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Aerial Color Infrared Photography for Determining Early In-Season Nitrogen Requirements in Corn

Ravi P. Sripada,* Ronnie W. Heiniger, Jeffrey G. White, and Alan D. Meijer

ABSTRACT

In-season determination of corn (*Zea mays* L.) N requirements via remote sensing may help optimize N application decisions and improve profit, fertilizer use efficiency, and environmental quality. The objective of this study was to use aerial color-infrared (CIR) photography as a remote-sensing technique for predicting in-season N requirements for corn at the V7 growth stage. Field studies were conducted for 2 yr at three locations, each with and without irrigation, in the North Carolina Coastal Plain. Experimental treatments were a complete factorial of four N rates at planting (N_{PL}) and five N rates at V7 (N_{V7}). Aerial CIR photographs were taken at each of the locations at V7 before N application. Optimum N_{V7} ranged from 0 to 207 kg N ha^{-1} with a mean of 67 kg N ha^{-1}. Significant but weak correlations were observed between optimum N_{V7} rates and the band combinations relative green, Relative Green Difference Vegetation Index, and Relative Difference Vegetation Index as measured in CIR photos. High proportions of soil reflectance in the images early in the corn growing season (V7) likely confounded our attempts to relate spectral information to optimum N_{V7} rates. The primary obstacles to applying this technique early in the season are the use of relative digital counts or indices that require high-N reference strips in the field and strong background reflectance from the soil. When the N_{PL} treatments that were nonresponsive to N_{V7} (i.e., optimum N_{V7} = 0) were removed from the analysis, the normalized near infrared, the Green Difference Vegetation Index, the Green Ratio Vegetation Index, and the Green Normalized Difference Vegetation Index were the best predictors of optimum N_{V7} rate (r^2 = 0.33).

Crop N requirements in general and corn N requirements in particular change from year to year, from field to field, and within fields (Mamo et al., 2003). Thus, quantifying the optimum in-season N requirement is an important step toward an economically and environmentally viable corn production system (Varvel et al., 1997). High levels of NO_3–N in the groundwater have been attributed to agricultural practices in the southeastern Coastal Plain, making groundwater NO_3 contamination a regulatory and social issue threatening regional crop production. Nitrate losses from fertilizer use can be minimized by matching fertilizer N rates and timing with the specific needs of a crop, thus mitigating a potential source of surface and groundwater pollution (Ferguson et al., 2002).

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Traditional methods of estimating in-season optimum N requirements for corn are based on soil testing (Magdoff, 1991), tissue N concentrations (Tyner and Webb, 1946), and chlorophyll concentration or leaf greenness (Varvel et al., 1997). However, these methods require multiple samples to be taken, can be expensive and time consuming, and often produce inaccurate estimates of crop N requirement (Blackmer and Schepers, 1996). There is a need for faster, more accurate, and possibly more economical methods for collecting crop information for estimating in-season N requirements.

Remote sensing via aerial color and CIR photography has been used to detect N deficiencies in corn (Blackmer et al., 1996) and determine N fertilizer requirements for site-specific application by utilizing green (G) and relative G (Rel G) digital counts early in the corn-growing season (Scharf and Lory, 2002). Sripada et al. (2005) used a linear-plateau function of the Green Difference Vegetation Index (GDVI; Table 1) measured relative to a well-N-fertilized reference plot (an area that is never N deficient) [Relative GDVI (RGDVI); Table 1] to predict economic optimum N rates for corn at the VT stage (Ritchie et al., 1993) with reasonable success. These studies showed that color and/or CIR photographs obtained between growth stages V7 and VT could be used to predict N deficiency and corn N requirements. However, the promising results from these studies were constrained by the need to remove pixels showing soil and the requirement that no N be applied before the photographs were taken (Scharf and Lory, 2002) or were focused on application of N at a later stage of crop growth (Sripada et al., 2005).

The spectral reflectance of a crop canopy is a combination of the reflectance spectra of plant and soil

Abbreviations: AOI, areas of interest; B, blue; CIR, color infrared; DVI, Difference Vegetation Index; G, green; GDVI, Green Difference Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GOSAVI, Green Optimized Soil Adjusted Vegetation Index; GRVI, Green Ratio Vegetation Index; GSAVI, Green Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; NIR, near infrared; Norm G, normalized green; Norm NIR, normalized near infrared; Norm R, normalized red; N_{PL}, nitrogen applied at planting; NRI, Nitrogen Reflectance Index; NSI, Nitrogen Sufficiency Index; N_{V7}, nitrogen applied at V7; OSAVI, Optimized Soil Adjusted Vegetation Index; PBRS, Peanut Belt Research Station; R, red; RDVI, Relative Difference Vegetation Index; Rel G, relative green; Rel NIR, relative near infrared; Rel R, relative red; RGDVI, Relative Green Difference Vegetation Index; RGNDVI, Relative Green Normalized Difference Vegetation Index; RGOSAVI, Relative Green Optimized Soil Adjusted Vegetation Index; RGRVI, Relative Green Ratio Vegetation Index; RGSAVI, Relative Green Soil Adjusted Vegetation Index; RNDVI, Relative Normalized Difference Vegetation Index; ROSAVI, Relative Optimized Soil Adjusted Vegetation Index; RRVI, Relative Ratio Vegetation Index; RSAVI, Relative Soil Adjusted Vegetation Index; RVI, Ratio Vegetation Index; TRS, Tidewater Research Station; SAVI, Soil Adjusted Vegetation Index.

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Table 1. Color-infrared spectral bands, band combinations, and vegetation indices used in analysis.

