ABSTRACT

SRIPADA, RAVI PRAKASH. Determining In-Season Nitrogen Requirements for Corn Using Aerial Color-Infrared Photography. (Under the direction of Ronnie W. Heiniger and Jeffrey G. White)

Fast, accurate methods to determine in-season corn (*Zea mays* L.) nitrogen (N) requirements are needed to provide more precise and economical management and potentially decrease groundwater N contamination. The objectives of this study were to: (i) determine if there is a response to in-season N applied to corn at (V7: N_{V7}) and pre-tassel (VT: N_{VT}) under irrigated and non-irrigated conditions; (ii) develop a methodology for predicting in-season N requirement for corn at the V7 and VT stages using aerial color infrared (CIR) photography; (iii) validate the RGDVI-based remote sensing technique for determining in-season N requirements for corn at VT growth stage and to test the robustness of the model across years; (iv) examine the response of corn agronomic parameters (biomass, plant N concentration, and total N uptake) and spectral parameters (near-infrared [NIR], red [R], and green [G]) from CIR measured at the V7 and VT growth stages to changing environments (year), irrigation, and N applied at planting (N_{PL}); and (v) determine the relationships between corn agronomic parameters and spectral parameters that influence the prediction of optimum N_{V7} and N_{VT} rates.

Field studies were conducted for four years over a wide range of soil conditions and water regimes in the North Carolina Coastal Plain. A two-way factorial experimental design was implemented as a split-plot in randomized complete blocks with N_{PL} as the main plot factor and N_{V7} or N_{VT} as the sub-plot factor. Corn agronomic parameters were measured and aerial CIR photographs were obtained for each site at V7 or VT prior to N application.

Significant grain yield responses to N_{PL} and N_{V7}, 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}. Spectral radiation of corn measured using the Green Difference Vegetation Index (GDVI) relative to high-N reference strips using a linear-plateau model was the best predictor of optimum N_{VT} ($R^2 = 0.67$).

Optimum N rates at V7 (N_{V7}) ranged from 0 to 207 kg N ha^{-1} with a mean of 67 kg N ha^{-1}. Very weak correlations were observed between optimum rates of N_{V7} and band combinations with significant correlations for relative G, RGDVI, and relative difference vegetation index (RDVI). 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 rates of N_{V7}.

In the VT validation study, the difference between predicted and observed optimum N_{VT} rates ranged from -30 to 90 kg N ha^{-1}. Overall, the remote sensing technique was successful ($r^2 = 0.85$) in predicting optimum N_{VT} rates despite the inherent constraints of predicting yield potential in any particular year. Although the model tended to over-predict optimum N rates, it was able to capture changes in optimum N rates across the range of conditions tested. N_{PL} significantly influenced corn agronomic parameters measured at V7 and VT.

Corn spectral parameters measured at V7 and VT also varied with year and N_{PL}. G and NIR were significantly correlated with biomass and total N uptake. Relative indices using G and NIR were related to plant N concentration. The spectral index

RGDVI showed consistently significant relationships with corn agronomic parameters measured at VT when analyzed across irrigated and non-irrigated experiments.

Lack of adequate N prior to VT resulted in a loss of yield potential that was irreversible, that is, not regained by N additions at VT. Thus adequate N applied at planting and/or at layby (e.g., V7-8) is necessary to maintain yield potential through VT. 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. There exists a potential to improve in-season estimates of N requirements earlier in the season by investigating further into the use of high resolution images and by the ability to identify non-responsive sites.

DETERMINING IN-SEASON NITROGEN REQUIREMENTS FOR CORN USING AERIAL COLOR-INFRARED PHOTOGRAPHY

by

RAVI PRAKASH SRIPADA

A dissertation submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the degree of
Doctor of Philosophy

In

SOIL SCIENCE

Raleigh, NC

2005

Approved by:

Ronnie W. Heiniger
Dr. Ronnie W. Heiniger
(Co-Chair of Advisory Committee)

Dr. Jeffrey G. White
(Co-Chair of Advisory Committee)

Dr. David A. Crouse

Dr. Randy Weisz

Dr. John L. Havlin
(Chair of Advisory Committee)

DEDICATION

To my

Mother **Lakshmi Sripada**

and

Father **Sastry Narasimha Sripada**

BIOGRAPHY

Ravi Prakash Sripada was born in Khammam and is a native of West Godavari district located in the coastal region of Andhra Pradesh in South India. He is the youngest son of Sastry N. Sripada and Lakshmi Sripada. His childhood and early schooling years were spent in the cities of Vijayawada and Hyderabad in southern India. He completed his B.Sc. (Ag) in 1998 with emphasis in Agronomy at Acharya N.G. Ranga Agricultural University, Hyderabad India. In August 1999 he moved to Fort Collins, CO to pursue higher studies. He completed his Master's program with emphasis on Soil and Crop Sciences at Colorado State University in 2001. In August 2001, he set out to Raleigh to pursue his Doctoral program in the department of Soil Science at North Carolina State University, Raleigh NC. In December, 2003 he was married to Sandhya Gunturu.

ACKNOWLEDGEMENTS

I would like to extend my deep gratitude and appreciation to my major advisor Dr. Ronnie W. Heiniger who was instrumental in the development of this project and spent countless hours assisting with field work and documenting the results. I would like to acknowledge the help and support of Dr. Jeffrey G. White for his support and guidance provided throughout this study. Without their help this study would not have been possible.

Likewise the support of author’s advisory committee members Drs. John L. Havlin, David A. Crouse, and Randy Weisz is greatly appreciated.

I would like to extend my appreciation and deep gratitude to Alan D. Meijer for his help in getting the field work done in time and in collecting data for this study.

Heart felt thanks are extended to Brian Roberts, Jared Williams, Dianne Farrer, and Hong Nan who contributed in the gathering of the data for this study. An expression of gratitude goes to the author’s friends and fellow graduate students for their encouragements and contributions of humor during my academic endeavors. A special note of thanks is due to the faculty members and secretarial staff of the Department of Soil Science at North Carolina State University for their support during my time at North Carolina State University. I would like to acknowledge the support staff at the Tidewater Research Station, Plymouth NC, and the Peanut Belt Research Station, Lewiston-Woodville, NC in conducting the field experiments.

Finally, I would like to express my deepest and sincerest thanks to my parents Sastry N. Sripada and Lakshmi Sripada, wife Sandhya Sripada and family members (Ramesh L.N. Sripada, Rajesh Sreepada, UshaRani Sripada, SitaMahaLakshmi Sreepada, Ramakrishna S. Gunturu, Lakshmi Gunturu, Sudha K. Gunturu, niece Pranathi L. Sreepada, and nephew Praneel S. Sreepada) for their never-ending encouragement and support, which has enabled the completion of this degree.

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CHAPTER ONE

INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

Accurate and timely information on crop input parameters is important because of the environmental and economic impacts of agriculture and the need to produce more food more efficiently to feed a growing population. One major input in the agricultural production systems of the southeastern USA is nitrogen (N) fertilizer. Fertilizer N applied to crops, e.g., corn (*Zea mays* L.), that is not taken up by the crop may be lost by leaching into the groundwater, or by denitrification, volatilization, and soil erosion. Apart from the inherent genetic characteristics of the crop, N loss can be minimized by matching the N supplying capacity of soil and fertilizer N application with the N uptake pattern of corn. Among other factors, the N uptake pattern of corn is primarily governed by soil moisture and environmental conditions during the growing season.

As is evident from many past and on-going studies, corn N requirements are usually more efficiently achieved by multiple fertilizer applications rather than one single application (Blackmer et al., 1996; Andraski et al., 2000). The traditional practice for N management in corn in the southeast US has been to apply N as a split application, first at the time of planting and the other around the V3-V7 growth stage (Ritchie et al., 1993). Research has shown that approximately one-third of the total N uptake in corn occurs after the tassel has appeared (Fig. 1: Ritchie et al., 1993; Crozier, 2002). Therefore, there is an enormous potential to apply N as late as tasseling (VT) to meet some of the N requirements and minimize losses. There is general agreement on the value of applying N in split applications (Russelle et al., 1983; Blackmer et al., 1989; Jokela and Randall, 1997). However there is considerable debate over the methods and/or processes used to quantify the second split N application and this is an area of active research.

Traditional methods of estimating in-season N requirements for corn are based on soil testing (Magdoff, 1991), tissue N concentrations (Tyner and Webb, 1946), chlorophyll concentrations, or leaf greenness (Varvel et al., 1997a). Tissue N concentrations and N uptake levels at particular growth stages have been used as indicators of N need for corn. All these methods require multiple samples to be taken, can be expensive and time consuming, and often produce inaccurate estimates of N requirements (Blackmer and Schepers, 1996). There is a need for a faster and possibly more economical alternative methodology for collecting crop information and estimates of N requirements. Our research attempts to use remote sensing technologies as an alternative to the existing methodologies for estimating in-season N requirements for corn.

The objectives of this research were to:

i) determine if there was a response in corn productivity to late-season N applied at VT under irrigated and non-irrigated conditions in the Southeast USA;

ii) develop an in-season model based on remotely sensed data to predict the amount of sidedress N required by corn at VT that could be used under different initial N levels and simultaneously account for any confounding soil reflectance;

iii) develop an in-season model to predict the amount of sidedress N required by corn at the V7 growth stage, which could be used under different N levels and simultaneously account for any confounding soil reflectance;

iv) validate the best model developed to estimate optimum N rate at VT, and to determine if the model was robust across varying environments such as changing moisture regimes;

v) examine the response of corn agronomic parameters (biomass, plant N concentration, and total N uptake) and spectral parameters (near-infrared [NIR], red [R], and green [G]) from CIR measured at the V7 and VT growth stages to changing environments (year), irrigation, and N applications at planting (N_{PL});

vi) determine the relationships between corn agronomic parameters and spectral parameters that influence the prediction of optimum N rates at growth stages V7 and VT.

LITERATURE REVIEW

Response of Corn to In-season N Fertilization

Fertilizer N recovery by the crop may sometimes be greater when N application is delayed compared to application at planting (Russelle et al., 1983; Jokela and Randall, 1997). This is probably due to greater exposure of N applied at planting to a range of possible loss processes (immobilization, leaching, denitrification, and clay fixation) at a time when N uptake rates are relatively low. Most of the research on N application after planting has compared applications at or before planting to sidedress applications at growth stage V8 or earlier. In many cases, no yield differences between preplant and sidedress N applications were reported (Jokela and Randall, 1989; Roth et al., 1995). In other cases, sidedress N applications gave small yield increases (Bundy et al., 1992; Reeves and Touchton, 1986; Welch et al., 1971). However, even when grain yield is not affected by N applications at V8, total dry matter production may be reduced with sidedress N applications (Jokela and Randall, 1989). For irrigated corn grown on sandy soils, sidedress applications (at silking) tend to produce higher yields than preplant applications (Bundy et al., 1983; Rehm and Wiese, 1975).

Research on response to N applications in corn later than the V8 growth stage has been limited. Nitrogen applied late in irrigated systems can be moved into the root zone by irrigation water. Jung et al. (1972) observed equivalent yields when a single N application was made from 5 to 8 wks (corresponding to V5 to V12 growth stages) after planting, but yields began to decline when N application was delayed until the ninth week or later. Supplemental N applications in the middle Atlantic coastal plain, later than normal sidedress time, that is, V16, can produce yields higher than those obtained with preplant or sidedress (V5) applications alone (Evanylo, 1991; Rehm and Wiese, 1975). On irrigated silty clay loam soils in the mid-west, Olson et al. (1986) measured higher grain yields (averaged over a 15 yr period) when N was applied at the V11 to V12 stage than when it was applied at planting. Studies by Russelle et al. (1983) in the mid-west measured higher yields when N was applied at V8 or V16 than when it was applied at planting or V4 under irrigated conditions. In the mid-west, Blackmer and Shepers (1995a) observed significant responses to N applied as late as R4-R5 stage, in conjunction with improved ability to determine yield potential and corresponding N requirement.

Late N applications in rainfed production systems might behave differently. For example, N may not be absorbed by the root system when rainfall is limited after N applications. Only a few reports of N applications later than V8 in rainfed systems are available. Studies in Kentucky under rainfed conditions by Miller et al. (1975) obtained a large yield response to N and equivalent yields regardless of whether N was applied in May, June, July, or a May–June split. Randall et al. (1997) found equivalent corn yields with all N fertilizer applied at planting or with one-third applied at planting and the remaining delayed until V16 in southern Minnesota. In summary, most trials with N applications later than V8 have found little or no evidence of grain yield reduction with delayed N applications.

Determination of Corn N Requirements

Predictions of crop N requirements and yield are derived from the product of field area and estimates of fertilizer rates based on tissue N, available soil N, or yield per unit area. When compared to the traditional methods of soil and tissue sampling, collecting such information on a large scale can be achieved more economically using remote sensing techniques. Aerial photography is a remote sensing technique in which a photograph of a scene of interest on the Earth's surface is taken from an aircraft in flight. Image-based remote sensing can provide valuable crop information over both time and space. Infrared images obtained late in the growing season can be used with crop growth models to map crop yields and also to predict yields. Image based remote sensing can also be used to monitor seasonal variability of soil and crop-characteristics such as soil moisture, biomass production, crop evapo-transpiration, crop nutrient deficiencies, and weed or insect infestations (Moran et al., 1997). This information can be used as an aid in decision making to target crop and soil inputs according to the requirements of the field which should result in optimal profitability and protection of the environment.

