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

Ravi P. Sripada, Ronnie W. Heiniger, Jeffrey G. White,* and Randy Weisz

ABSTRACT

Fast and accurate methods of determining in-season corn (*Zea mays* L.) N requirements are needed to provide more precise and economical management and potentially decrease groundwater N contamination. The objectives of this study were (i) to determine if there is a response to late-season N applied to corn at pretassel (VT) under irrigated and nonirrigated conditions, and (ii) to develop a methodology for predicting in-season N requirement for corn at the VT stage using aerial color infrared (CIR) photography. Field studies were conducted for 3 yr over a wide range of soil conditions and water regimes in the North Carolina Coastal Plain. Different fertilizer N rates were applied (i) at planting (N_{PL}) to create a range of N supply, corn color, and near-infrared (NIR) radiance; and (ii) at VT (N_{VT}) to measure yield response to N_{VT}. Aerial CIR photographs were obtained for each site at VT before N application. Significant grain yield responses to N_{PL} and N_{VT} were observed. Economic optimum N_{VT} rates ranged from 0 to 224 kg ha^{-1} with a mean of 104 kg ha^{-1}. Better prediction of economic optimum N_{VT} rates was obtained with spectral band combinations rather than individual bands, and improved when calculated relative to high-N reference strips measured at VT. The best predictor of economic optimum N_{VT} (R^2 = 0.67) was a linear-plateau model based on corn color and NIR radiance expressed using the Green Difference Vegetation Index (GDVI) relative to high-N reference strips (Relative GDVI, RGDVI).

GROUND- AND SURFACE WATER N contamination from southeastern U.S. coastal plain agriculture is a regulatory and social issue threatening regional crop production. Matching fertilizer N rates and timing with crop N needs can reduce fertilizer nitrate (NO_3–N) losses and minimize a potential source of surface and groundwater pollution (Ferguson et al., 2002). Crop N requirements change from year to year, and quantifying the optimum in-season N requirement is an important step toward an economically and environmentally viable crop production system (Varvel et al., 1997). Traditional methods of estimating corn in-season N requirements 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 N requirements.

The traditional N fertilization practice for corn production in the southeastern USA has been to apply some amount of N as starter and the remainder as a split application (Crozier, 2002) from before the V4 growth stage to as late as the V8 (Ritchie et al., 1997) growth stage. This can be a problem since approximately one-third of the total N used by a corn crop is taken up after pollination under favorable soil moisture conditions, and N applied earlier may be lost through leaching and denitrification. Due consideration should be given to sidedress N applications at or near tasseling (VT), with adequate N applied earlier in the season to maintain yield potential through VT (Crozier, 2002).

Image-based remote sensing can be used to monitor seasonal variability of soil and crop characteristics such as soil moisture, biomass, crop evapotranspiration, and crop nutrient deficiencies (Blackmer et al., 1996). Remote sensing via aerial color photography has been used to detect N stress in corn (Blackmer and Schepers, 1996; Blackmer et al., 1996), predict corn yield potential (Taylor et al., 1997), and determine N fertilizer requirements for site-specific application by utilizing green (G) digital counts early in the growing season (Scharf and Lory, 2002). These studies showed that color and/or color infrared (CIR) photographs obtained between growth stages V7 and VT could be used to predict yield potential and crop N requirements.

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

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Abbreviations: AOI, areas of interest; B, blue; CIR, color infrared; DGPS, differential global positioning system; DN, digital number; 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; NCDA, North Carolina Department of Agriculture; NDVI, Normalized Difference Vegetation Index; NIR, near-infrared; Norm G, normalized green; Norm NIR, normalized NIR; Norm R, normalized red; N_{PL}, nitrogen applied at planting; NRI, Nitrogen Reflectance Index; N_{VT}, nitrogen applied at VT; OSAVI, Optimized Soil Adjusted Vegetation Index; 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; RMS, root mean square; 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; SAVI, Soil Adjusted Vegetation Index; UAN, urea–ammonium nitrate solution; VT, pretassel.

nents 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 (Lillesand and Kiefer, 1987). 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). Further, it has been reported that vegetation under stress shows decreased NIR reflectance, reduced R absorption in the chlorophyll active band (~680 nm), and a consequent shift of the R edge toward shorter wavelengths (Blackmer et al., 1996). Blackmer et al. (1994) demonstrated that corn leaf reflectance in the G (550 nm) was particularly sensitive to leaf N status.