Spectral index	Formula†‡	Reference
Norm NIR	NIR/(NIR + R + G)	–
Norm R	R/(NIR + R + G)	–
Norm G	G/(NIR + R + G)	–
Rel NIR	$NIR_{plot}/NIR_{reference\ plot}$	–
Rel R	$R_{plot}/R_{reference\ plot}$	–
Rel G	$G_{plot}/G_{reference\ plot}$	–
Difference Vegetation Index (DVI)	NIR − R	Tucker, 1979
Relative Difference Vegetation Index (RDVI)	$DVI_{plot}/DVI_{reference\ plot}$	–
Green Difference Vegetation Index (GDVI)	NIR − G	Tucker, 1979
Relative Green Difference Vegetation Index (RGDVI)	$GDVI_{plot}/GDVI_{reference\ plot}$	–
Ratio Vegetation Index (RVI)	NIR/R	Jordan, 1969
Relative Ratio Vegetation Index (RRVI)	$RVI_{plot}/RVI_{reference\ plot}$	–
Green Ratio Vegetation Index (GRVI)	NIR/G	–
Relative Green Ratio Vegetation Index (RGRVI)	$GRVI_{plot}/GRVI_{reference\ plot}$	–
Normalized Difference Vegetation Index (NDVI)	(NIR − R)/(NIR + R)	Rouse et al., 1973
Relative Normalized Difference Vegetation Index (RNDVI)	$NDVI_{plot}/NDVI_{reference\ plot}$	–
Green Normalized Difference Vegetation Index (GNDVI)	(NIR − G)/(NIR + G)	Gitelson et al., 1996
Relative Green Normalized Difference Vegetation Index (RGNDVI)	$GNDVI_{plot}/GNDVI_{reference\ plot}$	–
Soil Adjusted Vegetation Index (SAVI)	[(NIR − R)/(NIR + R + 0.5)] × 1.5	Huete, 1988
Relative Soil Adjusted Vegetation Index (RSAVI)	$SAVI_{plot}/SAVI_{reference\ plot}$	–
Green Soil Adjusted Vegetation Index (GSAVI)	[(NIR − G)/(NIR + G + 0.5)] × 1.5	–
Relative Green Soil Adjusted Vegetation Index (RGSAVI)	$GSAVI_{plot}/GSAVI_{reference\ plot}$	–
Optimized Soil Adjusted Vegetation Index (OSAVI)	(NIR − R)/(NIR + R + 0.16)	Rondeaux et al., 1996
Relative Optimized Soil Adjusted Vegetation Index (ROSAVI)	$OSAVI_{plot}/OSAVI_{reference\ plot}$	–
Green Optimized Soil Adjusted Vegetation Index (GOSAVI)	(NIR − G)/(NIR + G + 0.16)	–
Relative Green Optimized Soil Adjusted Vegetation Index (RGOSAVI)	$GOSAVI_{plot}/GOSAVI_{reference\ plot}$	–

† NIR, near infrared; R, red; G, green.
‡ A reference plot is one that received the highest N rate.

components as governed by the optical properties of these elements and radiant energy exchange within the canopy (Huete, 1988). High absorption of incident sunlight in the visible red (R: 600–700 nm) and strong reflectance in the near-infrared (NIR: 750–1350 nm) portions of the electromagnetic spectrum by photosynthetically active plant tissue is distinctive from that of soil and water (Lilleseater, 1982). Spectral reflectance in the R is inversely related to the in situ chlorophyll concentration while spectral reflectance in the NIR is directly related to the green leaf density (Gates et al., 1965; Knipling, 1970). A considerable amount of research with remote sensing of corn canopies (Blackmer et al., 1994; Schepers et al., 1992, Schepers et al., 1996) has shown that the G band (in combination with NIR band) is more highly associated than the R band with variability in leaf chlorophyll, leaf N content, and grain yield.

Linear combinations or some transformation of the spectral data from two or more radiometric wavebands may be more sensitive to crop N requirements than single waveband spectral data (Bausch and Duke, 1996). For example, Bausch and Duke (1996) developed an N Reflectance Index (NRI) to monitor the N status of irrigated corn from measured G (520–620 nm) and NIR (760–900 nm) canopy reflectance. The NRI was defined as the ratio of the NIR/G for an area of interest to the NIR/G of a well-N-fertilized reference area. Gitelson et al. (1996) proposed that the use of the G band in a Green Normalized Difference Vegetation Index (GNDVI, Table 1) might prove to be useful for assessing canopy variation in biomass.

Soil influences on incomplete canopy spectra are partly due to dependency of the soil background signal on the optical properties of the overlaying canopy (Lillesaeter, 1982). Differences in R and NIR flux transfers (Kimes et al., 1985) through a canopy can result in complex soil and vegetation interactions, which make it difficult to correct for soil background influences. Several indices such as the Difference Vegetation Index [DVI (Tucker, 1979); Table 1] and the Soil Adjusted Vegetation Index [SAVI (Huete, 1988); Table 1] have been developed to correct for soil influences.

While yield predicted from remote sensing (Shanahan et al., 2001) can be used to indirectly estimate N requirements, a more accurate method might be to use spectral reflectance to directly measure corn N requirements. So far, very few attempts have been made to predict sidedress N requirement in corn using remote sensing. Blackmer and Schepers (1995) developed an N Sufficiency Index (NSI) based on chlorophyll meter readings relative to a non-N-limited area to compare N status across fields and for fertigation in corn in the Great Plains. Scharf and Lory (2002) had greater success using corn color in the form of Rel G from aerial color images compared with CIR images to predict optimum sidedress N in corn at the V6–V7 stage. The relationship developed by Scharf and Lory (2002) held only when the following conditions were met: (i) no N applied at planting, (ii) soil pixels removed from the image, and (iii) color expressed relative to that of well-fertilized corn in the same field. However, it is very common to apply N at planting in corn production in the southeastern USA (Crozier, 2002). In separating the soil pixels from the crop pixels, Scharf and Lory (2002) used an unknown "fuzziness" algorithm within Adobe Photoshop and the potentially subjective judgement of the person analyzing the images. The ability to separate soil pixels from plant pixels requires relatively high-resolution images, which Scharf and Lory (2002) obtained by photographing from low altitude (150 m). This resulted in vignetting, or concentric circles of

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brightness in the aerial photographs, which necessitated color correction.

The index approach (Gitelson et al., 1996; Baret and Fourty, 1997) to assessing plant color in a mixed scene has a potential advantage over the separation of soil and plant pixels as suggested by Scharf and Lory (2002), in that it does not require ultra-high-resolution images. However, Scharf and Lory (2002) indicate and we concur that, to date, these indices have not been screened to determine their utility in deriving N rate recommendations for corn early in the season from aerial CIR photographs. Sripada et al. (2005) used a linear-plateau function of the RGDVI from aerial CIR photographs to predict economic optimum N rates for corn at the VT stage. This approach did not require the removal of soil pixels and was applicable under a wide range of N availability, including when preplant N had been applied.