Spectral Reflectance of Crop Canopy

Crop reflectance is defined as the ratio of the amount of radiation reflected by an individual leaf or canopy to the amount of incident radiation. The pigments involved in photosynthesis (chlorophyll) absorb visible light (400–700 nm) selectively. Green, photosynthetically active leaves absorb mainly blue (B: ~ 450 nm) and red (R: ~ 660 nm) wavelengths and reflect mainly green (G: ~ 550 nm) wavelengths. Therefore, reflectance measurements at these wavelengths give a good indication of leaf greenness. Near-infrared light (NIR: 700–1400 nm) is more strongly absorbed by the soil than by the crop, and reflectance measurements at these wavelengths provide information on the amount of leaf area relative to the amount of uncovered soil. The color of a crop canopy perceived from above is not just determined by the color of the leaves but also by the color of the soil, especially when the crop is in its early stages. Soil color is a function of mineralogy, organic matter content, moisture content, surface roughness, and shadowing (Bausch and Duke, 1996).

Taken as a whole, the spectral reflectance of a crop canopy is a combination of the reflectance spectra of the plant and soil components, governed by the optical properties of these elements and radiant energy exchanges within the canopy. Spectral reflectance in the R and B regions of the electromagnetic spectrum is inversely related to the in situ chlorophyll density due to chlorophyll absorption of these wavelengths, while spectral reflectance in the NIR region is directly related to the green leaf density (Gates et al., 1965; Knipling, 1970). Further, it has been reported (Chang and Collins, 1983) that vegetation under stress shows a decrease in reflectance in the NIR bands (750-1300 nm) and a reduced R absorption in the chlorophyll active band (680 nm).

Development of Vegetation Indices

The amount of green vegetation is one of the principle factors influencing the reflectance of crop canopies. As leaf area and biomass increase, there is a progressive and characteristic decrease in the reflectance of the chlorophyll absorption region, an increase in the NIR reflectance, and a decrease in the middle infrared reflectance. High absorption of incident sunlight in the visible R portion and strong reflectance in the NIR portion of the electromagnetic spectrum by photosynthetically active tissue in plants is distinctive from that of soil and water. Vegetation indices developed from spectral observations in these two wavelength ranges have correlated highly with plant stand variables such as green leaf area, chlorophyll content, fresh and dry above-ground phytomass, percent ground cover by vegetation, and grain and forage yield. (Rouse et al., 1973; Wiegand et al., 1973; Richardson et al., 1982). From theoretical diffusion models, Allen et al. (1970)

showed that spectral reflectance and transmittance of a plant canopy are functions of total leaf area, absorptance and scattering of radiation in specific wavelengths, and background reflectivity.

Linear combinations, ratios, and differences of the visible (400-700 nm) and NIR wavelength interval spectra have been devised that reduce the radiance observations to a single numerical green vegetation dominated index (VI: Kauth et al., 1976; Kauth et al., 1979; Tucker, 1979), and a soil dominated index (SI: Kauth and Thomas, 1976). Spectral reflectance indices have also been used to assess yields in cereals such as barley (*Hordeum vulgare* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.), and sorghum [*Sorghum bicolor* (L.) Moench]. A number of vegetation indices have been developed for interpreting aerial imagery. Of all the techniques for monitoring vegetation evaluated to date, the use of R and NIR spectral data has had the most applications with a variety of vegetation types. The combination of NIR and R spectral data has proven useful for estimating the leaf-area index (LAI) of tropical rain forests (Jordan, 1969), the green leaf area and biomass of soybeans (Holben et al., 1980), LAI of winter wheat (Wiegand et al., 1979); predicting grain yield in winter wheat (Colwell et al., 1977; Tucker et al., 1980) monitoring crop condition in wheat (Richardson and Wiegand, 1977); and estimating the severity of drought stress in winter wheat (Thompson and Wehmanen, 1979; Tucker et al., 1980).

Several investigators have examined the use of ratios, particularly the NIR:R ratio, and other transformations of two or more spectral bands to enhance the relationship between spectral and agronomic properties of vegetative canopies. An assumption in the formulation of vegetation indices is the idea that all bare soil in an image will form a line in bivariate spectral space. Nearly all of the commonly used vegetation indices are concerned with R-NIR space. For this reason an R-NIR line for bare soil is assumed, which is considered as the line of zero vegetation (Fig. 2). The ratio-based indices use the assumption that all the iso-vegetation lines converge at a single point and these indices measure the slope of the line between the point of convergence and the R-NIR point of the pixel. The distance based or the orthogonal vegetation indices use the assumption that all iso-vegetation lines remain parallel to soil line, and they measure the perpendicular distance from the soil line to the R-NIR point of the pixel (ERDAS, 1997). Jordan (1969) developed the ratio vegetation index (RVI), which is the ratio of the radiance in the NIR to that in the R. The index RVI measures the slope of the line between the origin of R-NIR space and the R-NIR value of image pixel.

Single-date vegetation indices vary from field to field due to drought (Thompson and Wehmanen, 1979), management practices, soil properties, and weather (Colwell et al., 1977; Richardson et al., 1982), and from plot to plot where seeding rate or planting date, fertility, and number of irrigations were varied (Tucker et al., 1980; Daughtry et al., 1980; Aase and Siddoway, 1981; Pinter et al., 1981; Walburg et al., 1982). Weigand et al. (1991) pointed out that if most uncertainty in yield prediction by spectral reflectance indices is site-dependent, then it is necessary to relate yield to these indices across good and poor environments within the production area. Single-date vegetative indices should be used with caution to predict yields (Daughrty et al., 1983) compared to vegetation indices cumulative over time. Cumulative indices have been shown to be good indicators of potential yield for a variety of crops and growing conditions (Moran et al., 1997;

Daughrty et al., 1983), as they account for the potential additive effect of the vegetation indices during crop cycle, which account for differences in yield.

The normalized difference vegetation index (NDVI; Rouse et al., 1973) is the difference between the radiance in the NIR and R bands divided by the sum of the radiances in the NIR and the R bands, where NDVI = (NIR - R)/(NIR + R). It has been the most widely used vegetation index (Kaufman and Tanre, 1992). The NDVI ranges between –1.0 and 1.0, with vegetation having positive values. In order to evaluate the impact of vegetation cover on sensor readings, Lukina et al. (1999) evaluated percent vegetation coverage at different wheat growth stages and row spacing. Their work demonstrated a high correlation (0.80-0.97) between percent vegetation coverage and NDVI measurements. The NDVI has been considered as an indirect measure of crop yield, including that of wheat (Colwell et al., 1977; Tucker et al., 1980, Pinter et al., 1981).

There are several disadvantages to using NDVI. The sensitivity of NDVI to LAI weakens with increasing LAI beyond a threshold value, which is typically between 2 and 3. Variations in soil brightness may produce large variations in NDVI from one image to the next. Differences between the true NDVI, as would be measured at the surface, and that actually determined from space are sensitive to attenuation by the atmosphere and by aerosols (Liu and Huete, 1995).

Various approaches have been taken to counter some of NDVI's disadvantages. Rasmussen (1992) calculated a sampling interval weighted average NDVI by integrating multi-temporal spectral measurements with time, which improved millet grain yield estimates from a single spectral measurement. Smith et al. (1995) reported that taking two spectral measurements and combining the NDVI values using a linear model improved correlation with wheat grain yield compared to one measurement. Recent work has shown that NDVI measurements in winter wheat starting from the beginning of erect growth to the stage when leaf sheaths are strongly erect can provide reliable prediction of both N uptake and biomass (Stone et al., 1996; Solie et al., 1996). Pinter et al. (1981) also reported that summing NDVI values from late season (flowering to grain fill) spectral measurements was a more stable predictor of millet and sorghum grain yield than a single spectral measurement. Later, Crippen (1990) postulated that the red radiance subtraction in the numerator of NDVI was irrelevant, and formulated the infrared percentage vegetation index (IPVI). It is the radiance in the NIR band divided by the sum of the radiances in the NIR and R bands. [IPVI = NIR/(NIR + R)]. Gitelson et al. (1996) proposed that the use of the G band as with the green normalized difference vegetation index (GNDVI) may prove to be more useful for assessing canopy variation than the indices involving the R band. The GNDVI is the difference between the radiances in the NIR and G bands divided by the sum of the radiances in the NIR and G bands [GNDVI = (NIR - G)/(NIR + G)]. Jackson and Pinter (1986) reported that orthogonal G vegetation indices are superior to ratio indices for discriminating between architecturally different canopies, especially when satellite data are used. Huete et al. (1985) concluded that the soil brightness influence on the ratio indices behaved oppositely to that of the orthogonal indices.

Influence of Soil on Canopy Reflectance

In early experiments with visible and infrared reflectance from wheat canopies, Stanhill et al. (1972) reported that the difference in crop absorptivity could be accounted for by the differences in biomass and degree of ground cover. Huete et al. (1985) measured percent green canopy cover by projecting a 35-mm slide onto a dot grid and counting the dots of light and shaded surface. Non-green components contribute to the canopy spectral reflectance, and vegetation indices have been reported to vary due to the presence of non-green vegetation and due to soil background (Huete, 1989).

Soil influences on incomplete canopy spectra are partly due to dependency of the soil background signal on the optical properties of the overlaying canopy (Jackson et al., 1980; Lillesaeter, 1982; Heilman and Kress, 1987; Huete, 1987). Differences in R and NIR flux transfers (Kimes et al., 1985; Sellers, 1987; Choudhary, 1987) through a canopy result in complex soil-vegetation interaction, which makes it difficult to subtract or correct for soil background influences. 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 relatively recent indices such as the soil adjusted vegetation index (SAVI: Huete, 1988) and the atmospherically resistant vegetation index (ARVI; Kaufman and Tanre, 1992) have been developed to correct for these influences. The SAVI is a transformation of NDVI, which can be used to adequately describe dynamic soil-vegetation systems. The transformation involves a shifting of the origin of reflectance spectra in NIR-R wavelength space to account for first-order soil-vegetation interactions and differential R and NIR extinction through vegetation canopies. The SAVI is calculated using the formula $[(NIR - R)/(NIR + R + L)] \times (1 + L)$, where L is a correction factor which ranges from 0 for very high vegetation cover to 1 for very low vegetation cover. The SAVI is also a method by which spectral indices may be refined or calibrated so that soil substrate variations are effectively normalized and are not influencing the vegetation measure. Huete (1988) showed that the iso-vegetation lines do not converge at a single point, and selected the L -factor in SAVI where lines of specified vegetation density intersect the soil line. The net result is an NDVI with an origin not at the point of zero R and NIR reflectance. For high vegetation cover, L is 0 while L is 1.0 for low vegetation cover; an L-value of 0.5 is used for intermediate vegetation and values of SAVI range from –1.0 to 1.0. Based on the studies conducted by Huete (1988), the optimal adjustment factor varies with vegetation density; however a single adjustment factor (L = 0.5) was shown to reduce soil noise considerably. As the vegetation density becomes greater, the adjustment factor becomes lower. Thus, with prior knowledge of vegetation densities, one may choose the best correction term. The SAVI could thus be used for low vegetation cover such as an early season annual crop canopy with a correction factor of 0.5 (Huete, 1988), while a lower correction factor would be used for very dense vegetation such as a forest canopy.

Many vegetation indices are mathematically related to each other. Perry and Lautenschlager (1984) have shown that most indices can be divided into two classes: 1) ratio-based indices (NDVI, DVI [Difference vegetation index; Tucker, 1979], and GNDVI; Gitelson et al., 1996), and 2) distance-based indices or orthogonal indices represented by PVI (Perpendicular vegetation index; Richardson and Wiegand et al., 1977), SAVI (Huete, 1988), and OSAVI (optimized soil adjusted vegetation index; Rondeaux et al., 1996).

Color Infrared Photography in Detecting N Differences

Nitrogen stress may impose limitations on the use of vegetation indices to determine crop growth due to changes in radiation-use efficiency. Previous research (Schepers et al., 1992; Schepers, 1994) with the chlorophyll meter considered the effects of several factors (i.e., hybrid, stages of growth, environment conditions, plant disease, etc.) on corn leaf chlorophyll assessments for N management. Increases in R reflectance were related to decreases in chlorophyll content resulting from lower N supply (Filella et al., 1995). 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 with variability in leaf chlorophyll, N content, and final grain yield than is the R band. More recently, Gitelson et al. (1996) provided evidence that the G band as utilized in the GNDVI is more sensitive than the R band employed in the NDVI in detecting the wide range of chlorophyll levels in individual leaves of forest species. While the work by Gitelson et al. (1996) did not focus on the use of GNDVI for estimating grain yield, it provided a hypothesis suggesting a potential advantage of GNDVI over NDVI. Shanahan et al. (2001) found that GNDVI measured during mid grain-filling period could be used to produce relative yield maps for corn depicting spatial variability in fields and offering a potential alternative to the use of a combine yield monitor.

Because of the number of factors that can influence crop spectral characteristics, Blackmer and Schepers (1995b) developed an N sufficiency index relative to chlorophyll meter readings from a non-N-limited area to compare N status across fields and for fertigation in corn in the Great Plains. Likewise, Bausch and Duke (1996) developed an

N Reflectance Index (NRI) to monitor 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 for a well N-fertilized reference (an area that is never N deficient). Scharf and Lory (2002) used relative G to predict optimum sidedress N in corn at the V6-V7 stage. However, they found that the relationship did not hold under conditions where N was applied at or prior to planting or where there were confounding effects of soil reflectance in the aerial image.

The desirable characteristics of aerial photography for agriculture include low cost, flexible spectral bands and bandwidths, and data redundancy due to overlapping frames (Mausel et al., 1992). The disadvantages include vignetting effects, bi-directional reflectance variations due to wide fields of view, band-to-band mis-registration, and difficulties in frame registration and mosaicing. Infrequent repeat cycle, clouds, and instability in spectral-agronomic parameter relationships caused by calibration problems and by variation in atmospheric layers are the major limitations to the use of remote sensing for crop production forecasting. As indicated by Adamsen et al. (1999), digital cameras potentially can be used to monitor the status of crops in a timely manner, and could potentially be used as a valuable management tool as more data and data analysis tools become available.