Vegetation indices developed from spectral observations in the R and NIR wavelengths have shown strong correlations with plant variables such as green leaf area of a tropical rain forest (Jordan, 1969), winter wheat (*Triticum aestivum* L.) (Wiegand et al., 1979), and soybean [*Glycine max* (L.) Merr.] (Holben et al., 1980), and with grain yield and severity of drought stress in winter wheat (Tucker et al., 1980). The normalized difference vegetation index (NDVI; Rouse et al., 1973), defined as the ratio of the difference and the sum of the reflectance in the NIR and R regions of the spectrum, has been the most widely used spectral vegetation index. The NDVI is a good indicator of crop stress, and has been considered an indirect measure of crop yield (Shanahan et al., 2001). Jordan (1969) developed the ratio vegetation index (RVI), which is the ratio of the radiance in the NIR to that in the R, and functionally similar to NDVI.

One of the problems with using the spectral reflectance of corn canopies at V7 to determine yield potential or N requirement is the interference of the soil background. Soil influences on incomplete canopy spectra are partly due to dependency of the soil background signal on the optical properties of the overlaying canopy (Heilman and Kress, 1987; Huete, 1987). Differences in R and NIR flux transfers (Kimes et al., 1985; Choudhury, 1987) through a canopy can result in complex soil and vegetation interactions, which make it difficult to correct for soil background influences. However, Huete et al. (1985) found that the sensitivity of vegetation indices to soil background was greatest in canopies with intermediate levels of vegetation cover (50% green cover). Several indices—such as the difference vegetation index (DVI; Tucker, 1979) and the soil adjusted vegetation index (SAVI; Huete, 1988)—have been developed to correct for soil influences.

Another method of correcting for soil interference on incoming radiation is the use of relative indices. 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 NIR/G for an area of interest to NIR/G for a well N-fertilized reference (an area that is never N deficient). Gitelson et al. (1996) proposed that the use of the G band in a vegetation index could prove to be more useful than the R band for assessing canopy variation in biomass. The green NDVI (GNDVI) is the difference between the detected radiation in the NIR and G bands divided by the sum of the the detected radiation in the NIR and G bands [GNDVI = (NIR − G)/(NIR + G)]. Shanahan et al. (2001) suggested that corn GNDVI measured during mid–grain-filling period could be used to produce relative yield maps depicting spatial variability in fields, providing a potential alternative to the use of a combine yield monitor.

Although the ability to predict yield could be used to estimate N requirements, a more accurate method may be to use spectral reflectance or radiance to directly measure crop N requirements. To date, very few studies have been conducted to predict corn side-dress N requirement using remote sensing. Blackmer and Schepers (1995) developed an N sufficiency index (NSI) based on corn chlorophyll meter readings relative to a non–N-limited area to compare N status across fields and for fertigation in the Great Plains. Scharf and Lory (2002) used relative G to predict corn optimum sidedress N at V6 to V7. However, they found that the relationship 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 the color of well-fertilized corn in the same field.

The objectives of this study were (i) to determine if there is a response to late-season N applied to corn at pretassel (VT) under irrigated and nonirrigated conditions, and (ii) to develop a methodology for predicting in-season N requirement for corn at the VT stage using aerial CIR photography.

MATERIALS AND METHODS

Field studies were conducted in North Carolina at five locations in 2000 and at three locations in both 2001 and 2002, with irrigated and nonirrigated sites at two of these: Peanut Belt Research Station (PBRS) and Tidewater Research Station (TRS). Soil classification, tillage, and site identification are described in Table 1. The sites covered a wide range of soils, weather patterns, and management practices typical of southeastern U.S. corn production.

A two-way factorial experimental design was implemented as a split-plot in randomized complete blocks with three replications in 2000 and 2001, and four replications in 2002, with the initial N applied at planting (N_{PL}) as the main plot factor and sidedress N applied at VT (N_{VT}) as the subplot factor. Main plots were 9.1 m long and 20 rows wide in 2000 and 2002, and 16 rows wide in 2001, with 0.91-m row spacing. The subplots were four rows wide at all sites. Urea-ammonium nitrate solution (UAN, 30% N) was surface-applied at planting and VT using a CO_2–pressurized backpack sprayer. The sprayer was calibrated for the different N rates before each treatment application. In 2000 the N_{PL} and N_{VT} rates were 0, 56, 112, 168, and 224 kg ha^{-1}. In 2001 the N_{PL} and N_{VT} rates were 0, 112, 168, and 224 kg ha^{-1}. In 2002 the N_{PL} rates were 0, 56, 112, and 224 kg ha^{-1} and the N_{VT} rates were 0, 56, 112, 224, and 280 kg ha^{-1}. With the exception of N management, standard management practices for the region were followed at each site (Table 1). Fertilizer rates other than N were based on

Table 1. Soil type and classification and cultural practices for the experimental sites.