Consequently, our main objective was to develop a similar in-season model to predict the amount of sidedress N required by corn at an early stage (V7) that could be used under different initial N levels and that could simultaneously account for any confounding soil reflectance. Specifically, we wanted to determine the potential of using indices derived from NIR, R, and G spectral bands of aerial CIR photographs under field conditions in determining N requirements of corn at V7 growth stage.

MATERIALS AND METHODS

Field studies were conducted with irrigated and nonirrigated experiments over 2 yr, 2002 and 2003, at three sites, one located at the Peanut Belt Research Station (PBRS) near Lewiston-Woodville, NC, and the remaining two at the Tidewater Research Station (TRS) near Plymouth, NC. Although both research stations are located in the Coastal Plain of North Carolina, the PBRS is located in the large river valleys and flood plain systems, and the TRS is in the lower Coastal Plain-Pamlico system. Sites 3 and 5 and Sites 9 and 11 are all on the same research station (TRS) but are separated by distances greater than 1 and 3.3 km, respectively. Two pairs of experiments were conducted each year at TRS to increase the number of data points that could be used to model the relationship between corn spectral characteristics and optimum N rate at V7 and provide economies in aerial image acquisition. The paired irrigated and nonirrigated sites were separated by distances of ~25 to 50 m. The soil classification data for the experimental sites are described in Table 2.

A two-way factorial experimental design was implemented as a split-plot in randomized complete blocks with five replications in 2002 and four replications in 2003 with the initial N_{PL} as the main-plot factor and sidedress N_{V7} as the subplot factor. Since the objective of this study concerned the response of corn to N_{V7} at varying levels of N fertility at planting, this split-plot design was used to help ensure that responses to N_{V7} were determined under similar conditions (proximate split plots within main plots) and to provide greater accuracy for the comparisons of the subplot factor N_{V7} and the interaction $N_{PL} \times N_{V7}$. The main plots were 9.1 m long and 18.2 m wide encompassing 20 rows with 0.91-m row spacing. The subplots were four rows (3.64 m) wide at all sites. Aqueous urea-ammonium nitrate solution (UAN, 30% N) was surface-applied at planting and at V7 using a CO_2–pressurized backpack sprayer. The N application rates were 0, 56, 112, and 224 kg ha^{-1} at planting and 0, 56, 112, 224, and 280 kg ha^{-1} at V7. The N_{V7} rates were determined in reaction to similar V7 N-response trials conducted in 2000 (not shown in this manuscript) that indicated a need for higher N rates to achieve a yield plateau. The sprayer was calibrated for the different N rates before each treatment application. With the exception of N management, the standard management practices corresponding to the region were followed at each site. Conventional tillage was used at all sites. Fertilizer rates other than N were based on North Carolina Department of Agriculture soil test results and recommendations (Hardy et al., 2002). The hybrid 'Pioneer 31G98' was planted at approximately 60000 seeds ha^{-1} across all sites and years. Herbicides were applied based on weeds present and excellent weed control was obtained at all sites. From planting to the R5 (dent) growth stage, if the total precipitation received was less than 1.3 cm over a 5-d period, then the irrigated sites were watered using overhead sprinkler irrigation at the rate of 2.5 cm wk^{-1}.

Determining Response to Nitrogen Applied at V7

To determine grain yield, the center two rows of each plot were harvested using a Gleaner (AGCO Corp., Duluth, GA) two-row combine. Moisture content and grain yield were recorded using a HarvestMaster Grain Gauge (Juniper Systems, Inc., Logan, UT). Grain yield was adjusted to a moisture content of 155 g kg^{-1}. The grain yield response to year, irrigation, and applied N was analyzed using PROC MIXED in SAS Version 8 (SAS Inst., Cary, NC). For the yield analysis, irrigation, N_{PL}, and N_{V7} were considered as fixed effects and year and site as random effects.

Determination of Optimum Rates of Nitrogen Applied at V7

Grain yield response to N was initially modeled as a linear-plateau function and as a quadratic-plateau function using PROC NLIN in SAS Version 8 (SAS Inst., Cary, NC). If the

Table 2. Soil type and classification for the experimental sites.

Site	Location†	Year	Irrigation‡	Soil series	Soil taxonomic classification
1	PBRS	2002	IR	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
2	PBRS	2002	NI	Goldsboro sandy loam	fine-loamy, siliceous, thermic, Aquic Paleudults
3	TRS	2002	IR	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
4	TRS	2002	NI	Hyde loam	fine-silty, mixed, thermic, Typic Umbraquults
5	TRS	2002	IR	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
6	TRS	2002	NI	Cape Fear loam	clayey, mixed, thermic, Typic Umbraquults
7	PBRS	2003	IR	Norfolk loamy coarse sand	fine-loamy, siliceous, thermic, Typic Paleudults
8	PBRS	2003	NI	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
9	TRS	2003	IR	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
10	TRS	2003	NI	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
11	TRS	2003	IR	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
12	TRS	2003	NI	Hyde loam	fine-silty, mixed, thermic, Typic Umbraquults

† PBRS, Peanut Belt Research Station, Lewiston-Woodville, NC; TRS, Tidewater Research Station, Plymouth, NC.
‡ IR, irrigated; NI, nonirrigated.

quadratic term in the quadratic-plateau model was significantly different from zero as determined by a t test at the $\alpha = 0.05$ level, then the quadratic-plateau model was considered to be the better fit compared with the linear-plateau model. In this data set, the quadratic term of the quadratic-plateau model was significant for only 3 of the 48 response curves shown in Fig. 1. Therefore, to be consistent, the linear-plateau model was used as the model for determining optimum N rates. When using a linear-plateau function, if the slope of the linear portion is such that the response to N is profitable, both the agronomic and economic optimum N rates are at the inflection point, the point beyond which there is no further increase in yield with increased applications of N fertilizer. If any of the responses did not fit a linear-plateau function as determined by the significance of the model at an α of 0.05, then treatment means were compared in PROC GLM using a