Tissue and Stalk N Concentrations in Determining N Requirements in Corn

Nitrate Concentration

The relationship between the availability of soil N and the NO_3 concentration of a crop may not be simple and straight forward. This relationship is not linear, and it is difficult to translate observations on NO_3 concentration into quantitative statements on the N deficiency or excess. The NO_3 concentration does not uniquely reflect the crop's N status (Schroder et al., 2000). Irrespective of N supply, NO_3 concentrations drop as the plant develops (Hanway, 1962; Bindford et al., 1990). Plant organs also differ in NO_3 concentrations, with stalks generally containing more NO_3 than leaf blades (Hanway, 1962; Iverson et al., 1985a). According to Iverson et al. (1985b) and McClenahan and Killorn (1988), N sufficiency in corn is indicated by NO_3 concentrations in the range of 0.9 – 1.9% NO_3-N in the dry matter of the basal 5 cm of cornstalks around the V6 stage. However, recent research showed that many sources of variation make NO_3 concentration a questionable indicator of the N status at that stage (Fox et al., 1989; Bundy and Andraski, 1993).

End-of-season stalk N content has been used as an indicator tool for determining N status in corn at harvest time. Although this tool gives an after-the-fact look at plant growth, it is very valuable in future planning for N fertilizer needs. Stalk sample NO_3-N concentrations have been classified into four categories: low (< 0.25 g N kg^{-1}), marginal (0.25 - 0.70 g N kg^{-1}), optimal (0.70 - 2.0 g N kg^{-1}), and excess (> 2.0 g N kg^{-1}). Within the optimal range, yield may increase without a change in stalk sample NO_3-N concentration. In the excess category, there is luxury uptake, and even as uptake increases, it does not usually increase yields (Blackmer and Mallarino, 1996). Bindford et al. (1990) concluded that corn crops have been N sufficient if the stalk fraction between 15 and 35 cm above the soil surface contains 0.25-1.80% NO_3-N in the dry matter. Results from later research have confirmed the potential of this test (Bundy and Andraski, 1993; Piekielek et al., 1995; Varvel et al., 1997b). This indicator may provide valuable hints on fertilizer use in subsequent corn crops. The value of these indicators may be slightly improved by the establishment of a reference plot within a field. The reference plot, a representative part of the crop, receives an additional supply of N. Subsequently, the ratio of concentrations as observed in the reminder of the field and that of the reference plot is used as an indicator of the N status of a young corn crop (McClenahan and Killorn, 1988).

Total Nitrogen Concentration

Experiments on the response of corn to N applications have shown positive relationships between final yields and either the total N concentration of young corn plants (Bindford et al., 1992) or the total N concentration of the ear leaf around anthesis (Cerrato and Blackmer, 1991; Soltanpour et al., 1995). Therefore total N concentration has been evaluated for its potential as an indicator of the N status of corn. However, because the total N concentration reaches a plateau as N supply increases, total N has proved to be an unsuitable indicator for detection of excess N in corn. Moreover, the definition of a critical N level, beyond which response to N is unlikely, is difficult due to considerable variation within and among site years (Cerrato and Balckmer, 1991; Bindford et al., 1992).

Critical N concentrations in the ear leaf between tasseling and silking range from 2.6 to 3.6% in the dry matter (Soltanpour et al., 1995). Cerrato and Blackmer (1991) have pointed out that critical N concentrations are often overestimated due to the use of incorrect regression models. They concluded that crops could be considered non-responsive to N above an ear-leaf N concentration of 2.1%. Cerrato and Blackmer (1991) considered the variation within and across sites too large to use the total N concentration of the ear leaf as a practical diagnostic tool. Variation in total N concentrations caused by factors other than N probably stems from the crop stage-dependent nature of the total N concentration (Greenwood et al., 1990).

SPAD Meter

Transmitting artificial light through a leaf has also been used to assess leaf greenness. This is the basic operating principle of the Specialty Products Agricultural Division (SPAD) meter (Minolta, 1990). The SPAD-502 chlorophyll meter (Minolta Camera CO., Ltd., Osaka, Japan) measures relative chlorophyll concentration by measuring the light transmittance through the leaf at 650 and 940 nm. The transmittance at 940 nm is used as a reference to compensate for factors such as leaf moisture content and thickness, while the 650 nm source is sensitive to chlorophyll concentration. SPAD-502 chlorophyll meters have been used to estimate chlorophyll concentrations and infer N status of single leaves of wheat, corn, and other plants (Wood et al., 1993; Blackmer and Schepers, 1995a). Work by Wood et al. (1992) found high correlation between SPAD-502 chlorophyll meter readings and corn tissue N concentrations between the stage when the tassel begins to develop rapidly and mid-silk growth stages. Nitrogen concentration, chlorophyll concentration, and SPAD meter readings are strongly correlated (Wood et al., 1992; Waskom et al., 1996), but SPAD meter readings are poor predictors of excess N because not all N is converted into chlorophyll when there is excess (Wood et al., 1992; Varvel et al., 1997b). However, N deficiency is immediately reflected in a low chlorophyll concentration, which is accurately registered by the SPAD meter.

Nitrogen sufficiency is not represented by a unique SPAD meter value, as meter values of N sufficient crops increase with crop age (Blackmer and Schepers, 1995a; Sunderman et al., 1997; Varvel et al., 1997a; Bullock and Anderson, 1998). Critical

SPAD meter readings beyond which crops can be considered non-responsive to N range from 42 at V6 (Jemison and Lytle, 1996) to 55 in the reproductive stage (Piekielek et al., 1995). SPAD meter values of older leaves can be lower than those of younger leaves (Piekielek and Fox, 1992). Therefore, changes in the observed meter values over time do not necessarily reflect a change in crop N status.

SPAD meter values also decrease in crops under drought stress (Schepers et al., 1996). Additionally, hybrid (Schepers et al., 1996; Sunderman et al., 1997; Waskom et al., 1996), planting time (Jemison and Lytle, 1996), and site year effects in general (Blackmer and Schepers, 1995a; Varvel et al., 1997a) have been reported to impact SPAD readings. Finally, meter types and meter batches within one type may differ in output (Piekielek and Fox, 1992). These sources of variation suggest the need for a strict sampling protocol, for correction for leaf thickness, and for normalization of measurements through amply fertilized reference plots. Work done by Schepers et al. (1992) in using a SPAD meter to measure chlorophyll concentration of corn leaves suggested that readings be normalized to high N strips in the field. Thus, many plants must be sampled to obtain a representative average value to adequately assess the plant N status for the particular sampling date. When using reference plots, a SPAD ratio of 0.92–0.95 in relation to these reference plots is considered indicative of N sufficiency (Blackmer and Schepers, 1995a; Piekielek et al., 1995; Bausch and Duke, 1996; Waskom et al., 1996; Sunderman et al., 1997; Varvel et al., 1997a).

Crop Color

Recently, the development of indicators of crop N status has focused on the use of color. These indicators either refer to the color of individual leaves (leaf greenness) or to the color of the entire crop (field greenness). The color can be determined objectively with reflectance and absorption measurements. Most of the time, field greenness is assessed with hand held portable reflectometers or with reflectometers from airplanes, whereas leaf greenness is assessed with the convenient SPAD meter (Minolta, 1990).

Lukina et al. (2001) working with wheat in Oklahoma used NDVI to predict in-season N requirements at Feekes 4-6 (Large, 1954) growth stage. The N fertilization optimization algorithm (NFOA) was developed to determine the prescribed N rate needed for each 1 m^2 based on potential grain yields with no added fertilization [YP_0 = NDVI (Feekes 4–6)/days from planting where growing degree days (GDD) > 0] and the specific Response Index (RI) for each field (Lukina et al., 2001). An RI was calculated by dividing average NDVI from a non-N-limiting strip (created in each field by fertilizing a strip at a rate where N would not be limiting throughout the season) by the average NDVI in a parallel strip that is representative of the N availability across the field as affected by N fertilizer applied by the farmer (Mullen et al., 2001). The potential yield with added N fertilization (YP_N) was calculated based both on the RI_{NDVI} and the YP_0 as $YP_N = YP_0 \times RI_{NDVI}$. Percent N in the grain (PNG) was predicted based on YP_N that includes inverse relation to yield level: $PNG = b_0 + b_1 \times YP_N$. The in-season fertilizer N requirement (FNR) was calculated as FNR = (GNUP – FNUP)/0.70; where GNUP is the predicted percent N in grain calculated as $GNUP = YP_N \times PNG$, FNUP is the predicted forage N uptake calculated as $FNUP = b_0 + b_1 e^{b2NDVI}$, and 0.70 represents the theoretical maximum NUE of an in-season N application. Stone et al. (1996) developed a plant nitrogen spectral index (PNSI) for correcting in-season wheat N deficiencies from canopy radiance data measured in the R (671±6 nm) and NIR (780±6 nm) portions of the electromagnetic spectrum. The PNSI is the absolute value of the inverse of the NDVI. Blackmer et al. (1996) presented spectroradiometer measured reflected radiation of corn at the dent growth stage (R5) which showed that canopy radiance near 550 nm and 710 nm was superior to canopy radiance near 450 nm or 650 nm for detecting N deficiencies. Their results also showed that the ratio of canopy radiance in the 550- to 600-nm interval to the 800- to 900-nm interval provided sensitive detection of N stress.

Summary

The traditional practice in the southeast USA for corn production has been to apply some amount of N as starter and the remainder as a split application from before V4 to as late as the V8 growth stages. This is 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. Due consideration should be given to sidedress N applications at or near VT, with adequate N applied at planting and/or at layby (e.g., V7-8) to maintain yield potential through VT (Crozier, 2002).

Tissue sampling for N availability (Piekielek and Fox, 1992) is well documented and requires considerable effort for sample collection and processing. In addition, results are not immediately available. Blackmer and Schepers (1995) demonstrated use of the SPAD chlorophyll meter and the N Sufficiency Index (NSI), that is, SPAD measurements for an area of interest normalized to SPAD measurements for a reference area that is not N deficient, as effective tools to schedule N fertigation for corn “as needed” by the crop. Data obtained with the SPAD chlorophyll meter is a point measurement on a single leaf from a single plant. Remote sensing has the capability of sampling a plant community (a function of pixel size) rather than a single point on a single plant and rapidly assessing the spatial variability in a field. To date very few studies have been done to predict side-dress N requirement in corn using remote sensing. The use of reflectance as an indicator of the crop N status is still in its infancy (Bausch et al., 1996; Bausch and Duke, 1996; Schepers et al., 1996), relative to the other indicators discussed above. Well-fertilized reference plots appear to be a prerequisite to utilize reflectance measurements as a reliable diagnostic tool in order to correct for effects on crop color not caused by N, e.g., by diseases, pests, plant density, appearance of the relatively lightly colored tassels, senescence, etc.

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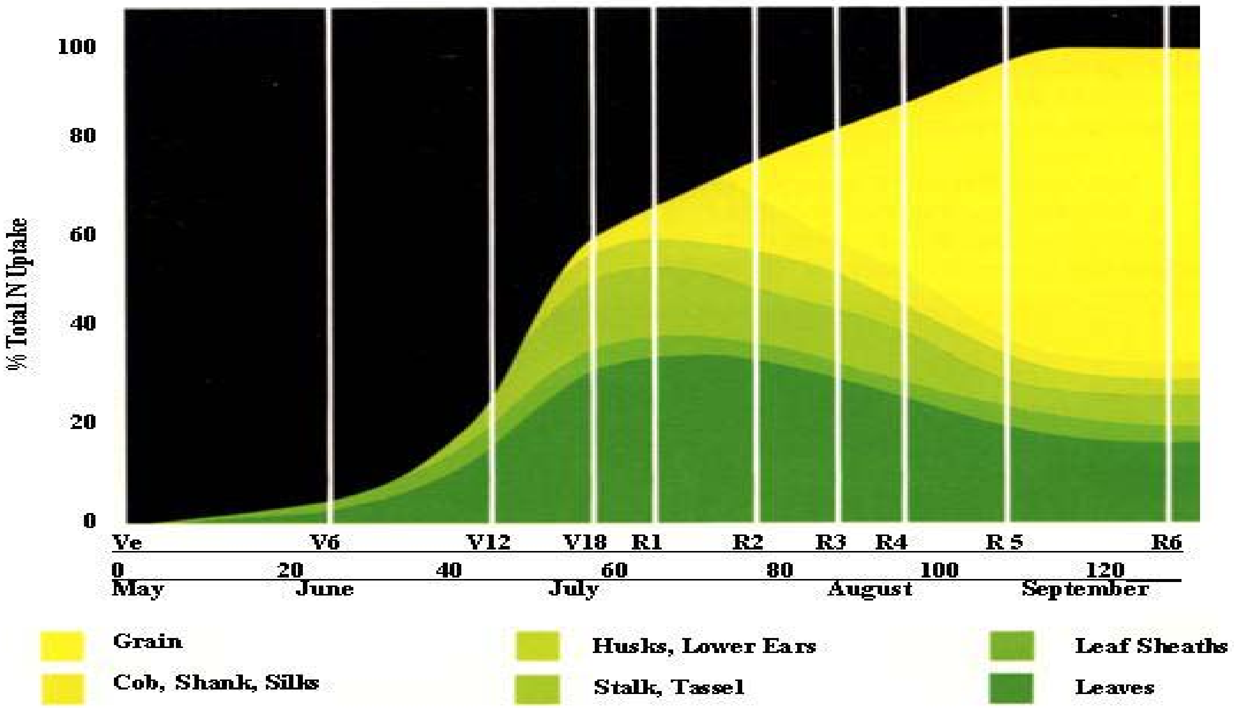

Fig. 1. Nitrogen uptake of a corn plant in Iowa in relationship to growth stages from emergence through physiological maturity (modified from Ritchie et al., 1993).