Site	Location†	Year	Irrigation‡	Tillage§	Soil series	Soil taxonomic classification
1	PBRS	2000	IR	CT	Norfolk loamy sand	fine-loamy, siliceous, thermic Typic Paleudults
2	PBRS	2000	NI	CT	Norfolk loamy sand	fine-loamy, siliceous, thermic Typic Paleudults
3	DNT	2000	NI	NT	Kirskey clay loam	fine-silty, siliceous, thermic Aquic Hapludults
4	HSOR	2000	NI	NT	Arapohoe coarse loam	coarse-loamy, mixed, nonacid, thermic Typic Humaquepts
5	HSSR	2000	NI	NT	Dragston sandy loam	coarse-loamy, mixed, thermic Aeric Ochraquults
6	TRS	2000	NI	CT	Hyde clay loam	fine-silty, mixed, thermic Typic Umbraquults
7	TRS	2000	IR	CT	Cape Fear loam	clayey, mixed, thermic Typic Umbraquults
8	PBRS	2001	IR	CT	Norfolk loamy sand	fine-loamy, siliceous, thermic Typic Paleudults
9	PBRS	2001	NI	CT	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
10	HSOR	2001	NI	NT	Arapohoe coarse loam	coarse-loamy, mixed, nonacid, thermic, Typic Humaquepts
11	TRS	2001	IR	CT	Cape Fear loam	clayey, mixed, thermic Typic Umbraquults
12	TRS	2001	NI	CT	Cape Fear loam	fine-silty, mixed, thermic Typic Umbraquults
13	PBRS	2002	IR	CT	Norfolk loamy sand	fine-loamy, siliceous, thermic Typic Paleudults
14	PBRS	2002	NI	CT	Norfolk loamy sand	fine-loamy, siliceous, thermic Typic Paleudults
15	TRS	2002	IR	CT	Cape Fear loam	clayey, mixed, thermic Typic Umbraquults
16	TRS	2002	NI	CT	Cape Fear loam	clayey, mixed, thermic Typic Umbraquults
17	TRS	2002	IR	CT	Hyde clay loam	fine-silty, mixed, thermic Typic Umbraquults

† PBRS, Peanut Belt Research Station, Lewiston-Woodville, NC; DNT, Denton Farms, Denton, NC; HSOR, Haslin Farms–Organic Ridge, Belhaven, NC; HSSR, Haslin Farms–Sandy Ridge, Belhaven, NC; TRS, Tidewater Research Station, Plymouth, NC.
‡ IR, irrigated; NI, nonirrigated.
§ CT, conventional tillage; NT: no till.

North Carolina Department of Agriculture (NCDA) soil test results and recommendations (Hardy et al., 2002). The hybrid 'Pioneer 31G98' was planted at approximately 60 000 seeds ha^{-1} with 0.96-m row spacing 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 plots were watered using overhead sprinkler irrigation at the rate of 2.5 cm wk^{-1}.

Determining Response to Nitrogen Applied at Pretassel

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, Logan, UT). Grain yield was adjusted to a moisture content of 155 g kg^{-1}. The grain yield response to year, irrigation, and N were analyzed using PROC MIXED in SAS Version 8 (SAS Institute, Cary, NC) with year, irrigation, N_{PL}, and N_{VT} considered as fixed effects and site as a random effect.

Determination of Economic Optimum Pretassel Nitrogen Rates

Grain yield response to N was modeled as a quadratic-plateau function using PROC NLIN in SAS Version 8 (SAS Institute, Cary, NC). Economic optimum N rates were calculated using the first derivative of the quadratic-plateau function and a price ratio of 4:1, defined as the ratio of the price per kilogram of N to the price per kilogram of corn. If a response did not fit a quadratic-plateau function as determined by the significance of the model ($\alpha = 0.05$), treatment means were compared using Fisher's protected LSD to determine the optimum N level. In situations where the yield response to fertilizer N was not significant as measured by either of the above methods, the economic 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 (DGPS) with 1-m accuracy (Trimble AG 132, Trimble Navigation, Sunnyvale, CA) was used to georeference the targets. Aerial CIR photographs were taken at each of these sites at VT using the technique described by Flowers et al. (2001). The aerial CIR images were obtained at altitudes (~750–900 m) such that the entire experimental field and surrounding area (~6 ha) was 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 and a TIFFEN 52 mm Yellow no. 12 filter (Eastman Kodak Co., Rochester, NY) were used. The film was AR-5-processed to obtain false CIR slides. 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 Systems, San Jose, CA), resulting in a ground resolution of 0.43 to 0.55 m. Differences in ground resolution were due to different altitudes at which the images were obtained. Digital images were georegistered using ERDAS Imagine version 8.7 (ERDAS, Atlanta, GA). The root mean square (RMS) error after the georegistration was <1 m.