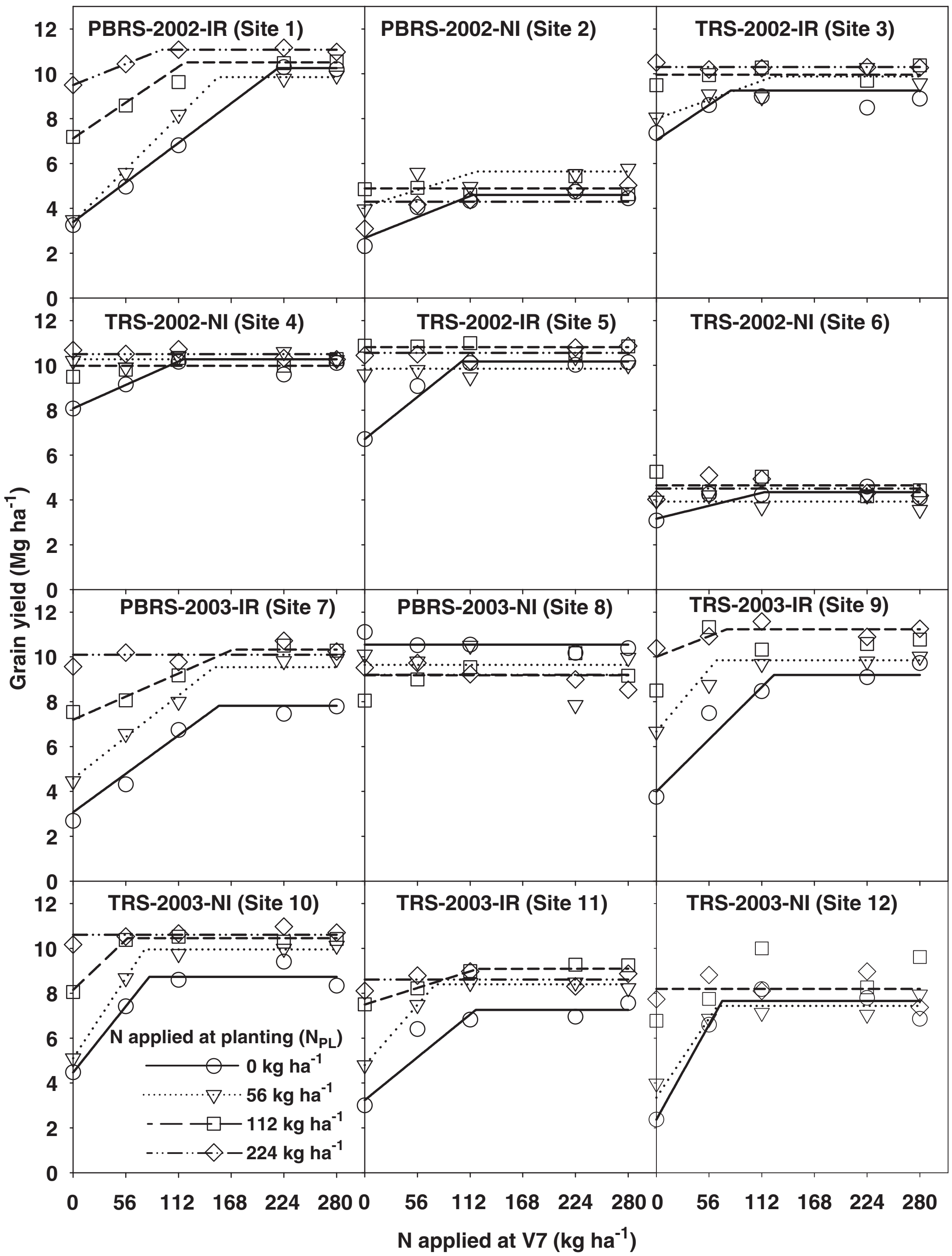

Fig. 1. Linear-plateau fit of corn grain yield response to N applied at growth stage V7 (N_{V7}) for different rates of N applied at planting (N_{PL}) at the different experimental sites (Table 2) during 2002 and 2003. Each point is the mean of four replicates. Absence of a line indicates that optimum N rate was derived using a series of linear contrasts. PBRS, Peanut Belt Research Station, Lewiston-Woodville, NC; TRS, Tidewater Research Station, Plymouth, NC; IR, irrigated; NI, nonirrigated.

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series of linear contrasts as well as by protected LSD to determine the optimum N level. These two methods gave consistent results. In situations where the yield response to fertilizer N was not significant as measured by either of the above methods, the optimum N rate was set equal to zero.

Image Acquisition and Conversion to Spectral Radiation

Aerial targets were placed at the four corners of each field for obtaining geographic coordinates for use in image georegistration. A differential global positioning system with 1-m accuracy (Trimble AG 132, Trimble Navigation, Sunnyvale, CA) was used to georeference the targets. Aerial CIR photographs were taken at V7 before N application at each of these sites using the technique described by Flowers et al. (2001). The aerial CIR images were obtained at altitudes (≈750 to 900 m) such that the entire experimental field and surrounding area (≈6 ha) were covered in a single image and under conditions as cloud free as possible using a belly-mounted platform and a 35-mm Canon AE-1 camera (Canon USA, Lake Success, NY). Kodak Ektachrome professional Infrared EIR 135–36 film along with a TIFFEN 52-mm Yellow No. 12 filter (Eastman Kodak Co., Rochester, NY) was used for obtaining the CIR images. The film was AR-5 processed to obtain false-CIR slides.

The spectral properties of the CIR film used for obtaining images were described by Flowers et al. (2003). The CIR film emulsions respond to light within the visible and NIR (~490–900 nm) regions of the electromagnetic spectrum. The digitized images are represented by 24-bit true color with three bands [8-bit R, 8-bit G, and 8 bit blue (B)]. At each pixel in the image, the color values represent RGB digital counts within the range 0 to 255. The spectral properties of CIR film result in wide overlapping wavelength bands. With the yellow filter, Band 1 (NIR) of the image covered the wavelengths between ≈490 and 900 nm, Band 2 (R) covered the wavelengths between ≈490 and 700 nm, and Band 3 (G) covered the wavelengths between ≈490 and 620 nm. While these bands overlap, differences in spectral sensitivity exist between them. Maximum sensitivity occurs at 730 nm in the NIR band, at 650 nm in the R band, and at 550 nm in the G band (Eastman Kodak, 1996).

Slides were digitized using the procedure described by Blackmer et al. (1996) with a Konica slide scanner (Konica Q-scan, Konica Corp., Mahwah, NJ) and Adobe Photoshop v. 4.0 (Adobe Syst., San Jose, CA), resulting in a ground resolution of 0.43 to 0.55 m (0.18 to 0.30 m^2). Differences in ground resolution were due to the slightly different altitudes at which the images were obtained. Digital image data were georegistered using ERDAS Imagine version 8.7 (ERDAS Inc., Atlanta, GA) image-processing software. The root mean square error after the georegistration was less than 1 m.