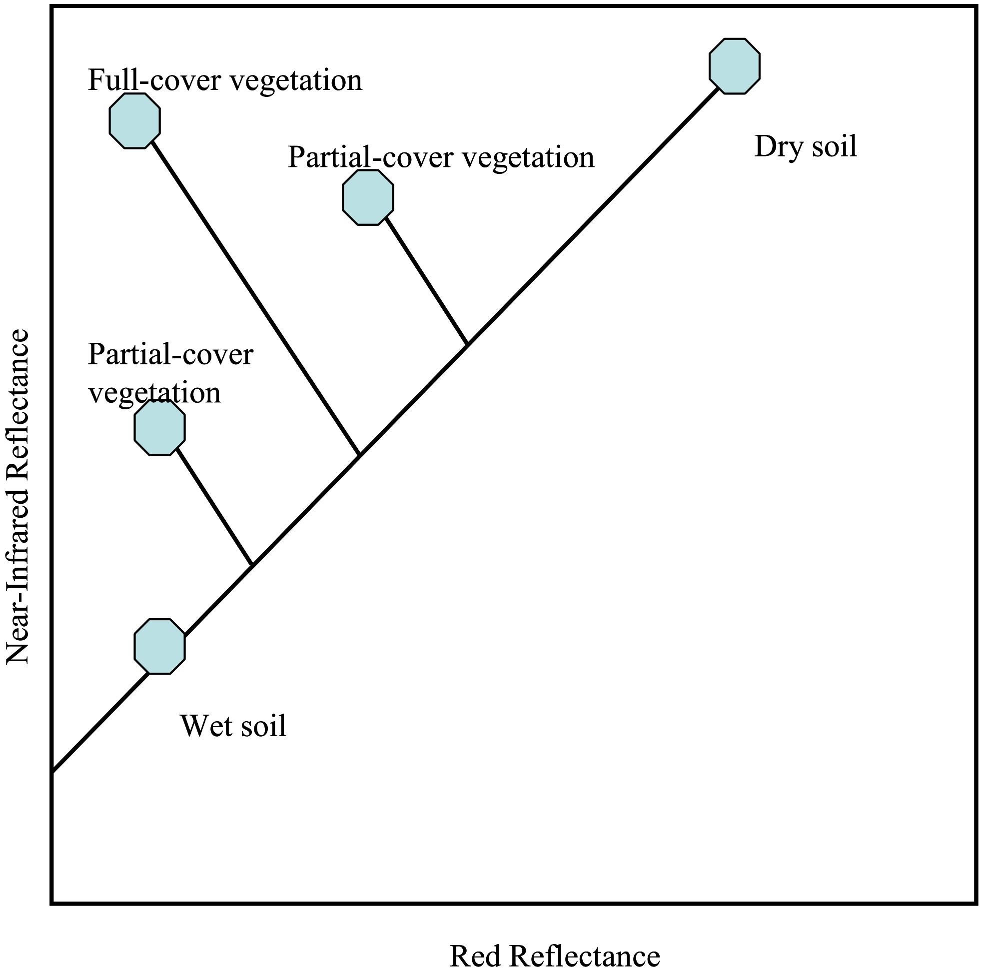

Fig. 2. Relationship in near-infrared – red spectral space of vegetation to soil background using a perpendicular vegetation index (modified from Richardson and Wiegand, 1977).

CHAPTER TWO

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

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

ABSTRACT

Fast, accurate methods to determine 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 to (i) determine if there is a response to late-season N applied to corn at pre-tassel (VT) under irrigated and non-irrigated conditions, and (ii) 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 three years over a wide range of soil conditions and water regimes in the North Carolina Coastal Plain. Different fertilizer N rates were applied at planting (N_{PL}) and at VT (N_{VT}) to create a range of N supply and variability in corn spectral characteristics and to measure yield response to N_{VT}. Aerial CIR photographs were obtained for each site at VT prior to N application. Significant grain yield responses to N_{PL} and N_{VT} were observed. The 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. Spectral radiation of corn measured using the Green Difference Vegetation Index (GDVI) relative to high-N reference strips using a linear-plateau model was the best predictor of optimum N_{VT} (R^2 = 0.67).

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. Crop N requirements change from year to year, and quantifying the optimum in-season N requirement is an important step towards an economically and environmentally viable crop production system. Traditional methods of estimating corn in-season optimum 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 Southeast has been to apply some amount of N as starter and the remainder as a split application from before V4 to as late as the V8 (Ritchie et al., 1993) growth stages. 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 at planting and/or at layby (e.g., V7-8) to maintain yield potential through VT (Crozier, 2002). In the Mid-West, Blackmer and Shepers (1995) observed significant responses to N applied as late as R4-

R5 growth stage. Applying N at R4-R5 improved the ability to determine yield potential and corresponding N requirement compared to earlier growth stages.

Image-based remote sensing can be used to monitor seasonal variability of soil and crop characteristics such as soil moisture, biomass production, crop evapotranspiration, and crop nutrient deficiencies (Blackmer et al., 1996). Remote sensing via aerial color photography has been used in corn to detect N deficiencies (Blackmer et al., 1994), 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 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 components as governed by the optical properties of these elements and radiant energy exchange within the canopy. 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. 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 blue shift of the R edge (Blackmer et al., 1996).

Vegetation indices developed from spectral observations in the R and NIR wavelengths have shown strong correlations with plant variables such as green leaf area in 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 (Tucker et al., 1980, Pinter et al., 1981). 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 identical to NDVI.

One of the problems with using the spectral reflectance of the corn canopy 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 radiances in the NIR and G bands [GNDVI = (NIR - G)/(NIR + G)]. Shanahan et al. (2001) found that corn GNDVI measured during mid grain-filling period could be used to produce maps depicting relative spatial variability in yield, 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 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-V7. However, they found that the relationship did not hold under conditions where N was applied at or prior to planting or where there were confounding effects of soil reflectance.

The preliminary objective of this study was to determine if there was a response to late-season N applied to corn at VT under irrigated and non-irrigated conditions in the Southeast. The primary objective was to develop an in-season model based on remotely sensed data to predict the amount of side-dress N required by corn at VT that could be used under different initial N levels and that could simultaneously account for any confounding soil reflectance.

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 non-irrigated 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 weather (Fig. 1) 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 sub-plot 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. The hybrid 'Pioneer 31G98' was planted at approximately 60,000 seeds ha^{-1} across all sites and years. Herbicides were applied based on weeds present and excellent weed control was obtained at all sites. Depending on the rainfall, water was applied to the irrigated plots at the rate of 25.4 mm a week.

Determining Response to N_{VT}

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 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 N_{VT} 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 model and a price ratio of 4:1, defined as the ratio of the price per kilogram of N to the price per megagram 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 one-meter 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 such that the entire experimental field 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, Inc., 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.

The spectral properties of the CIR film used for obtaining images were described by Flowers et al. (2003). 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 represents 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 – 900 nm, band 2 (R) covered the wavelengths between ~490 – 700 nm, and band 3 (G) covered the wavelengths between ~490 – 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). Digital images were georegistered using ERDAS Imagine version 8.7 (ERDAS Inc. Atlanta, GA).

Areas of interest (AOI) corresponding to each individual plot were identified, which included approximately equal number 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 2). Relative bands (Rel NIR, Rel R, Rel G) and indices (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 N Applications

Corn yields reached high levels (Table 3) at most of the experimental sites, and were significantly affected by N_{VT} fertilization (Table 4). Sites 1, 2, 6-9, and 11-16, which spanned 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 three years. All of the two-way interactions involving N_{VT} (N_{VT} × year, N_{VT} × irrigation, $N_{VT} \times N_{PL}$) were significant (Table 4). 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. 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. 2 and 3. The main effects of N_{PL} and N_{VT} were also significant; however, the factors that interacted with N_{PL} and N_{VT} produced different degrees of positive response.

Favorable rainfall and temperature (Fig. 1) fostered above-average grain yields in 2000 and 2001, 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}. During the 2002 growing season, factors such as high temperature and inadequate rainfall (Fig. 1) 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 underlies 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. Thus the 2002 data were not used in developing the final model.

To test the consistency of the N_{PL} and N_{VT} yield responses across different sites within one year under non-irrigated conditions, Sites 2- 6 were chosen for analysis (Table 5), 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. 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 the high residual N already present in the soil.

At many sites, lack of adequate N prior to VT resulted in a loss of yield potential that was irreversible, that is, not regained by N additions at VT (Fig. 2 & 3). 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 at planting and/or at layby (e.g., V7-8) to maintain yield potential through VT (Crozier, 2002). Practical limitations to applying N at VT include the availability of high-rise applicators and the need to minimize damage to the corn crop.

Predicting Optimum N_{VT} Rates from Spectral Data

The different N_{PL} rates created a range of spectral variability 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 6). 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 normalized bands compared to 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 6) for indices composed of the NIR and G bands (GDVI, RGDVI) showed somewhat better relationships with economic optimum

N_{VT} compared to 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 to using reflectance at 675 nm (R).

In this study, the raw DN values for the NIR and G were not significantly correlated to economic optimum N_{VT} rates (Table 6). However, both NIR and G showed a trend across all the experimental sites, with greater radiance values for plots that had greater economic optimum N_{VT} rates, and vice versa. The range of radiance values for NIR (Fig. 4) was narrower compared to G (Fig. 5). Under reduced chlorophyll concentrations resulting from limited N supply in sweet peppers (*Capsicum annum*, L. var. 'Yolo Wonder'), Thomas and Oerther (1972) showed that leaf reflectance in 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 6). 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 to single wavebands.

In our study, better prediction of economic optimum N_{VT} was observed with the relative indices (Table 6) 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. Work done by Schepers et al. (1992) using a SPAD meter to measure the 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 linear prediction of optimum N_{VT}. Overall, linear-plateau models using RDVI and RGDVI were the best predictors ($R^2 = 0.69$ and 0.67, respectively; Table 6) 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 optimum N_{VT} was not consistent when analyzed separately for each irrigation treatment and year (not shown). For RGDVI (Fig. 6), the parameter estimate for the y intercept *a*, which is the maximum economic optimum N_{VT} rate, was slightly greater for the irrigated model compared to the non-irrigated model (Table 7; Fig. 7), 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 7). The lack of differences (Table 7) between the linear-plateau models separated by irrigation (Fig. 7) and year (Fig. 8) 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. 6).

This 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 to 1.02) that is responsive to economic optimum N rates is a concern, because even very small variation in the RGDVI values can change the predicted economic optimum N rate significantly (Fig. 6). 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. 6). 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. The primary 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 prior to VT resulted in a loss of yield potential that was irreversible, that is, not regained by N additions at VT. Thus adequate N applied at planting and/or at layby (e.g., V7-8) 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 potential groundwater pollution thus minimized.

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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: Non-irrigated.

[§] CT: Conventional tillage; NT: No till.

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)	$[(NIR - R)/(NIR + R + 0.5)] \times 1.5$	Huete, 1988
Relative Soil Adjusted Vegetation Index (RSAVI)	$SAVI_{plot}/SAVI_{reference\ plot}$	-
Green Soil Adjusted Vegetation Index (GSAVI)	$[(NIR - G)/(NIR + G + 0.5)] \times 1.5$	-
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.

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

	Grain yield			
Site	Minimum	Maximum	Mean	Std Dev
	-----------------------------Mg ha^{-1}-----------------------------			
1	5.1	13.2	11.0	1.7
2	6.4	14.3	11.5	1.6
3	2.6	10.1	6.5	1.7
4	4.9	14.0	11.2	1.8
5	2.3	11.0	6.0	2.2
6	1.8	12.5	7.6	2.6
7	2.4	11.4	7.3	2.3
8	3.8	14.7	11.0	2.7
9	2.8	13.1	9.1	2.3
10	3.1	14.6	11.4	2.8
11	3.0	11.2	8.0	2.0
12	2.2	12.2	8.9	2.2
13	2.7	12.3	8.1	2.1
14	2.1	9.0	4.3	1.2
15	5.0	11.2	9.4	1.4
16	7.3	11.7	9.8	0.9
17	2.3	6.4	4.3	0.9

Table 4. 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 non-irrigated 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

*,**, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

Table 5. ANOVA for corn grain yield as affected by N at planting (N_{PL}) and at pretassel (N_{VT}) among different sites in year 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

*,**, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

Table 6. Regression analysis of economic optimum N rate (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.

	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

*, **, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

Table 7. 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	***
$x0_{2000}$	0.956	0.008	0.939	0.973	***
$X0_{2001}$	0.960	0.009	0.941	0.980	***
Contrasts					
a_{2000} Vs. a_{2001}	-	-	-	-	NS
b_{2000} Vs. b_{2001}	-	-	-	-	NS
$x0_{2000}$ Vs. $x0_{2001}$	-	-	-	-	NS
			Comparing irrigated model with non-irrigated 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	***
$x0_{IR}$	0.959	0.009	0.938	0.980	***
$x0_{NI}$	0.958	0.007	0.942	0.974	***
Contrasts					

a_{IR} Vs. a_{NI}	-	-	-	-	NS
b_{IR} Vs. b_{NI}	-	-	-	-	NS
$x0_{IR}$ Vs. $x0_{NI}$	-	-	-	-	NS

*,**,***, NS Significant at the 0.05, 0.01, and 0.001 probability levels and not significant, respectively.