The spectral properties of the CIR film used for obtaining images are described by Flowers et al. (2003). The CIR film emulsions respond to light within the visible and NIR regions of the electromagnetic spectrum (490–900 nm). The digitized images are represented by 24-bit true color with three bands: 8-bit red (R), 8-bit green (G), and 8-bit blue (B). For each pixel in the image, the primary color value is represented by a digital number within the range of 0 to 255 for each spectral band. 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, maximum sensitivity in the NIR band occurs at 730 nm, in the R band at 650 nm, and in the G band at 550 nm (Eastman Kodak, 1996). These differences in spectral sensitivity offer increased information through the use of spectral band combinations and vegetation indices (Table 2).

Areas of interest (AOI) corresponding to each individual plot, excluding the plot borders, were identified on the images; these included an approximately equal number of pixels for

Table 2. Spectral 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.

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 spectral band for each individual plot. Using the DN for the individual bands, a series of spectral indices were calculated (Table 2). Relative bands (Rel NIR, Rel R, 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 and 1 was added to DVI and GDVI, and all relative indices, respectively.

The digital counts for the NIR, R, and G bands and all of the indices were regressed against the economic 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 Institute, Cary, NC). The models (linear-plateau) for the relationship between the optimum N rate and an index were tested for differences among years and between irrigation treatments using PROC NLMIXED in SAS Version 8 (SAS Institute, Cary, NC). The parameters of a linear plateau model are the intercept a (the plateau for economic optimum N rate), slope b (of the linear portion of the model), and x_0 (the inflection point, the point beyond which there is no change in economic optimum N rate with change in the RGDVI values).

The NLMIXED procedure fits nonlinear mixed models, that is, models in which both fixed and random effects enter nonlinearly. Given the random effect, which in this study was the plateau for the economic optimum N rate, this procedure allows specification of a conditional normal distribution for the data. Successful convergence of the optimization problem results in parameter estimates along with their approximate standard errors based on the second derivative matrix of the likelihood function. The NLMIXED procedure was used to estimate the parameters for the linear-plateau model for each year and irrigation treatment. The estimated parameters were then tested for differences among years and between irrigation treatments using contrast statements.

RESULTS AND DISCUSSION

Yield Responses to Nitrogen Applications

Corn yields reached high levels at most of the experimental sites, and were significantly affected by N_{VT} fertilization (Table 3). Corn grain yields across the experimental sites ranged from 1.8 to 14.3 Mg ha^{-1} with a mean of 8.7 Mg ha^{-1} in 2000, 2.2 to 14.7 Mg ha^{-1} with a mean of 9.7 Mg ha^{-1} in 2001, and 2.1 to 12.3 Mg ha^{-1} with a mean of 7.2 Mg ha^{-1} in 2002. Sites 1, 2, 6 to 9, and 11 to 16, which comprised two locations, were used in an analysis to test the influence of year, irrigation, N_{PL}, and N_{VT} on yield. This resulted in an analysis of two irrigation treatments, four or five levels of N_{PL}, and four or five levels of N_{VT} over a period of 3 yr. All of the two-way interactions involving N_{VT} (N_{VT} × year, N_{VT} × irrigation, N_{VT} × N_{PL}) were significant (Table 3). The two-way interactions of N_{VT} with year and with irrigation were expected based on the well-documented variable N response of corn in different years and under different moisture regimes (Liang et al., 1991). The two-way interactions of N_{VT} with year and with N_{PL} were evident in the differing slopes of the response curves in Fig. 1. The main effects of N_{PL} and N_{VT} were also significant; however, the factors that interacted with N_{PL} and N_{VT} produced varying degrees of positive response.

An evaluation of growing-season weather data (State Climate Office of North Carolina, 2005) revealed near-average temperatures (0.7 and 0.6°C cooler than 30-yr avg. [23.3°C] in 2000 and 2001, respectively) and total precipitation (46 and 23 mm more than 30-yr avg. [563 mm] during 2000 and 2001, respectively). This provided a favorable environment for corn growth such that in certain situations a plateau for yield response was not observed, even at the highest N_{VT} application rate of 224 kg N ha^{-1}. However, in 2002, unusually hot

Table 3. ANOVA for corn grain yield as affected by year, irrigation, and fertilizer N at planting (N_{PL}) and at pretassel (N_{VT}) using data from all sites with irrigated and nonirrigated treatments (1, 2, 6–9, and 11–16).

Source of variation	df	Grain yield
Year	2	NS†
Irrigation	1	NS
N_{PL}	4	**
Year × N_{PL}	6	NS
Irrigation × N_{PL}	4	NS
Year × irrigation	2	NS
Year × irrigation × N_{PL}	6	NS
N_{VT}	5	**
Year × N_{VT}	6	**
Irrigation × N_{VT}	5	**
Year × irrigation × N_{VT}	6	NS
N_{PL} × N_{VT}	19	**
Year × N_{PL} × N_{VT}	18	NS
Irrigation × N_{PL} × N_{VT}	19	NS

** Significant at the 0.01 probability level.
† NS, not significant at the 0.05 probability level.

(1.6°C warmer than 30-yr avg.) and dry (132 mm less precipitation than 30-yr avg.) growing season weather culminated in drought conditions resulting in sites where there was no significant yield response to N_{VT} (not shown). The significant N_{VT} × year interaction was the basis for our decision not to include the 2002 data in the model development, as the continuous drought situation resulted in unrepresentative yield responses to N and unreliable economic optimum N rates.