Areas of interest (AOI) corresponding to each individual plot, excluding the plot borders, were identified on the images; these included an approximately equal number (~475) of pixels for each plot. The AOI included both corn plants and any soil that was visible between adjacent rows, that is, there was no separation of soil and crop pixels. The AOI were used to extract the mean digital number (DN) representing each band of imagery for each individual plot. Using the DN for the individual bands, a series of spectral indices were calculated (Table 1). Relative bands (Rel NIR, Rel R, and Rel G) and indices (e.g., RGDVI) were calculated as the ratio of the spectral value of a particular plot to the spectral value for the plot that received the highest N rate at a particular site. To avoid working with negative values, a constant value of 255 was added to DVI and GDVI, and a value of 1 was added to all relative indices. The digital counts for the NIR, R, and G bands and all of the indices were regressed against the optimum N rates using four different models. The linear and quadratic models were fit using PROC REG, and the linear-plateau and quadratic-plateau models were fit using PROC NLIN in SAS Version 8 (SAS Inst., Cary, NC).

RESULTS AND DISCUSSION

Yield Responses to Nitrogen Applications

Corn grain yields at different experimental sites ranged from 2.0 to 12.0 Mg ha^{-1} with a mean of 7.8 Mg ha^{-1} in 2002 and from 1.7 to 12.8 Mg ha^{-1} with a mean of 8.7 Mg ha^{-1} in 2003 (Table 3). The differences between years were attributed mainly to the near-drought conditions experienced during the 2002 growing season, which had high temperatures [1.1°C warmer than 30 yr-average (23.2°C)] and very low rainfall [136 mm less precipitation than 30-yr average (567 mm)] that likely resulted in loss of yield potential. In contrast, during the 2003 growing season, there were more moderate temperatures (0.5°C warmer than 30 yr-average) and adequate, timely rainfall (221 mm more precipitation than 30-yr average) that likely fostered efficient N utilization.

Environmental and water stresses can affect corn yield response to N as well as the spectral response of the corn canopy, and thereby influence the relationship

Table 3. Minimum, maximum, mean, and standard deviation for grain yield at the different experimental sites.

Site	Location†	Year	Irrigation‡	Grain yield: Minimum	Maximum	Mean	Standard deviation
				Mg ha^{-1}			
1	PBRS	2002	IR	2.9	11.9	8.5	2.55
2	PBRS	2002	NI	2.0	8.5	4.6	1.10
3	TRS	2002	IR	6.2	11.5	9.7	1.18
4	TRS	2002	NI	6.9	11.5	10.0	0.94
5	TRS	2002	IR	6.2	12.0	10.2	1.13
6	TRS	2002	NI	2.2	6.7	4.2	0.88
7	PBRS	2003	IR	1.7	11.9	8.3	2.32
8	PBRS	2003	NI	4.7	12.8	9.6	1.47
9	TRS	2003	IR	2.9	12.2	9.5	1.92
10	TRS	2003	NI	4.2	12.3	9.4	1.87
11	TRS	2003	IR	2.8	11.1	7.7	1.75
12	TRS	2003	NI	1.8	11.1	7.5	1.96

† PBRS, Peanut Belt Research Station, Lewiston-Woodville, NC; TRS: Tidewater Research Station, Plymouth, NC.
‡ IR, irrigated; NI, nonirrigated.

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Table 4. Analysis of variance (ANOVA) for corn grain yield as affected by irrigation and fertilizer N at planting (N_{PL}) and at V7 (N_{V7}).

Source of variation	df	Grain yield
Irrigation	1	NS
N_{PL}	3	*
Irrigation × N_{PL}	3	**
N_{V7}	4	*
Irrigation × N_{V7}	4	*
N_{PL} × N_{V7}	12	**
Irrigation × N_{PL} × N_{V7}	12	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

between spectral indices and optimum N rates. Given the overall objective of the study to develop an in-season model that could accurately predict crop N requirements under a wide range of growing conditions, it was important to test whether the yield response to N_{PL} and N_{V7} differed across water regimes. The three-way interaction involving irrigation, $N_{PL,}$ and N_{V7} was not significant (Table 4). However, the two-way interactions of irrigation with both N_{PL} and N_{V7} and of N_{PL} with N_{V7} were significant.

The two-way interactions of irrigation with N_{V7} and N_{PL} were expected based on the varied N uptake pattern of corn under varying environments and moisture regimes (Russelle et al., 1983). Higher amounts of N_{V7} were needed to optimize yields at Site 1 (Fig. 1), which was an irrigated site in an exceptionally dry year (2002) compared with Site 10 (Fig. 1), a nonirrigated site with adequate rainfall (2003). An additional application of almost 100 kg N ha^{-1} was needed in 2002 to reach similar yield levels compared with 2003 (Fig. 1), which is an indicator of the different N requirements during the two seasons.

The two-way interaction between N_{PL} and N_{V7} is evident by the dissimilar slopes among the N_{V7} response curves as seen in Fig. 1. The quantity of N_{V7} needed for grain yield to reach a plateau was greater for plots that received 0 and 56 kg ha^{-1} N at planting than plots that received 112 and 224 kg ha^{-1}. At Site 1 under low initial N conditions, the N_{V7} applications resulted in the maintenance or recovery of yield potential evident by the similar yield plateaus (Fig. 1). However, at Site 10, some yield potential was lost when no N was applied at planting. These results indicate that grain yield optimization can be achieved by using an in-season N application at the V7 stage, provided that adequate N is available from planting to V7. These results further demonstrate that there is an enormous potential for determining an in-season N_{V7} rate appropriate for the current season.

Optimum Rates of Nitrogen Applied at V7

The different N_{PL} rates helped create a range of optimum N_{V7} rates (Fig. 1). The range of optimum N_{V7} rates was 0 to 207 kg N ha^{-1} with a mean of 67 kg N ha^{-1} with a corresponding mean N_{PL} of 98 kg ha^{-1} over all trials. There were three sites in 2002 (Sites 4, 5, 6) that responded to N_{V7} only where no N had been applied at planting (N_{PL} = 0) (Fig. 1.). The Illinois Soil Nitrogen test (Khan et al., 2001) of soil samples taken at planting revealed that there were relatively high levels of readily labile soil N at sites 4 and 6 (Williams, 2005) compared to the other sites. One site in 2003 (Site 8) was non-responsive to N_{V7}; the high yields there indicated that this was also likely due to high levels of available soil N.