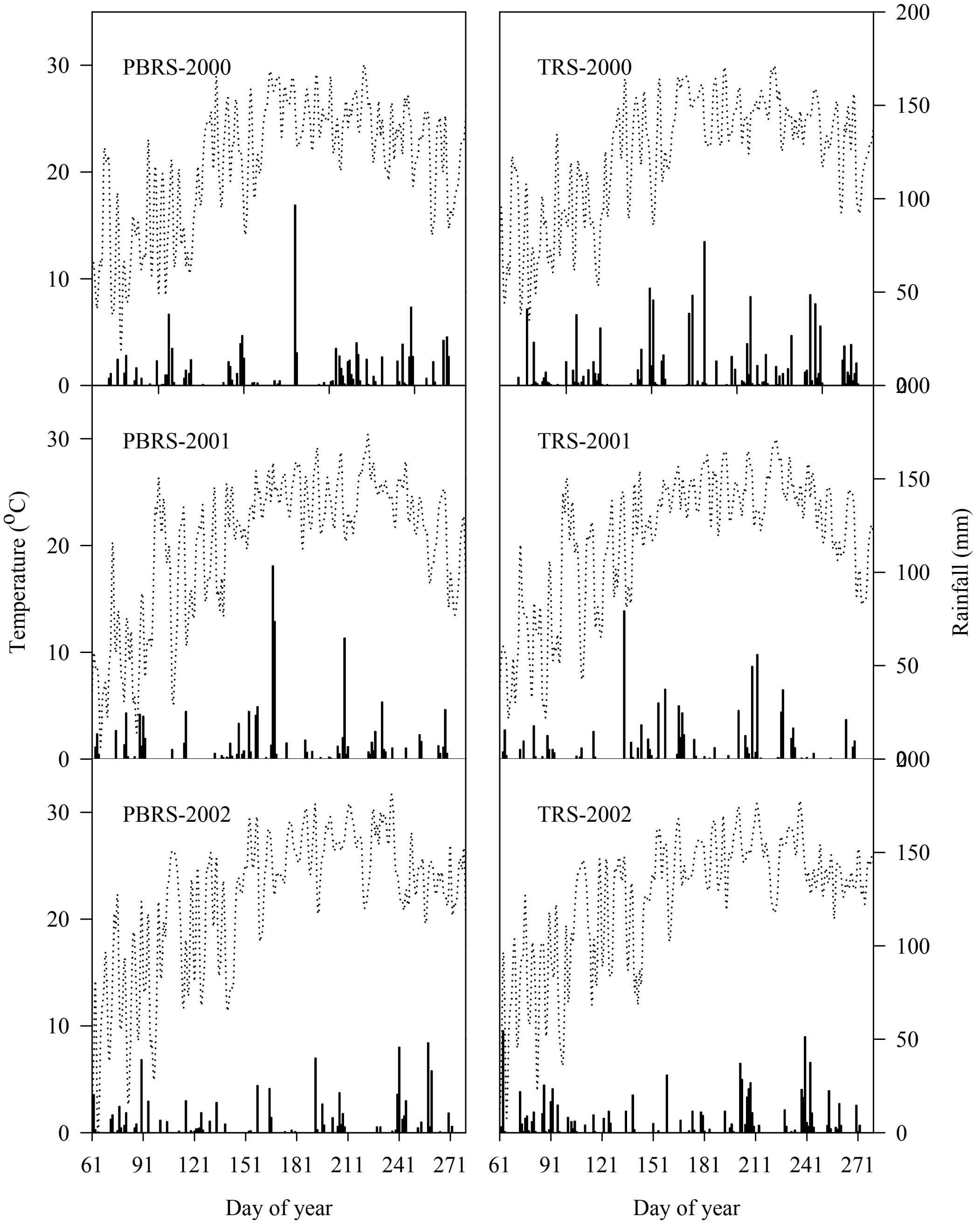


Fig. 1. Daily mean air temperature and rainfall at the Tidewater Research Station (TRS) and the Peanut Belt Research Station (PBRS) experimental sites during 2000, 2001, and 2002.

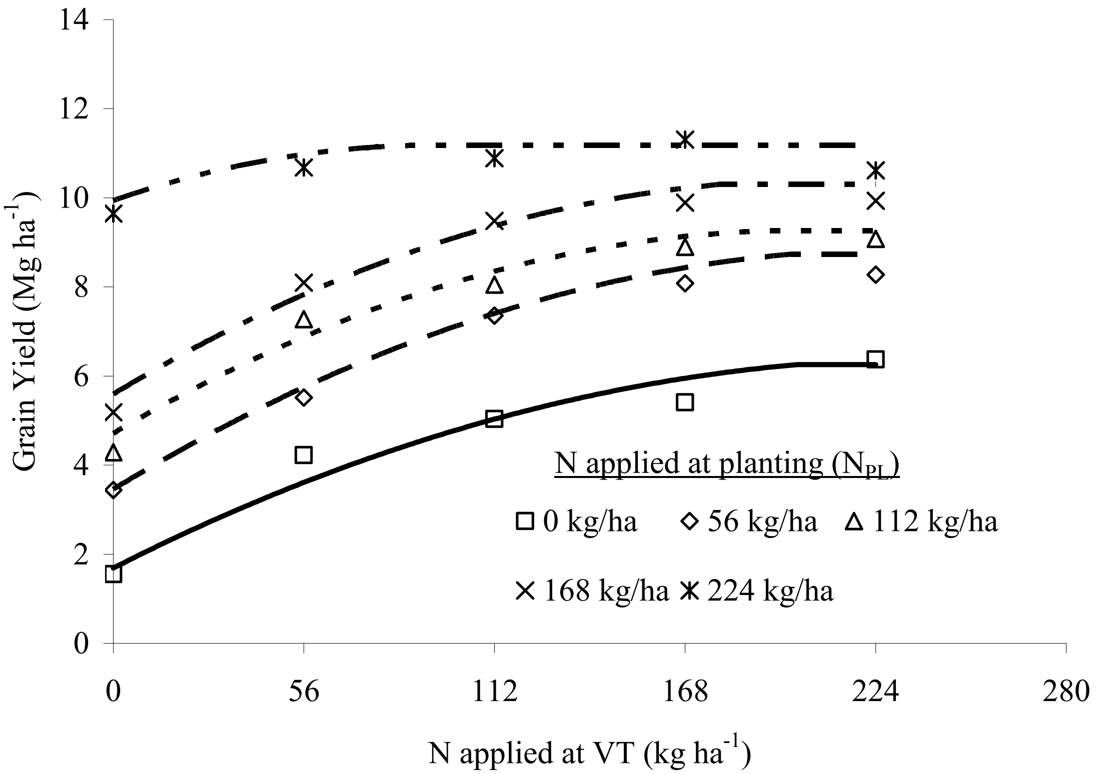


Fig. 2. Quadratic-plateau fit of corn grain yield response to N applied at VT (N_{VT}) for different rates of N applied at planting (N_{PL}) at the Tidewater Research Station (TRS: Site 6) during 2000. Each point is the mean of three replicates.

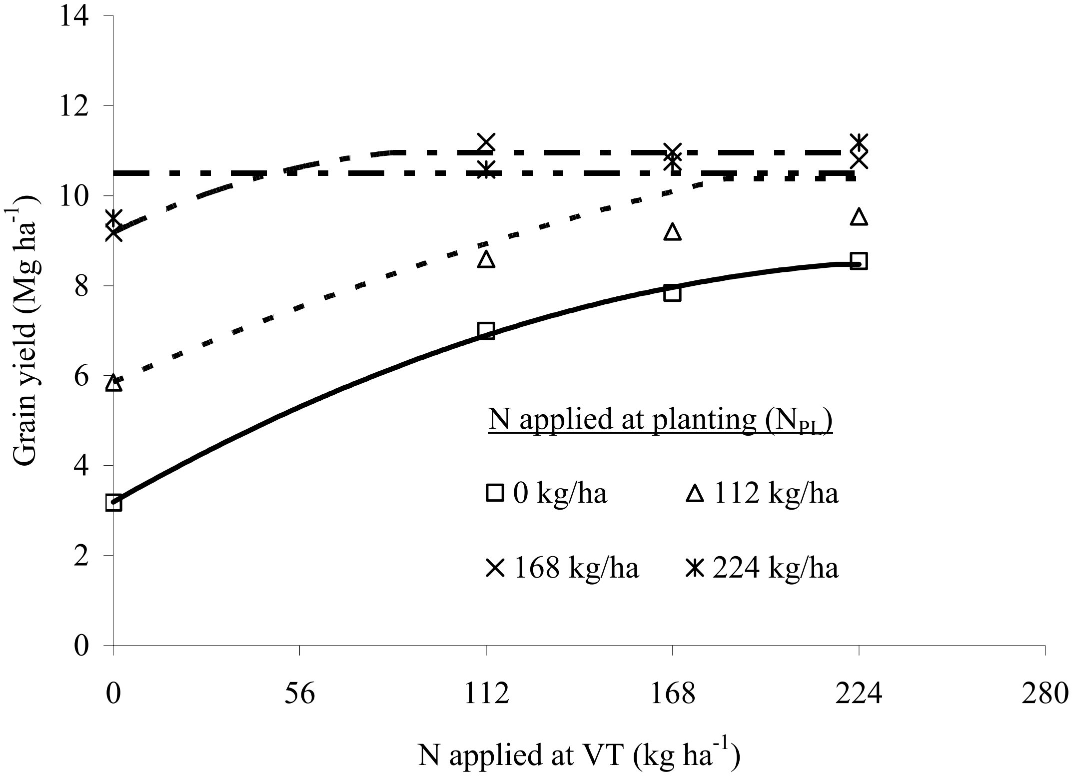


Fig. 3. Quadratic-plateau fit of corn grain yield response to N applied at VT (N_{VT}) for different rates of N applied at planting (N_{PL}) at the Peanut Belt Research Station (PBRS: Site 9) during 2001. Each point is the mean of three replicates.

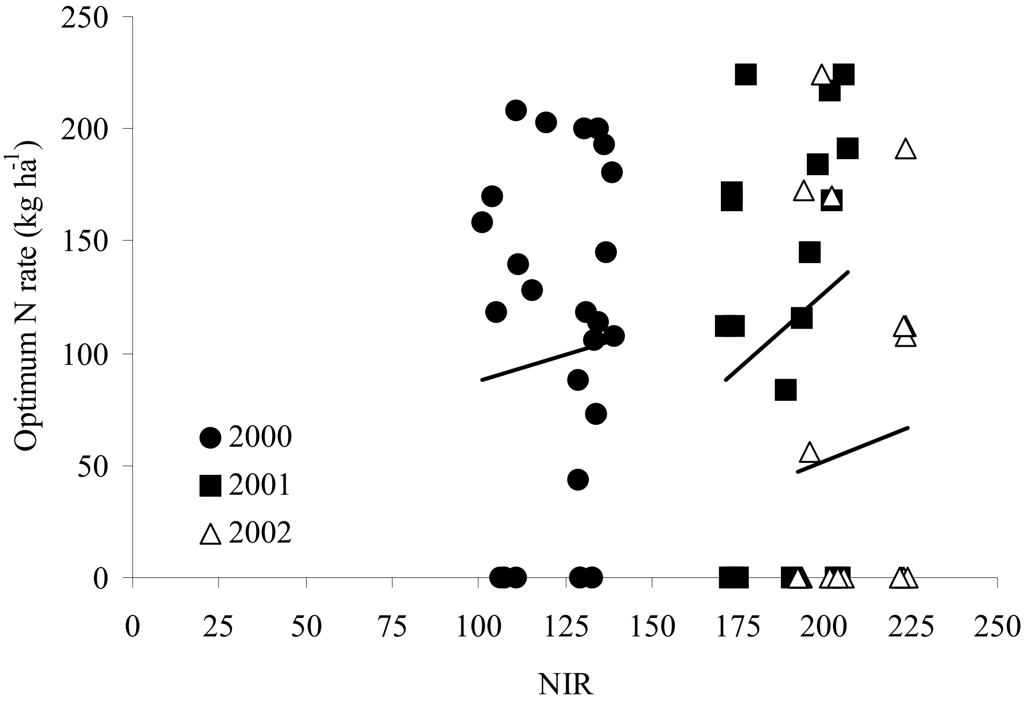


Fig. 4. Relationships between economic optimum N_{VT} and Near-Infrared (NIR) Digital Number (DN) separated by year.

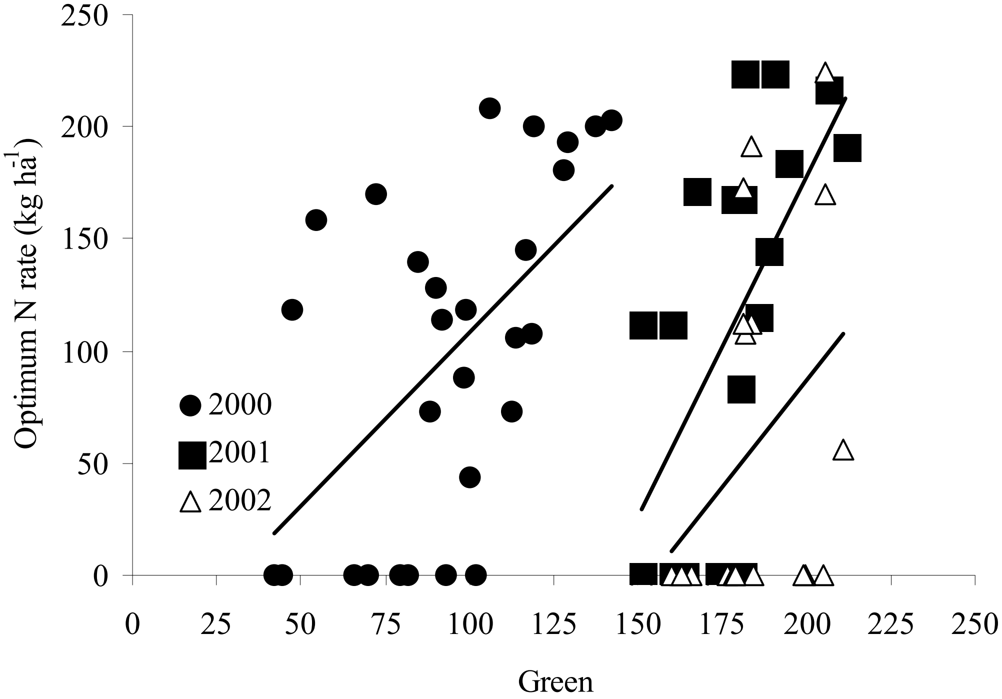


Fig. 5. Relationships between economic optimum N_{VT} and Green (G) Digital Number (DN) separated by year.