To test the consistency of the N_{PL} and N_{VT} yield responses across different sites within 1 yr under nonirrigated conditions, Sites 2 to 6 were chosen for analysis (Table 4), due to the unbalanced nature of the larger data set. The two-way interactions of N_{VT} with site and N_{PL} were significant. The main effects of these factors (and of site) were significant, indicating again that the factors interacting with N affected the degree of response. For example, in 2000 and 2001, a wide range of yield responses to N_{VT} were observed. These ranged from considerable yield responses to N_{VT} at Sites 1, 2, 5, 8, and 9, to low or no response at Sites 3, 6, 7, and 11 where corn was preceded by peanut (*Arachis hypogea* L.) and N_{VT} rates of 168 and 224 kg N ha^{-1} resulted in no yield increase. This was probably due to high mineralization of residual soil N following the legume (Smith and Sharpley, 1990).

At many sites, lack of adequate N before VT resulted in irreversible loss of yield potential that was not regained by N additions at VT (Fig. 1). This is apparent in the N_{VT} response curves for the lower N_{PL} rates, where the yield plateaus were lower than those of the higher N_{PL} rates. Since approximately one-third of the total N used by a corn crop is taken up after pollination given favorable soil moisture conditions, due consideration should be given to sidedress N applications at or near tasseling (VT), with adequate N applied earlier in the season to maintain yield potential through VT (Crozier, 2002). Practical limitations to applying N at VT include the availability of high-clearance applicators and the need to minimize damage to the corn crop.

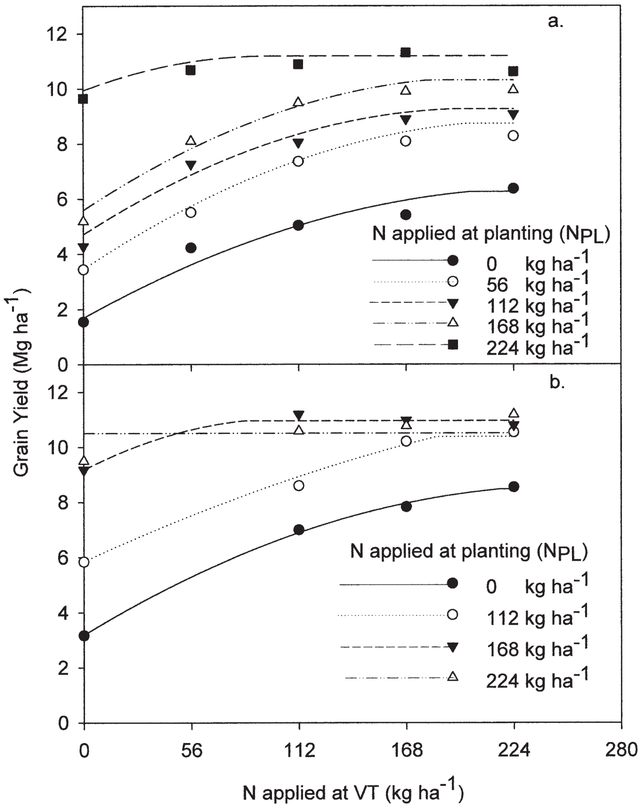

Fig. 1. Quadratic-plateau fit of corn grain yield response to N applied at VT (N_{VT}) for different rates of N applied at planting (N_{PL}) at (a) the Tidewater Research Station (TRS, Site 6) during 2000 and (b) the Peanut Belt Research Station (PBRS, Site 9) during 2001. Each point is the mean of three replicates.

Predicting Economic Optimum Pretassel Nitrogen Rates from Spectral Data

The different N_{PL} rates created a range of canopy color and NIR radiance in the field that was evident in the aerial CIR photographs, and subsequently resulted in a wide range of economic optimum N_{VT} rates. The range of economic optimum N_{VT} rates was 0 to 220 kg N ha^{-1} with a mean of 104 kg N ha^{-1}. The relationships of economic optimum N_{VT} with the absolute NIR and G bands were not significant, but the relationship with R was, albeit with a low $r^2 = 0.19$ (Table 5). However, the normalized bands were all significantly correlated with economic optimum $N_{VT,}$ and the correlation with normalized R was stronger than with absolute R. One possible interpretation for the significance of the nor-

Table 4. ANOVA for corn grain yield as affected by N at planting (N_{PL}) and at pretassel (N_{VT}) among different sites in 2000 using Sites 2, 3, 4, 5, and 6.