Predicting Optimum Nitrogen Rates from Spectral Data

The coefficients of determination (r^2 or R^2) of the relationships between optimum N rates and the spectral bands and indices across all years and irrigation treatments are shown in Table 5. Among four different mathematical models (linear, linear-plateau, quadratic, and quadratic-plateau) used to predict the relationship between optimum N_{V7} rates and spectral indices, only the linear model showed consistently significant relationships, albeit with relatively weak correlations ($r^2 \leq$ 0.22). Only Rel NIR (R^2 = 0.18) and RRVI (R^2 = 0.14) had significant quadratic relationships with optimum N_{V7} rates (Table 5). As a result, only the linear model was used for further analysis and discussion.

Since there was a significant irrigation × N_{V7} interaction for yield, we analyzed the same spectral indicators separately for each year and irrigation treatment. The coefficients of determination (r^2) for the linear relation-

Table 5. Regression analysis of optimum V7 N rate (N_{V7}; kg ha^{-1}) versus near infrared (NIR), red (R), green (G), and the various spectral indices. The model significance and the coefficient of determination (r^2 or R^2) for the linear, linear-plateau, quadratic, and quadratic-plateau are given.

Vegetation index	Model: Linear	Linear-plateau	Quadratic	Quadratic-plateau
	r^2	R^2		
NIR	NS	NS	NS	NS
Red	NS	NS	NS	NS
Green	NS	NS	NS	NS
Norm NIR	0.14*	NS	NS	NS
Norm R	0.18**	NS	NS	NS
Norm G	NS	NS	NS	NS
Rel NIR	NS	NS	0.18*	NS
Rel R	0.17**	NS	NS	NS
Rel G	0.20**	NS	NS	NS
DVI	0.20**	NS	NS	NS
RDVI	0.22**	NS	NS	NS
GDVI	0.14*	NS	NS	NS
RGDVI	0.21**	NS	NS	NS
RVI	0.15*	NS	NS	NS
RRVI	0.13*	NS	0.14*	NS
GRVI	0.10*	NS	NS	NS
RGRVI	0.13*	NS	NS	NS
NDVI	0.16**	NS	NS	NS
RNDVI	0.15**	NS	NS	NS
GNDVI	0.11*	NS	NS	NS
RGNDVI	0.15*	NS	NS	NS
SAVI	0.16**	NS	NS	NS
RSAVI	0.16**	NS	NS	NS
GSAVI	0.11*	NS	NS	NS
RGSAVI	0.15**	NS	NS	NS
OSAVI	0.16**	NS	NS	NS
ROSAVI	0.15**	NS	NS	NS
GOSAVI	0.11*	NS	NS	NS
RGOSAVI	0.15*	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

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ships between optimum N_{V7} rates and the various spectral bands and indices separated by year and irrigation treatment are shown in Table 6. The individual absolute spectral bands (NIR, R, and G) were not correlated with optimum N_{V7} rate when analyzed across all years and irrigation treatments (Table 5). However, when these relationships were examined for individual years and irrigation treatments (Table 6), optimum N_{V7} rates showed significant relationships with NIR in 2002 ($r^2 = 0.25$), G in both 2002 and 2003 ($r^2 = 0.25$ and 0.26, respectively), and R in 2002 ($r^2 = 0.24$) and under irrigation ($r^2 = 0.29$). In contrast to the absolute spectral bands analyzed across years and irrigation treatments, the relative R and G bands showed significant relationships with optimum N_{V7} rates though Rel NIR remained nonsignificant (Table 5 and 6).

Normalizing spectral bands often can correct for different levels of illumination compared with absolute bands. Across years and irrigation treatments, the Norm NIR and Norm R showed significant but weak relationships with optimum N rates (Table 5). When separated by year, Norm NIR and Norm R showed significant relationships with optimum N_{V7} rates in 2002 and with irrigation. However, Norm G, which did not have a significant relationship with optimum N_{V7} rates when analyzed across year and irrigation treatments, showed a significant relationship in 2003 (Table 6).

Another method of correcting for levels of illumination and soil reflectance, and for increasing sensitivity to crop parameters, is the use of indices combining two or more bands. In this study, the indices using the NIR and R bands (DVI, RVI, NDVI, SAVI, and OSAVI) showed stronger correlations than the indices using NIR and G bands (GDVI, GRVI, GNDVI, GSAVI, and GOSAVI) when analyzed across years and irrigation treatments (Table 5). Although the linear models were significant, there was considerable unexplained variability that would hinder the use of these indices to predict optimum N rates. When separated by year and irrigation, none of the absolute indices showed significant relationships with optimum N_{V7} rates in 2003 or without irrigation. With the exception of RVI, all the absolute spectral indices showed a significant relationship with optimum N_{V7} rates in 2002 and with irrigation (Table 6).

Using indices computed relative to high-N reference strips in the field can help reduce potential sources of variation that may occur due to images captured at different times and/or places and can help account for differential response to N from field to field (Schepers et al., 1992). Most indices showed stronger relationships when expressed relative to a high-N reference strip (RDVI, RGDVI, RGRVI, RGNDVI, RGSAVI, and RGOSAVI) although several (RRVI, RNDVI, and ROSAVI) weakened (Table 5). When analyzed separately for each year and irrigation treatment, none of the relative indices showed a significant relationship with optimum N_{V7} rates in 2003 or without irrigation, with the exception of RDVI and RGDVI, which showed significant relationships without irrigation. With the exception of RRVI, all the relative indices showed a significant relationship with optimum N_{V7} rates when the plots were irrigated. Among the different spectral bands

Table 6. Linear regression analysis of optimum N rate at growth stage V7 (N_{V7}; kg ha^{-1}) versus near infrared (NIR), red (R), green (G), and the various spectral indices separated by year and irrigation and when treatments that were nonresponsive to N_{V7} were eliminated.