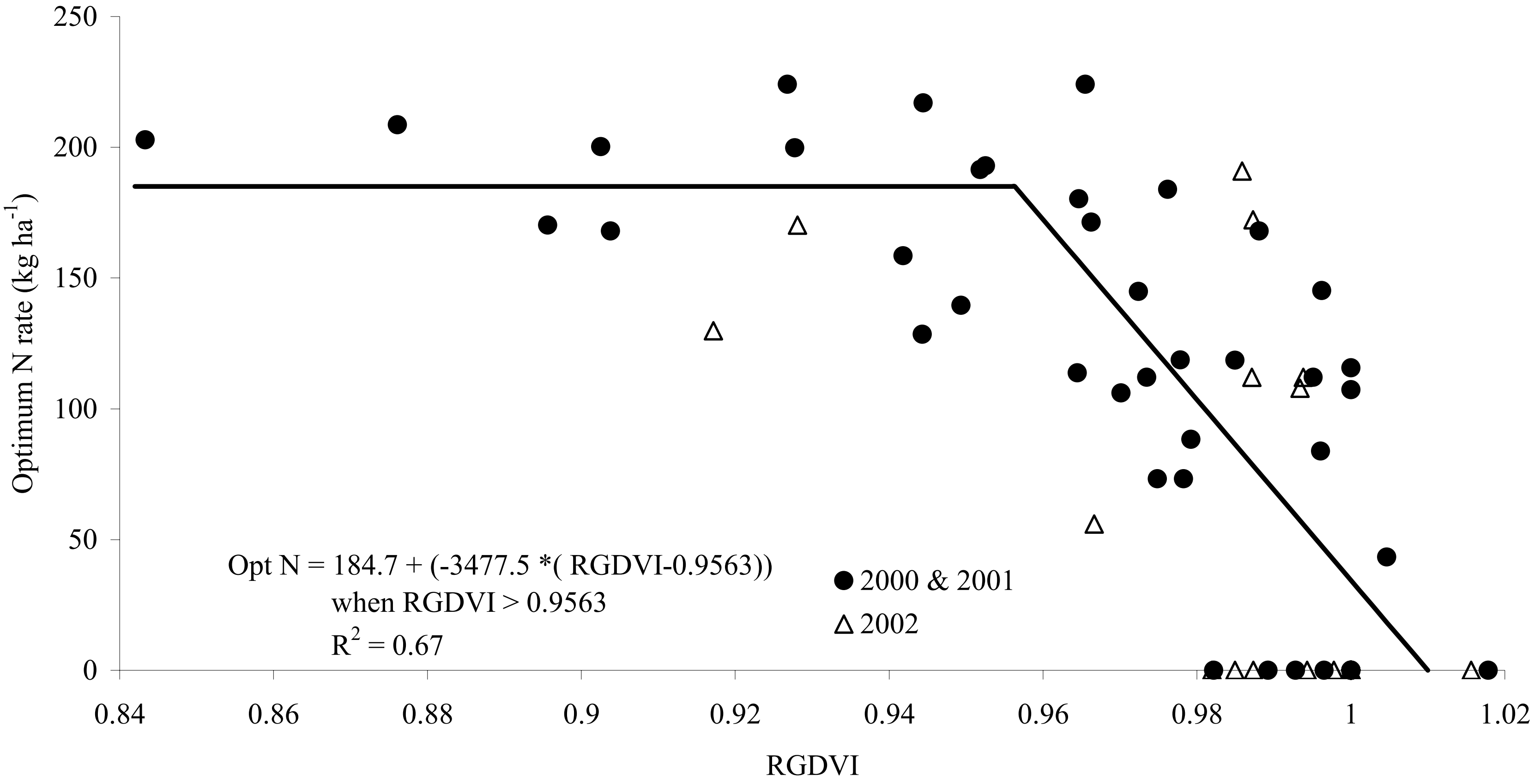


Fig. 6. Model showing the relationship between economic optimum N_{VT} rate and RGDVI. Data from 2002 were not used in developing the model.

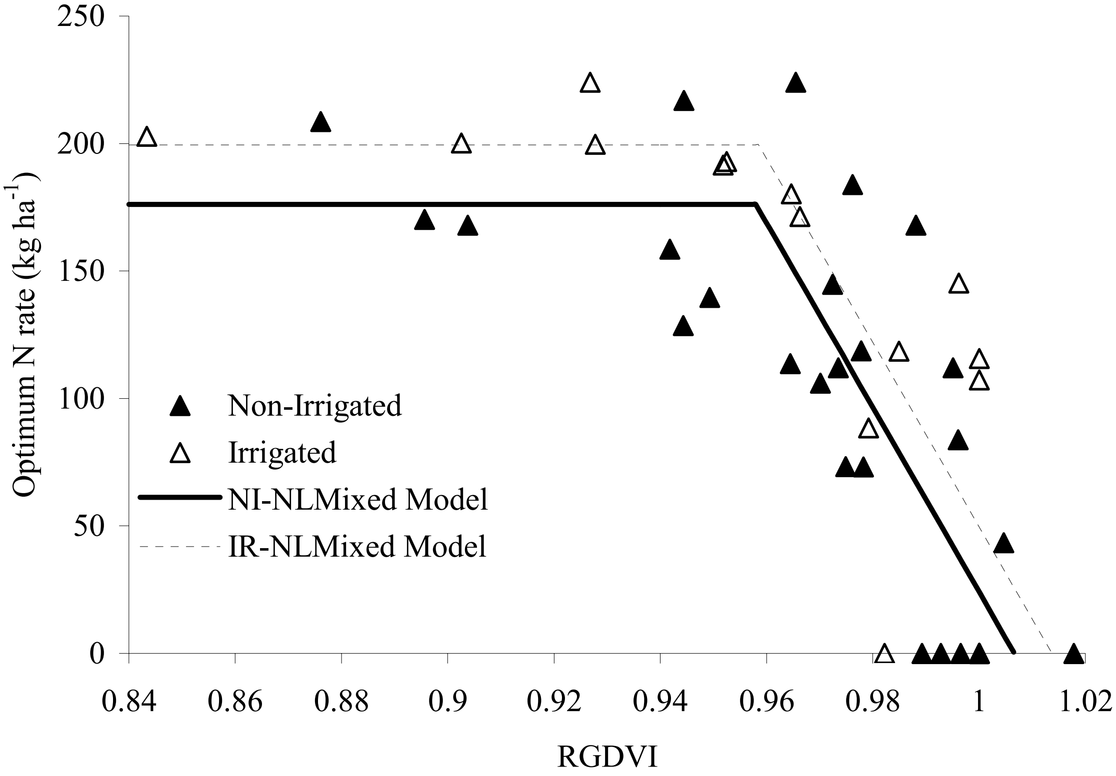


Fig. 7. Relationships between economic optimum N_{VT} rate and RGDVI, and the best-fit linear-plateau models separated by irrigation.

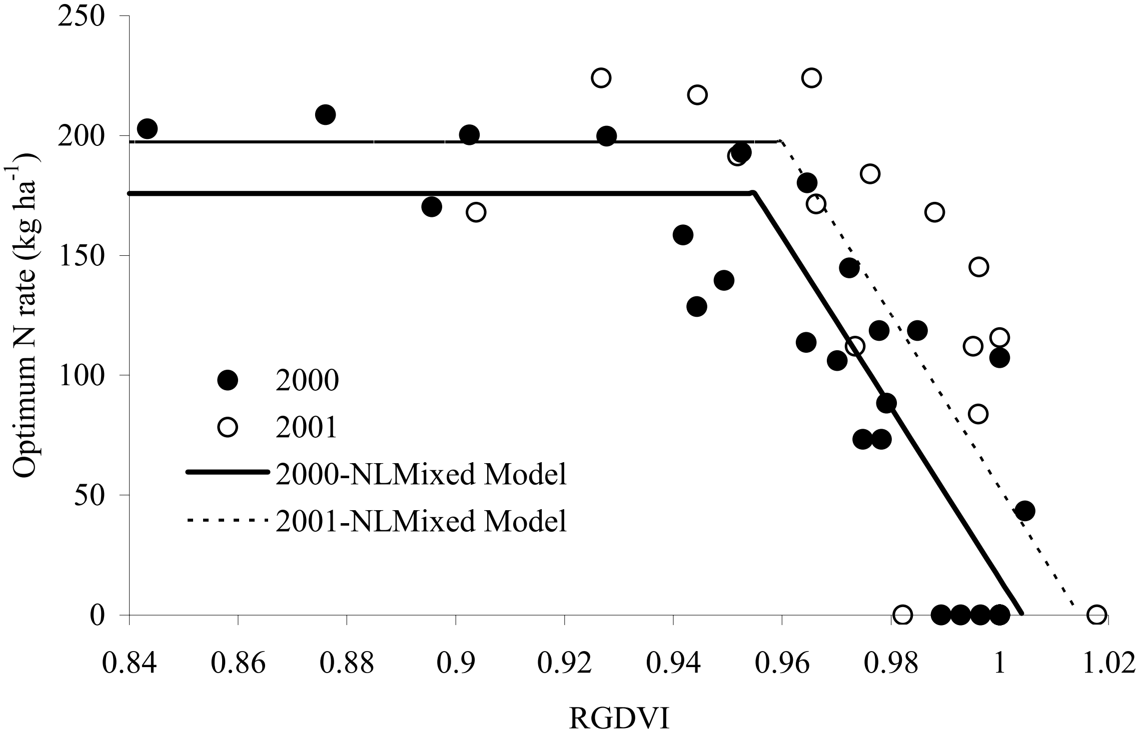


Fig. 8. Relationships between economic optimum N_{VT} rate and RGDVI, and the best-fit linear-plateau models separated by year.

APPENDICES

Appendix A. Table of the minimum, maximum, mean, and standard deviation (SD), for grain yields and economic optimum N rate at VT (N_{VT}) and the source of N_{VT} obtained for different N rates at planting (N_{PL}) at different the experimental sites.

Site	N_{PL}	n	Min	Max	Mean	SD	Optimum N_{VT}	Source of optimum N_{VT}†
	kg ha^{-1}		--------------Mg ha^{-1}------------				kg ha^{-1}	
1	0	15	5.1	11.0	9.1	1.8	200	QP
	56	NA	NA	NA	NA	NA	NA	NA
	112	15	9.3	13.0	11.5	1.2	88	QP
	168	15	9.4	12.8	11.6	1.0	118	QP
	224	15	10.2	13.2	12.1	1.0	0	MS
2	0	NA	NA	NA	NA	NA	NA	NA
	56	15	9.0	13.4	11.3	1.3	114	QP
	112	15	9.5	14.2	12.0	1.4	73	QP
	168	15	10.2	14.0	12.3	0.9	0	MS
	224	15	9.9	14.2	12.2	1.0	0	MS
3	0	15	2.6	8.1	5.7	2.0	145	QP
	56	13	3.9	10.1	7.4	1.9	106	QP
	112	14	3.8	9.0	6.4	1.6	73	QP
	168	15	2.8	8.0	5.7	1.6	43	QP
	224	15	4.4	9.0	7.4	1.0	0	MS
4	0	15	4.9	13.7	9.8	2.3	170	QP

	56	15	7.3	13.0	10.9	1.7	159	QP
	112	13	9.0	13.9	11.2	1.4	128	QP
	168	15	9.9	13.6	11.9	1.1	0	MS
	224	15	11.0	13.9	12.5	0.9	0	MS
5	0	15	2.3	8.0	5.4	1.9	209	QP
	56	14	3.1	8.5	6.7	1.7	140	QP
	112	15	3.4	10.6	7.0	2.1	129	QP
	168	15	4.0	10.9	7.8	1.9	0	MS
	224	14	4.9	10.5	7.8	1.9	0	MS
6	0	13	2.4	7.0	5.0	1.3	203	QP
	56	14	1.8	8.7	6.3	2.0	200	QP
	112	15	2.1	10.4	7.5	2.1	193	QP
	168	15	3.4	11.3	8.2	2.2	180	QP
	224	14	7.3	12.5	10.5	1.7	107	QP
7	0	14	2.5	9.0	6.0	2.0	NA	NA
	56	13	3.3	9.3	6.6	2.0	NA	NA
	112	15	2.4	11.3	7.8	2.4	NA	NA
	168	14	4.4	9.1	6.9	1.4	NA	NA
	224	14	4.5	11.4	9.3	2.0	NA	NA
8	0	12	3.9	10.5	7.9	2.4	191	QP
	112	12	7.8	13.4	11.0	2.0	NA	NA
	168	12	9.4	14.7	12.5	1.5	145	QP
	224	11	10.6	14.6	13.0	1.3	116	QP

9	0	12	2.8	13.2	7.0	2.9	217	QP
	112	12	5.2	9.8	8.3	1.6	184	QP
	168	12	8.6	12.0	10.5	1.1	84	QP
	224	12	8.4	12.1	10.5	1.1	0	MS
10	0	12	3.1	13.1	9.7	3.3	224	MS
	112	11	4.7	14.3	11.7	3.0	168	QP
	168	11	6.8	14.6	12.1	2.3	0	MS
	224	11	8.4	14.5	12.5	1.8	0	MS
11	0	12	3.0	8.6	6.1	1.7	224	MS
	112	12	4.4	11.2	8.0	2.2	170	QP
	168	12	5.9	10.8	8.7	1.7	0	MS
	224	12	6.6	10.6	9.3	1.1	0	MS
12	0	12	4.1	12.2	6.8	2.3	168	MS
	112	12	7.0	11.4	9.2	1.5	112	MS
	168	12	5.6	11.9	9.5	2.3	112	MS
	224	11	7.4	11.3	10.0	1.3	0	MS
13	0	24	2.7	9.1	6.2	1.6	130	QP
	56	25	4.0	9.4	7.0	1.7	170	QP
	112	25	5.6	11.4	9.2	1.6	172	QP
	224	25	8.1	12.3	9.8	1.3	0	MS
14	0	24	2.1	4.5	3.3	0.7	56	MS
	56	25	2.9	9.0	4.5	1.3	0	MS
	112	25	3.8	6.9	5.0	0.6	0	MS