Source of variation	df	Grain yield
Site	4	**
N_{PL}	4	**
Site × N_{PL}	16	NS†
N_{VT}	4	**
Site × N_{VT}	16	**
N_{PL} × N_{VT}	16	**
Site × N_{PL} × N_{VT}	64	NS

** Significant at the 0.01 probability level.
† NS, not significant at the 0.05 probability level.

Table 5. Regression analysis of economic optimum pretassel N rate (N_{VT}) (kg ha^{-1}) vs. 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 models are given.

	Model			
Vegetation index	**Linear**	**Linear-plateau**	**Quadratic**	**Quadratic-plateau**
	r^2	R^2		
NIR	NS†	NS	NS	NS
Red	0.19**	0.19*	NS	NS
Green	NS	NS	NS	NS
Norm NIR	0.25**	NS	0.33*	0.35*
Norm R	0.28**	NS	NS	NS
Norm G	0.12*	NS	NS	NS
Rel NIR	NS	NS	NS	NS
Rel R	0.38**	NS	0.48**	0.48**
Rel G	0.23**	NS	0.32**	0.33**
DVI	0.40**	NS	NS	NS
RDVI	0.44**	0.69**	NS	NS
GDVI	0.36**	NS	NS	NS
RGDVI	0.51**	0.67**	0.62**	NS
RVI	0.20**	NS	0.28*	NS
RRVI	0.30**	0.50**	0.48*	NS
GRVI	0.19**	NS	0.26*	NS
RGRVI	0.31**	0.47**	0.42**	NS
NDVI	0.28**	NS	0.34*	0.35**
RNDVI	0.44**	NS	NS	NS
GNDVI	0.24**	NS	NS	0.31**
RGNDVI	0.41**	0.46**	0.46*	NS
SAVI	0.28**	NS	0.34*	0.35**
RSAVI	0.41**	0.55**	NS	NS
GSAVI	0.24**	NS	NS	NS
RGSAVI	0.43**	0.53**	0.48*	NS
OSAVI	0.28**	NS	0.34*	0.35**
ROSAVI	0.33**	0.47**	NS	NS
GOSAVI	0.24**	NS	NS	0.31**
RGOSAVI	0.40**	0.41**	0.45*	NS

*** Significant at the 0.05 probability level.**
**** Significant at the 0.01 probability level.**
† NS, not significant.

malized bands compared with the absolute bands is that the normalization effect of simply dividing by the sum of all bands helps correct for different illumination conditions. The regression analyses (Table 5) for indices composed of the NIR and G bands (GDVI, RGDVI) showed somewhat better relationships with economic optimum N_{VT} compared with the indices composed of the NIR and R bands (RVI, NDVI). Thomas and Gaussman (1977) obtained similar results for relationships between the reflectance at 550 nm (G) and the chlorophyll concentration, compared with using reflectance at 675 nm (R).

In this study, the raw DN values for the NIR and G were not significantly correlated with economic optimum N_{VT} rates (Table 5). However, both NIR and G spectral bands showed a trend across all the experimental sites, with greater radiance (higher DN) for plots that had greater economic optimum N_{VT} rates, and vice versa (not shown). The range of DN values for NIR (100–206) was narrower compared with G (44–211). Under reduced chlorophyll concentrations resulting from limited N supply in sweet pepper (*Capsicum annum*, L. var. 'Yolo Wonder'), Thomas and Oerther (1972) showed that leaf reflectance in parts of the visible spectrum increased as N deficiency symptoms became more pronounced, with a maximum reflectance at 550 nm and maximum absorbance at 670 nm. They also observed a simultaneous increased reflectance in the NIR. Reflectance of field-grown corn leaves at different N fertilization levels measured by McMurtrey et al. (1994) showed two significant regions of spectral separation. As N deficiency increased, leaf reflectance at 550 nm (G) increased and leaf reflectance in the NIR decreased, while reflectance at 670 nm (R) was indistinguishable among the various N fertilizer levels.

In contrast to the individual spectral bands, all of the absolute spectral indices were correlated with economic optimum N_{VT} (Table 5). However, none of the absolute indices (indices not adjusted relative to high-N plots) accounted for more than 40% of the variability in optimum N_{VT}. Walburg et al. (1982) evaluated radiometer single waveband response to N effects on field-grown corn as well as the NIR/R ratio and a greenness index (Kauth and Thomas, 1976). The NIR/R ratio was shown to have enhanced response to N treatment differences in canopy reflectance compared with single wavebands.