Vegetation index	2002	2003	Irrigated	Nonirrigated	Eliminating nonresponsive treatments
N	24	20	24	20	27
			r^2		
NIR	0.25*	NS	NS	NS	NS
Red	0.24*	NS	0.29**	NS	0.26**
Green	0.25*	0.26*	NS	NS	0.22*
Norm NIR	0.18*	NS	0.40**	NS	0.32**
Norm R	0.19*	NS	0.41**	NS	0.27**
Norm G	NS	0.20*	NS	NS	0.26**
Rel NIR	NS	NS	NS	NS	NS
Rel R	0.22*	NS	NS	NS	NS
Rel G	0.28**	NS	0.18*	NS	NS
DVI	0.21*	NS	0.45**	NS	0.27**
RDVI	0.40**	NS	0.22*	0.23*	NS
GDVI	0.20*	NS	0.45**	NS	0.33**
RGDVI	0.42**	NS	0.19*	0.21*	NS
RVI	NS	NS	0.40**	NS	0.29**
RRVI	NS	NS	NS	NS	NS
GRVI	0.17*	NS	0.34**	NS	0.33**
RGRVI	0.21*	NS	NS	NS	NS
NDVI	0.19*	NS	0.42**	NS	0.30**
RNDVI	0.24*	NS	NS	NS	NS
GNDVI	0.18*	NS	0.37**	NS	0.33**
RGNDVI	0.25*	NS	NS	NS	NS
SAVI	0.19*	NS	0.42**	NS	0.30**
RSAVI	0.26*	NS	NS	NS	NS
GSAVI	0.18*	NS	0.37**	NS	0.33**
RGSAVI	0.27**	NS	NS	NS	NS
OSAVI	0.19*	NS	0.42**	NS	0.30**
ROSAVI	0.24*	NS	NS	NS	NS
GOSAVI	0.18*	NS	0.37**	NS	0.33
RGOSAVI	0.25*	NS	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

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and indices examined in this study combined over years and irrigation, Rel G (r^2 = 0.20), RGDVI (r^2 = 0.21), and RDVI (r^2 = 0.22) showed the strongest linear relationships with optimum N_{V7} rates (Table 5). Our results agree with those of Scharf and Lory (2002), which concluded that a high-N reference was necessary to predict N need from aerial photographs.

At a later stage in corn development (VT), Sripada et al. (2005) developed a linear-plateau model using RGDVI that explained 67% of the variability in economic optimum N rates. However, in the present study examining an earlier stage of corn development (V7), RGDVI was able to explain only 21% of the variability in optimum N rates. To illustrate the effects of year and irrigation on the relationship between RGDVI and optimum N_{V7} rates, RGDVI was plotted against optimum N_{V7} separated by irrigation (Fig. 2a) and year (Fig. 2b). The index RGDVI had a significant linear relationship with optimum N_{V7} rates in 2002 and when separated by irrigation treatment (Fig. 2a and Table 6). However, the linear model did not have a significant relationship in 2003 (Fig. 2b and Table 6).

The large levels of unexplained variability in the relationships between spectral indicators and optimum N

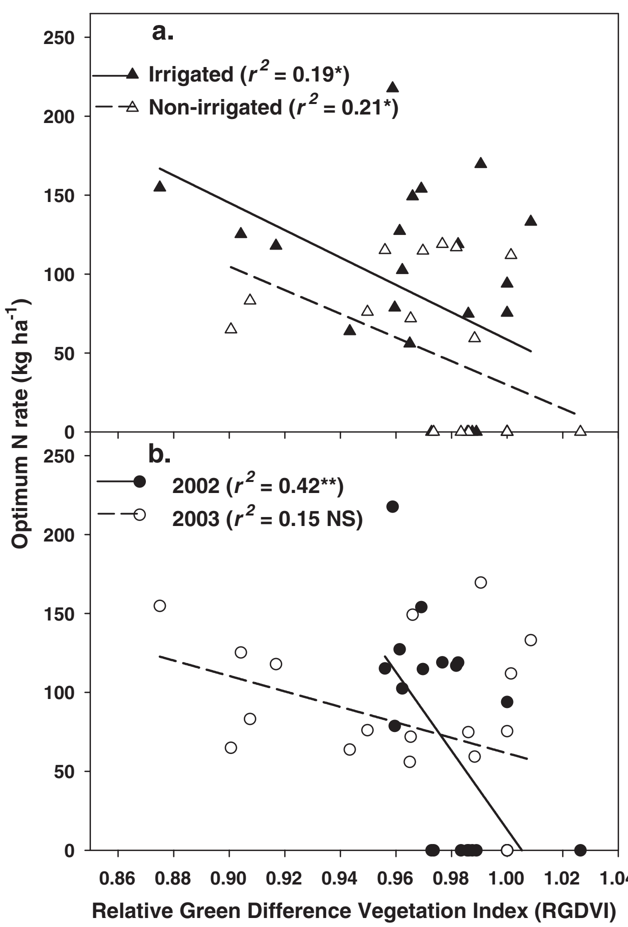

Fig. 2. Relationships between optimum N rate at growth stage V7 (N_{V7}) and Relative Green Difference Vegetation Index (RGDVI) (a) separated by irrigation and (b) separated by year. * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

rate at V7 compared with those reported at VT (Sripada et al., 2005) are probably due to the influence of soil reflectance and the inherently greater uncertainty of growing-season conditions from N application to maturity, especially in rainfed environments. Scharf and Lory (2002) in similar work done at the same growth stage (V7) observed improved relationships between economic optimum N rates and relative corn color from aerial photographs when soil pixels were removed from the images. They observed a linear relation between predicted economic optimum N rates and Rel G (R^2 = 0.70) or Rel B (R^2 = 0.79) reflectance. However, these relationships held only under conditions where no N was applied at planting and required that soil pixels in the image be eliminated before obtaining the digital counts. A similar analysis done in the present study by excluding all treatments except those where no N was applied at planting resulted in R being the only band or index that was significant (r^2 = 0.39; not shown). Unfortunately, the procedure to eliminate soil pixels from the image can be subjective, error prone, and laborious with no predefined protocol. Scharf and Lory (2002) obtained their images at lower altitude (150 m) than we did, resulting in higher-resolution images than ours. The lower spatial resolution of our images prevented separation of soil from plant pixels. The minimum resolution of the aerial CIR images obtained in this study was 0.45 m. Therefore, with 0.91-m row spacing, every pixel contained a combination of soil and plant. Hence, there was no possibility of removing the soil pixels from our images. Our study was conducted at 0.91-m row spacing; different results might be obtained with narrower rows, which tend to provide more equidistant plant spacing (for comparable seeding rates and plant populations) and thus better ground cover early in the season. To obtain images with resolution high enough to separate the soil pixels from the images would require the use of a higher focal length, larger format camera, and/or lower altitude, which would likely necessitate multiple images to capture a single field. This, in turn, could result in problems in correcting for slightly differing light intensity and digital characteristics.