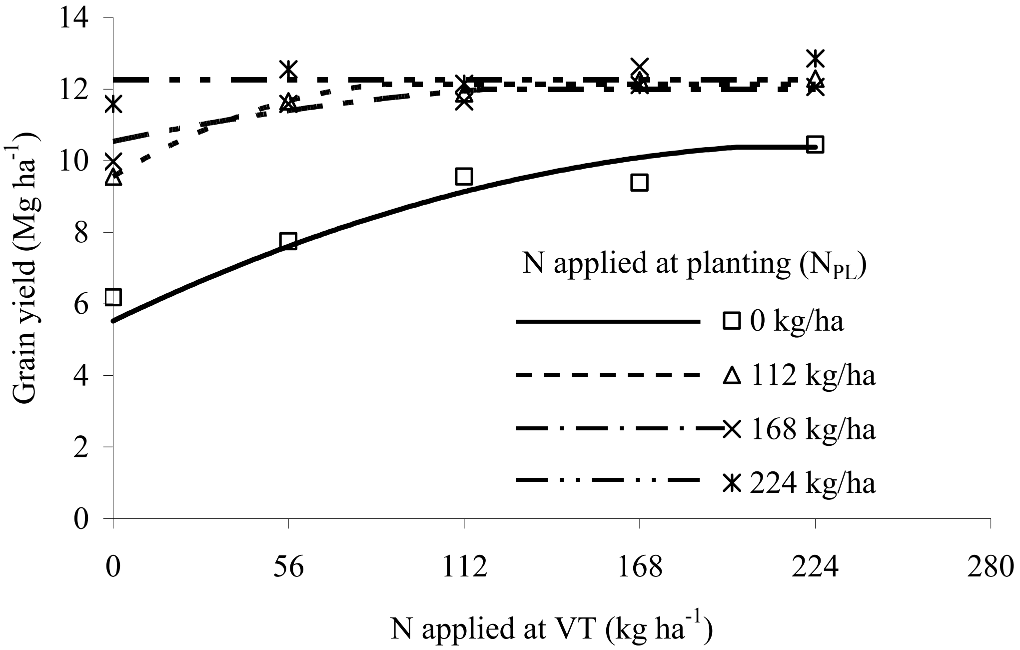
	224	25	2.5	7.8	4.4	1.3	0	MS
15	0	20	6.3	9.9	8.2	1.2	191	QP
	56	18	5.0	10.5	9.0	1.5	108	QP
	112	20	6.5	11.2	10.1	1.1	0	MS
	224	20	9.2	11.2	10.3	0.5	0	MS
16	0	19	7.3	10.9	9.1	1.0	112	MS
	56	20	8.5	11.6	10.1	0.8	112	MS
	112	20	7.7	11.5	9.6	0.9	0	MS
	224	20	8.9	11.7	10.2	0.7	0	MS
17	0	20	5.3	10.3	8.4	1.4	0	MS
	56	20	7.1	10.9	8.9	0.9	0	MS
	112	20	6.4	12.5	10.5	1.4	0	MS
	224	19	9.0	12.1	10.6	0.8	0	MS

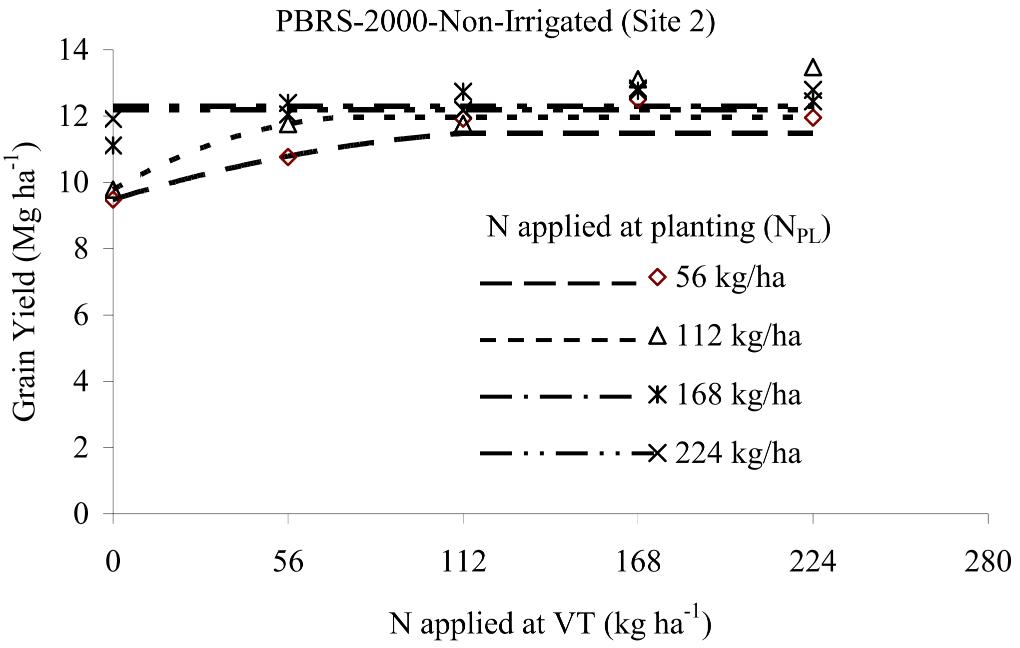
[†] QP: Optimum N rate derived using a Quadratic – plateau function;

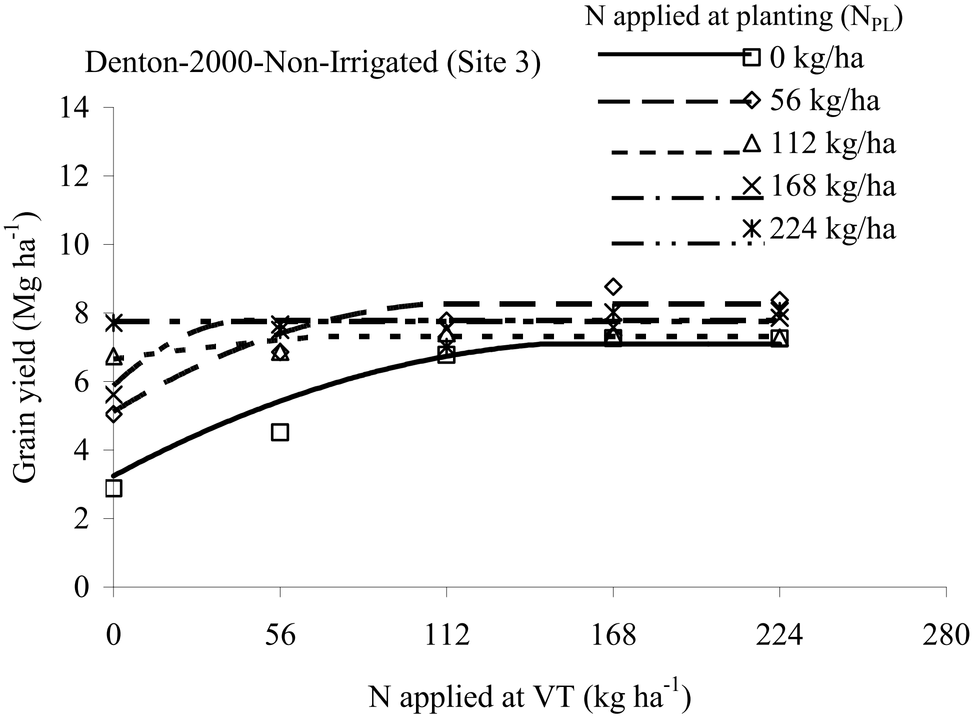
MS: Mean separation via Fisher's protected LSD; NA: Not available.

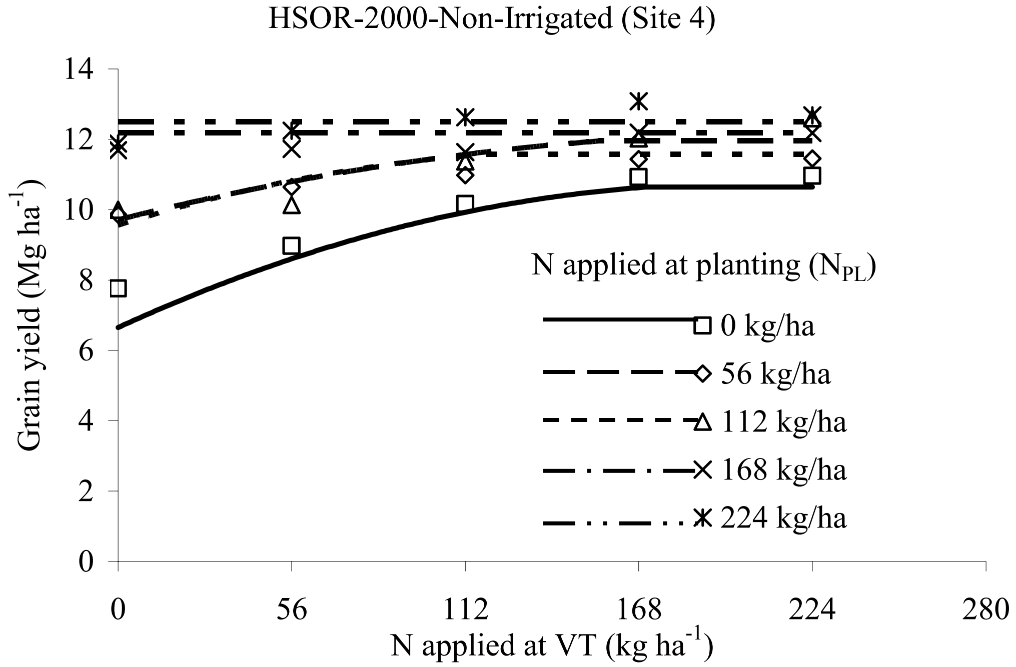
Appendix B. Quadratic-plateau fit of grain yield response to N applied at VT (N_{VT}) for the different rates of N applied at planting (N_{PL}) at the different experimental sites during 2000, 2001, and 2002. Absence of a line indicates that optimum N rate was derived using Fisher's protected Least Square mean separation.

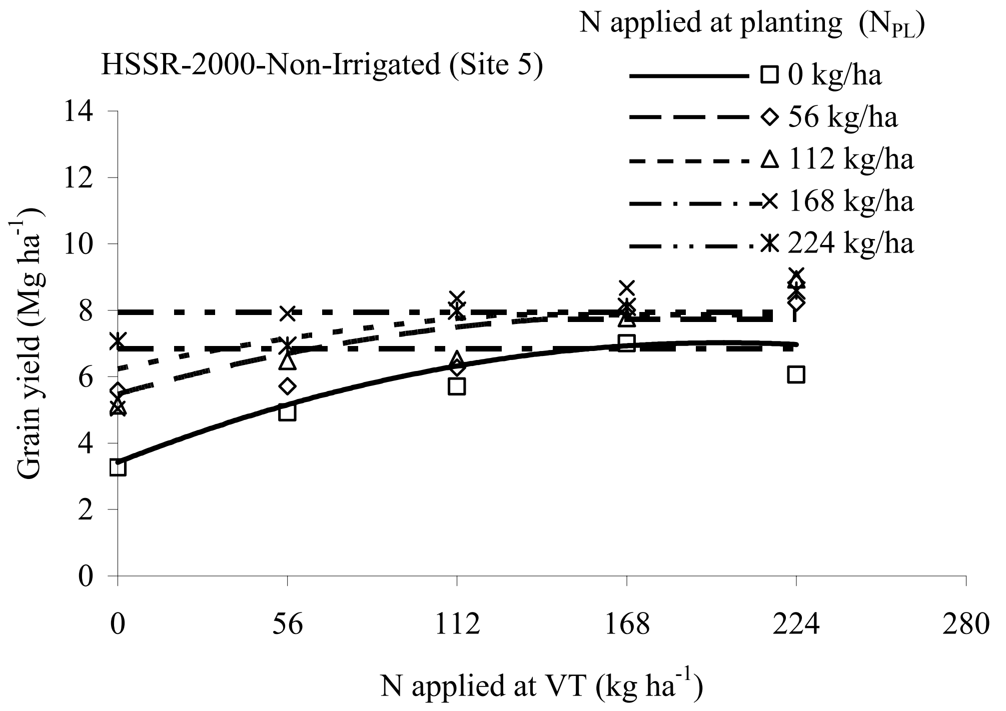
PBRS-2000-Irrigated (Site 1)



