may be the observed sensitivity of the index to changes in plant height, a parameter which failed to correlate strongly to fertilizer N rate. At the canopy level, NDVI is reportedly more sensitive to leaf area index (LAI) than it is to chlorophyll content (Daughtry et al., 2000; Eitel et al., 2008, 2009). Results do indicate however, the ability of NDVI to detect biomass N content. Subsequently, results suggest an index more sensitive to leaf N and less sensitive to plant height will be most useful in determining early season cotton leaf N status.

DISCUSSION

Concerning comparisons between sensors, results slightly contrast previous findings. Reported coefficients of determination between sensor NDVI reading comparisons by Tremblay et al. (2009) were much lower than those observed in this study.
Most concerning, however, are the strongly contrasting results on sensor saturations. As shown in Fig. 5, the GS saturated at lower NDVI readings than the Yara N Sensor. This directly contrasts responses Tremblay et al. (2009) noted for wheat and corn. In comparison with results of Sudduth et al. (2010), observed sensor relationships were much stronger in this study. Furthermore, quadratic trends noted in these cotton trials between NDVI relationships were significant. The stronger observed relationships may be due to only one site; however three unique, weather-variable data years were used to construct the dataset. This suggests that ground cover characteristics and soil properties associated with changes in locations may influence sensor readings more than inherent seasonal variability in crop status from year to year. However, conclusions of Sudduth et al. (2010) are in agreement with this study, as the off-nadir viewing sensor was more strongly correlated to crop N status.

Although sensor models were not significantly different early in the growing season, trends were evident in each year of the study. Models derived with the Yara N Sensor at pre-square or early square resulted in lower predicted NDVI values than the CC ACS-210 and GS Model 505 sensors. This trend was not consistent throughout the growing season. The Yara N Sensor NDVI values slowly shifted to greater magnitudes until they surpassed both the CC ACS-210 and GS Model 505 NDVI values by early flowering (Fig. 5). This shift in the relationship between the off-nadir, angled N Sensor, and the handheld GS Model 505 and CC ACS-210 is most likely due to varying soil interference and increasing LAI and differences in sensitivity to these properties due to different viewing angles. The handheld sensors may be less responsive to soil interference due to their much smaller field of view which is centered above the row. The Yara N Sensor should detect more soil reflectance early in the growing season due to its large field of view which encompasses several rows and middles. For these reasons, the percent plant material composition within the field of view for the nadir GS Model 505 and CC ACS-210 are most likely larger than the off-nadir Yara N Sensor early in the growing season. As the season progresses and LAI increases, the percent plant composition of the field of views should equilibrate. By early flowering, under similar growing conditions as experienced in 2008–2010, all field of views should be composed almost entirely of plant material.

Although general trends of the two nadir sensors appeared to be similar, the CC ACS-210 NDVI values were consistently lower than the Model 505 NDVI values. This trend may in part be explained by wavelength differences. Both sensors emit and measure emitted light in the red and NIR region, but they only emit the same wavelength in the red region at 650 nm. In the NIR region the two sensors differ by more than 100 nm: the CC ACS-210 emits light at 880 nm and the GS Model 505 emits light at 774 nm. Normal green vegetative plants are characterized by an increase in magnitude of reflected NIR light at 880 nm as compared to 774 nm regardless of plant health. Due to the calculation of NDVI, increased light reflectance in the NIR region will result in a lower NDVI value; thus, when sensing identical green vegetative plant material characterized by a typical signature reflectance curve, the CC ACS-210 will report lower NDVI values than the GS Model 505.

**CONCLUSIONS**

All tested NDVI sensors failed to consistently predict cotton leaf N status during the period before flowering, at which point in time a yield-impacting fertilizer N application could be made. Instead, analyzed NDVI sensors were quite sensitive to changes in plant height, which failed to correlate well to fertilizer N rate early in the 2008 and 2010 growing seasons. Although these instruments have been successfully used in wheat (Raun et al., 2001; Stone et al., 1996), this research suggests accurate detection of cotton leaf N status may require the...
utilization of an index which is less sensitive to plant height and other NDVI biomass-based factors and more sensitive to chlorophyll differences. Further research examining the sensitivity of other sensors and published indices is necessary before an on-the-go VRN can be driven in real-time by sensor readings. These results suggest the magnitude of NDVI readings from each sensor will vary and conversion equations may be necessary if a fertilizer N application algorithm developed from one sensor is coupled with another sensor.

ACKNOWLEDGMENTS

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REFERENCES