In our study, better prediction of economic optimum N_{VT} was observed with the relative indices (Table 5) than with individual spectral bands or absolute indices. Using indices computed relative to high-N reference strips in fields can help eliminate the potential errors that occur with images captured at different times and/or places. Schepers et al. (1992)—using a SPAD meter to measure chlorophyll concentration of corn leaves—suggested that readings be normalized to high-N strips in the field. Blackmer et al. (1996) used Rel R digital counts with reasonable success for qualitative assessment of within-field variation in corn N deficiency. Among the relative indices investigated in the present study, RGDVI accounted for the greatest amount of variability in the

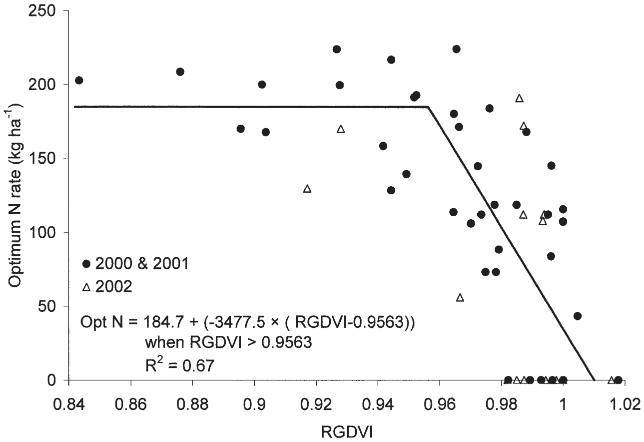

Fig. 2. Model showing the relationship between economic optimum pretassel N rate (N_{VT}) rate and Relative Green Difference Vegetation Index (RGDVI). Data from 2002 were not used in developing the model.

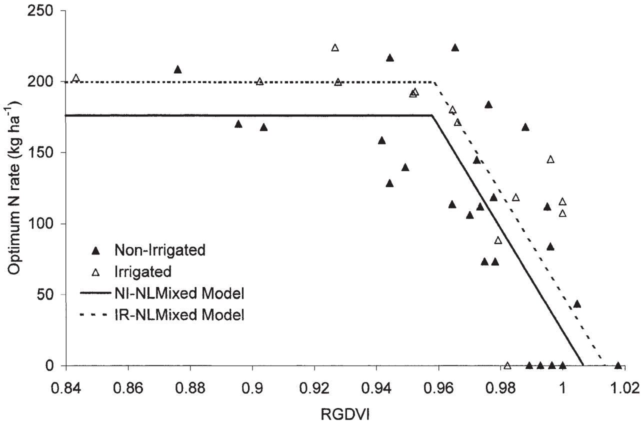

Fig. 3. Relationships between economic optimum pretassel N rate (N_{VT}) rate and Relative Green Difference Vegetation Index (RGDVI) and the best-fit linear-plateau models separated by irrigation.

linear prediction of economic optimum N_{VT}. Overall, linear-plateau models using RDVI (not shown) and RGDVI (Fig. 2) were the best predictors (R^2 = 0.69 and 0.67, respectively; Table 5) of optimum N_{VT}.

As shown by the yield results discussed previously, year and irrigation were important factors influencing yield response to N_{VT}. The linear-plateau models describing the relationships of predicted economic optimum N_{VT} with RDVI and RGDVI were tested for sensitivity to irrigation and year. Although RDVI showed a slightly higher R^2 for a linear-plateau relationship, the relationship with economic optimum N_{VT} was not consistent when analyzed separately for each irrigation treatment and year (not shown). For RGDVI (Fig. 2), the parameter estimate for the *y* intercept *a*, which is the maximum economic optimum N_{VT} rate, was numerically greater for the irrigated model compared with the nonirrigated model (Table 6, Fig. 3), as would be expected, but this "difference" was not significant. The estimates of the slope *b* and the inflection point x_0 between the two years and the two irrigation levels were also not significantly different (Table 6). The lack of differences (Table 6) between the linear-plateau models separated by irrigation (Fig. 3) and year (Fig. 4) indicate that year and irrigation did not significantly affect the model; thus, a combined model can be used to express the relationship between optimum N_{VT} rate and RGDVI (Fig. 2).

This combined model indicates that a gradual increase in RGDVI was associated with decreasing economic optimum N_{VT} rates. The values in the linear-plateau region, where the economic optimum N_{VT} rates show no response across RGDVI values, are from plots with relatively low N_{PL} rates, as would be expected. The narrow range of RGDVI values (0.9563–1.02) that is responsive to economic optimum N_{VT} rates is a concern, because even very small variation in the RGDVI values can change

Table 6. Model tests for differences in linear-plateau model parameters among year and irrigation treatments.