The strengths of many of the relationships of spectral indicators with optimum N_{V7} were improved by removing the N_{PL} treatments that were nonresponsive to N_{V7} (i.e., those for which optimum N_{V7} = 0 kg ha^{-1}) (Table 5). The exceptions were NIR and the relative indices, which were not significant. The indices Norm NIR, GDVI, GRVI, GNDVI, and GSAVI were the best predictors of optimum N_{V7} when the N_{PL} treatments that were nonresponsive to N_{V7} were eliminated from analysis (r^2 = 0.33; Table 6 and Fig. 3). The Illinois Soil Nitrogen Test (Khan et al., 2001) has shown promise in identifying sites in North Carolina where corn does not respond to N applications (Williams, 2005).

Practical Implications

The currently recommended practice for determining N rates for corn in North Carolina is based on "realistic

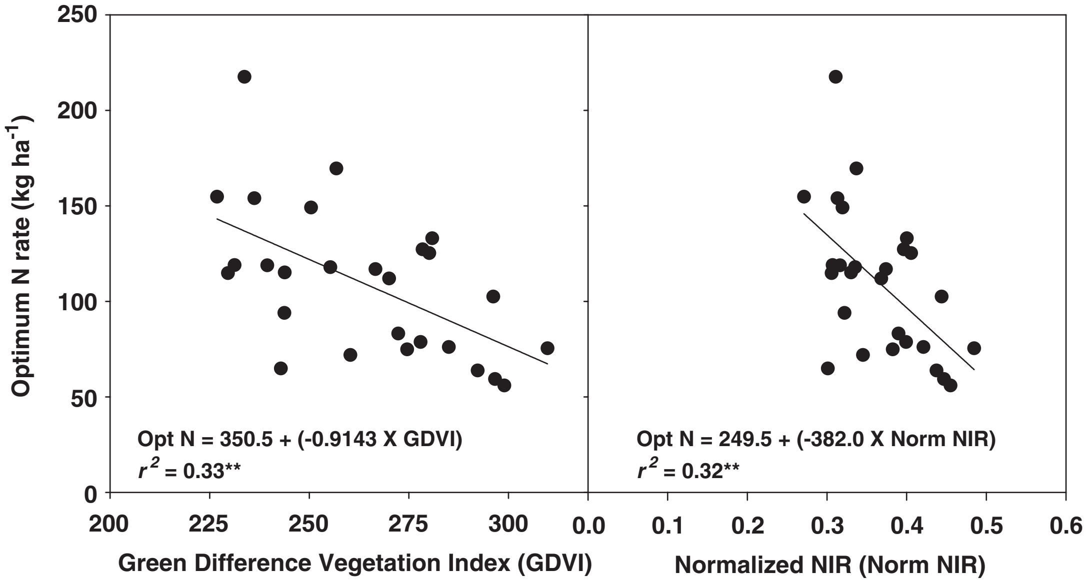

Fig. 3. Models showing the relationships of optimum N rate at growth stage V7 (N_{V7}) with (a) Green Difference Vegetation Index (GDVI) and (b) normalized near infrared (Norm NIR), both excluding the treatments that had an optimum N_{V7} rate of 0 kg ha^{-1}. ** indicates significance at the 0.01 probability level.

yield expectation" (RYE [Crozier, 2002]) estimates specific to the predominant soil series of a field. Similar determinations are common elsewhere in the warm and humid southeastern USA where no effective soil-test-based N recommendations yet exist. A small proportion of the total recommendation is applied at planting and the remainder sometime between the V2 and V7 growth stages. The earlier in the season that N is applied, the greater the risk that it will be lost by leaching, denitrification, or runoff, leaving insufficient N to meet the peak requirements of corn later in the season and adversely affecting yield. However, growers often find it more convenient to apply N early in the season.

Despite the examination of a number of spectral indices and methods for adjusting these indices for changing soil and light conditions, we had limited success relating in-season optimum N_{V7} rates to corn canopy color (R and G) or NIR radiance or any of the indices derived from mathematical combinations of the different spectral bands. When considered over years and irrigation, G, DVI, and GDVI expressed relative to a high-N reference plot (i.e., Rel G, RDVI, and RGDVI) had the strongest relationships with optimum N_{V7} rates. However, at best, these indices were able to explain only 22% of the variability in optimum N_{V7} rates. In 2002 or with irrigation, several indices explained over 40% of the variability in optimum N_{V7} (Table 6), but this performance was not maintained over years or without irrigation.

One obstacle in the field application of this technique is the requirement for high-N reference strips in the field. Rather than having one reference strip at random, a better method may be to have a series of reference strips across different soil series in the field and based on the farmers' knowledge about the variability in the field. Though this technique can be used to give a series of N application rates on a site-specific basis, the ability of application equipment to adjust rates and the need for more calibration strips could limit the use of this technique in precise application of N.

CONCLUSIONS

Greater success in predicting in-season N requirements for corn using aerial CIR photography was observed at VT (Sripada et al., 2005) compared with V7 in the present study. This is in agreement with the observations made by Scharf and Lory (2002) that soil pixels should be eliminated for improved relationships between corn color and optimum N rates at V7. In the present study, at the V7 growth stage, the groundcover was not complete, and the low resolution of the images did not permit the separation of soil and crop pixels, contributing in part to the lack of strong relationships between optimum N rates and spectral radiance compared with the complete canopy cover observed at VT (Sripada et al., 2005). By eliminating the sites where yield did not respond to N_{V7}, indices such as Norm NIR, GDVI, GRVI, and GNDVI were able to describe only as much as 33% of the variability in optimum N_{V7} rates. Optimum utilization of these indicators to estimate N_{V7} would thus be restricted to N-responsive sites. The primary difficulties in determining that a site will be nonresponsive to N are the unpredictability of available soil N and soil moisture in rainfed situations. Further research is needed to determine if stronger relationships between spectral indicators and optimum N_{V7} can be developed, perhaps by using higher-resolution images that would allow the removal of soil pixels from the image as did Scharf and Lory (2002). With high-resolution images, a supervised or unsupervised image classification algorithm could probably be developed to facilitate removal of soil pixels and thereby strengthen relationships between spectral information from aerial CIR photographs and optimum early-season N rates.

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