Parameter	Estimate	Standard error	Lower limit, 95% confidence interval	Upper limit, 95% confidence interval	*p* value
			Comparing 2000 model with 2001 model		
a_{2000}	176	15	142	210	***
a_{2001}	197	21	151	244	***
b_{2000}	−3620	676	−5124	−2112	***
b_{2001}	−3622	743	−5277	−1967	***
$x_{0\text{–}2000}$	0.956	0.008	0.939	0.973	***
$x_{0\text{–}2001}$	0.960	0.009	0.941	0.980	***
Contrasts					
a_{2000} vs. a_{2001}	–	–	–	–	NS†
b_{2000} vs. b_{2001}	–	–	–	–	NS
$x_{0\text{–}2000}$ vs. $x_{0\text{–}2001}$	–	–	–	–	NS
			Comparing irrigated model with nonirrigated model		
a_{IR}	198	20	155	242	***
a_{NI}	178	18	138	218	***
b_{IR}	−3619	953	−5743	−1495	**
b_{NI}	−3620	584	−4921	−2319	***
$x_{0\text{–}IR}$	0.959	0.009	0.938	0.980	***
$x_{0\text{–}NI}$	0.958	0.007	0.942	0.974	***
Contrasts					
a_{IR} vs. a_{NI}	–	–	–	–	NS
b_{IR} vs. b_{NI}	–	–	–	–	NS
$x_{0\text{–}IR}$ vs. $x_{0\text{–}NI}$	–	–	–	–	NS

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† NS, not significant.

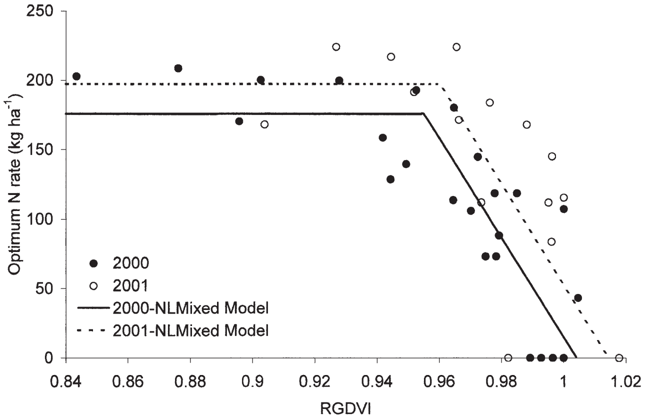

Fig. 4. Relationships between economic optimum pretassel N rate (N_{VT}) rate and Relative Green Difference Vegetation Index (RGDVI) and the best-fit linear-plateau models separated by year.

the predicted economic optimum N_{VT} rate significantly (Fig. 2). While we have not yet fully validated this model, an indicator of model aptness is provided by plotting the 2002 data excluded from model development in contrast to the data used to determine the final model along with the model itself (Fig. 2). The 2002 data do not have a linear-plateau trend by themselves, but exhibit behavior consistent with the overall model.

The use of a relative index to predict N application rates at VT requires the availability of high-N reference strips in the field, which is a potential limitation to the application of this technique. Rather than having one reference strip located at random, a better method may be to have a series of reference strips across the field based on the farmers' knowledge of field variability. Though this technique can provide N_{VT} application rates on a site-specific basis, the ability of application equipment to adjust rates and the potential need for multiple calibration strips can limit the use of this technique in precision application of N.

Scharf and Lory (2002) conducted similar work at a much earlier corn growth stage (V7) and observed a linear relationship between predicted economic optimum N rates and G ($R^2 = 0.70$) or B ($R^2 = 0.79$) reflectance. However, these relationships only held under conditions where no N was applied at planting and required that soil pixels in the image be eliminated before obtaining the digital counts. These are serious problems, since most growers apply N at planting, and the process for removing soil pixels from an image requires high resolution images and additional time and cost.

Given the positive results obtained in our study, it would be interesting to investigate how early in the season N requirements for corn can be predicted using our methods. The major technical obstacle in applying this technique earlier in the growing season is the influence of soil pixels on the calculation of the index values. Since this study was done at VT when canopy closure and groundcover were nearly complete, we would not expect significant interference from soil pixels. Another agronomic obstacle to applying this technique earlier in the season is the unpredictability of available soil moisture in rain-fed situations.

CONCLUSIONS

This study demonstrated a corn yield response to N_{VT} over a wide range of N fertility levels at planting. In many cases, however, lack of adequate N before VT resulted in a loss of yield potential that was irreversible, that is, not regained by N additions at VT. Thus, adequate N applied earlier in the season (e.g., V7–V8) is necessary to maintain yield potential through VT. Spectral reflectance of corn expressed using GDVI relative to high-N strips successfully predicted optimum sidedress N_{VT} rates. The prediction model was robust to a wide range of moisture regimes, environments (years), and available soil N. In principle, this technique can be used to determine late-season N rates for corn that optimize profitability. By assessing corn N requirements late in the season during the period of maximum N uptake and applying fertilizer appropriately, application of large amounts of N early in the season when corn uptake is low and leaching potential high might be avoided, and groundwater pollution thus minimized.

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