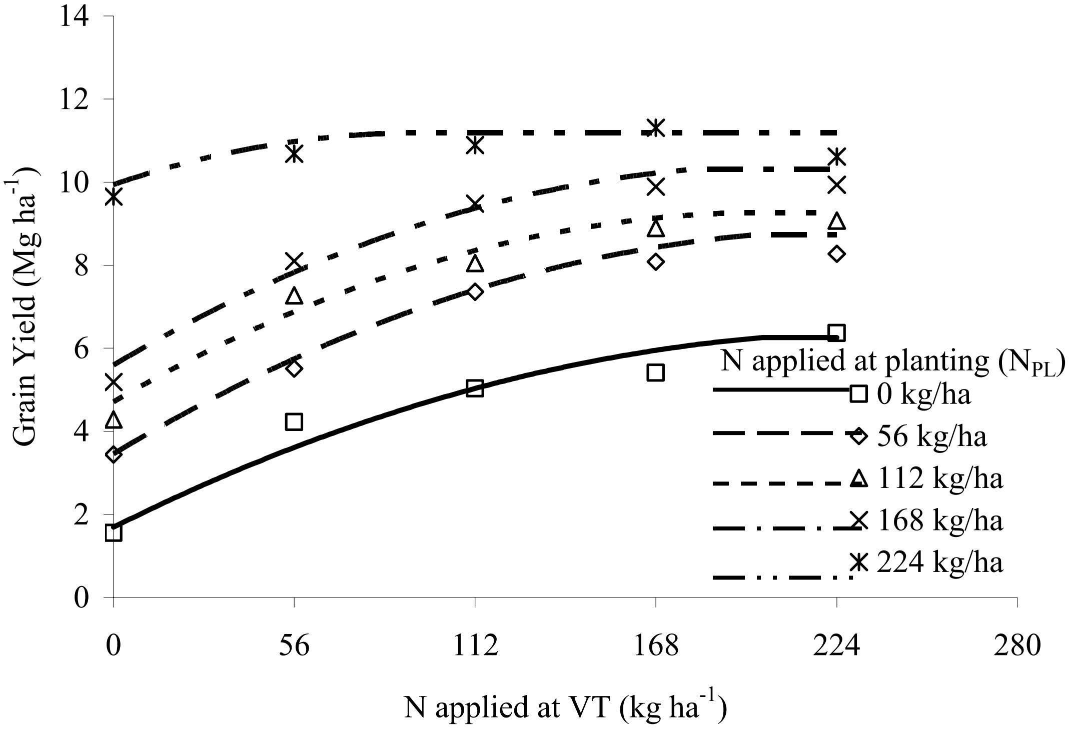

PBRS-2000-Non-Irrigated (Site 2)
Grain Yield (Mg ha^{-1})
14
12
10
8
6
4
2
0
0
56
112
168
224
280
N applied at VT (kg ha^{-1})
N applied at planting (N_{PL})
56 kg/ha
112 kg/ha
168 kg/ha
224 kg/ha


N applied at planting (N_{PL})
0 kg/ha
56 kg/ha
112 kg/ha
168 kg/ha
224 kg/ha
Denton-2000-Non-Irrigated (Site 3)
Grain yield (Mg ha^{-1})
14
12
10
8
6
4
2
0
0
56
112
168
224
280
N applied at VT (kg ha^{-1})

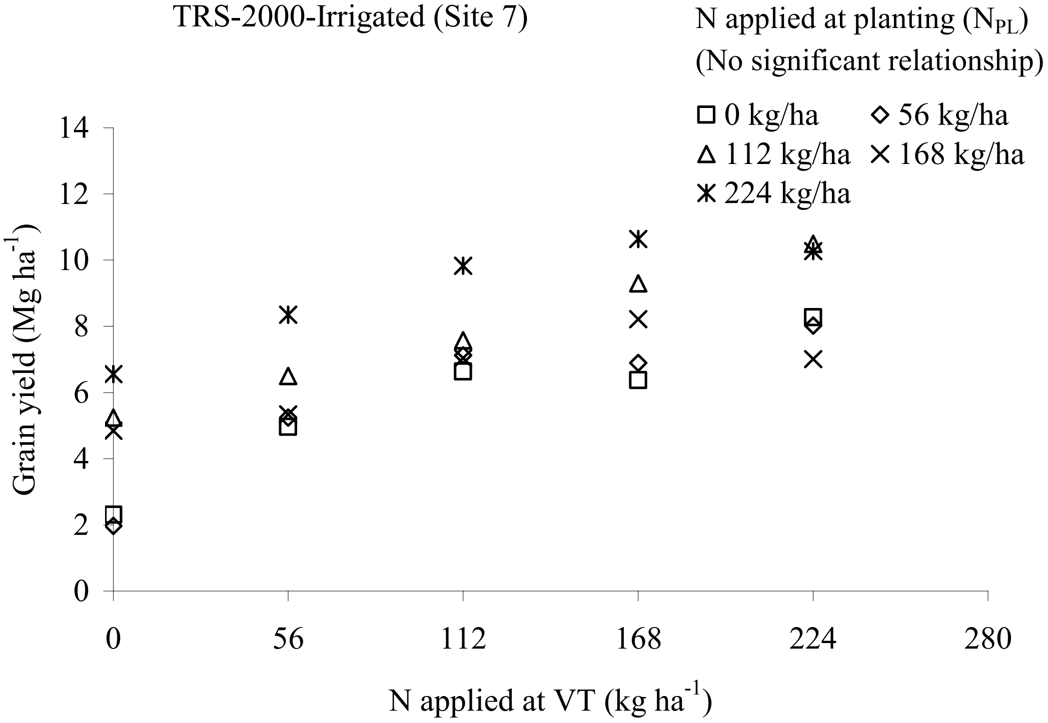

HSOR-2000-Non-Irrigated (Site 4)
Grain yield (Mg ha-1)
14
12
10
8
6
4
2
0
0
56
112
168
224
280
N applied at VT (kg ha-1)
N applied at planting (NPL)
0 kg/ha
56 kg/ha
112 kg/ha
168 kg/ha
224 kg/ha

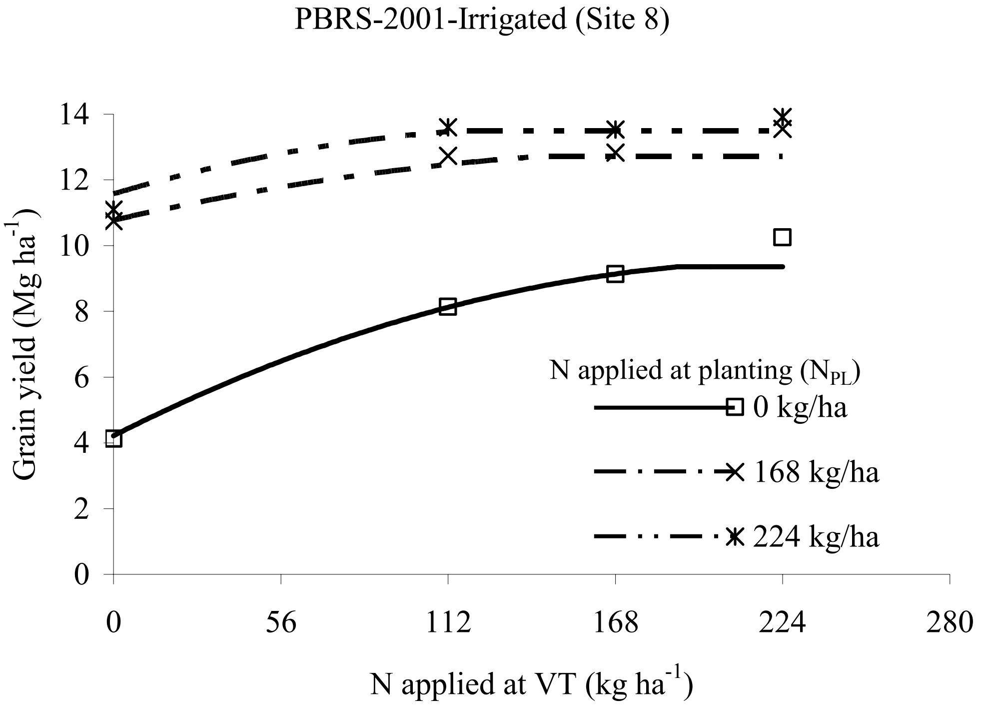

N applied at planting (NPL)
HSSR-2000-Non-Irrigated (Site 5)
0 kg/ha
56 kg/ha
112 kg/ha
168 kg/ha
224 kg/ha
Grain yield (Mg ha-1)
14
12
10
8
6
4
2
0
0
56
112
168
224
280
N applied at VT (kg ha-1)

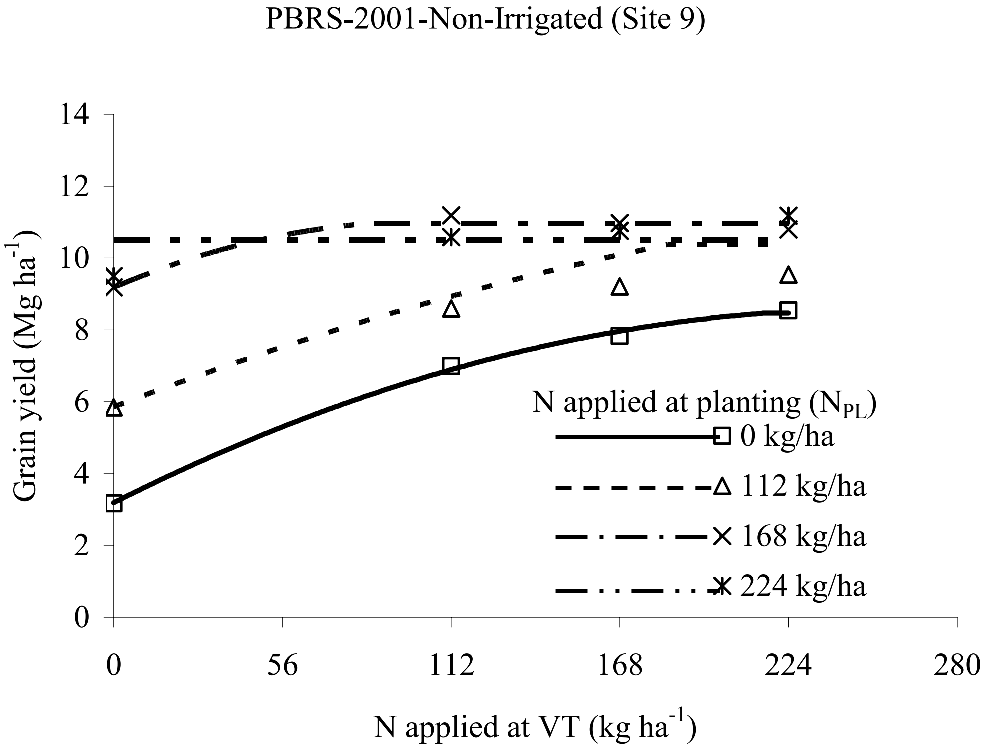
TRS - 2000- Non-Irrigated (Site 6)



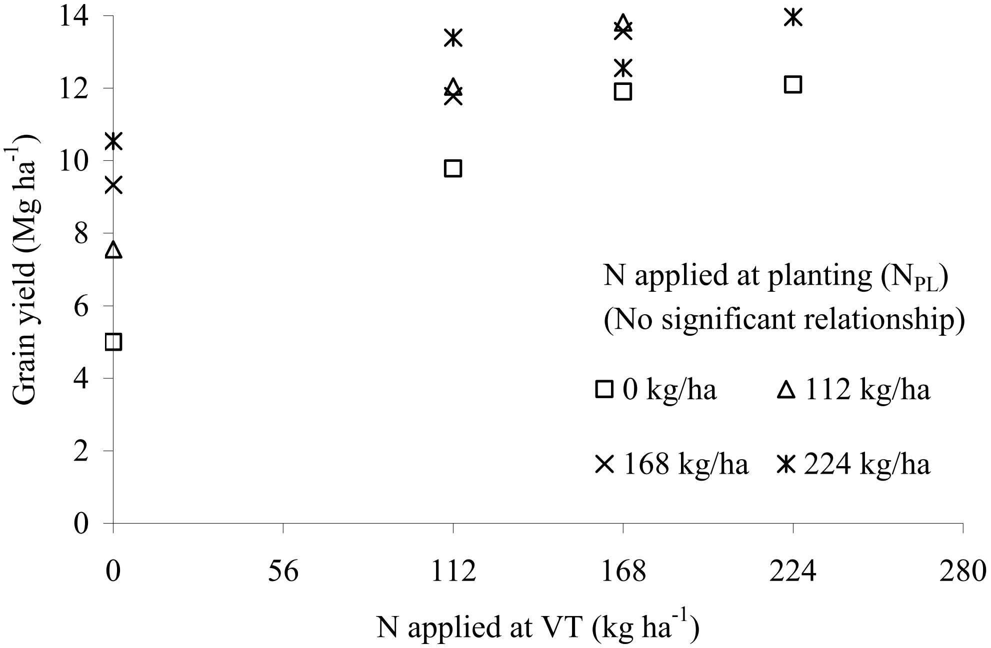
TRS-2000-Irrigated (Site 7)



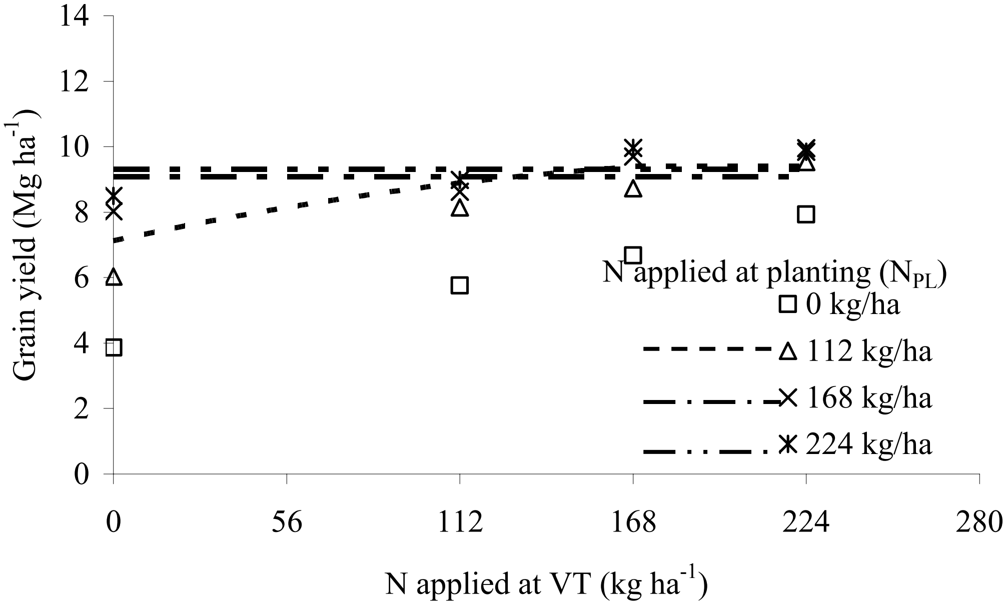

PBRS-2001-Irrigated (Site 8)


PBRS-2001-Non-Irrigated (Site 9)

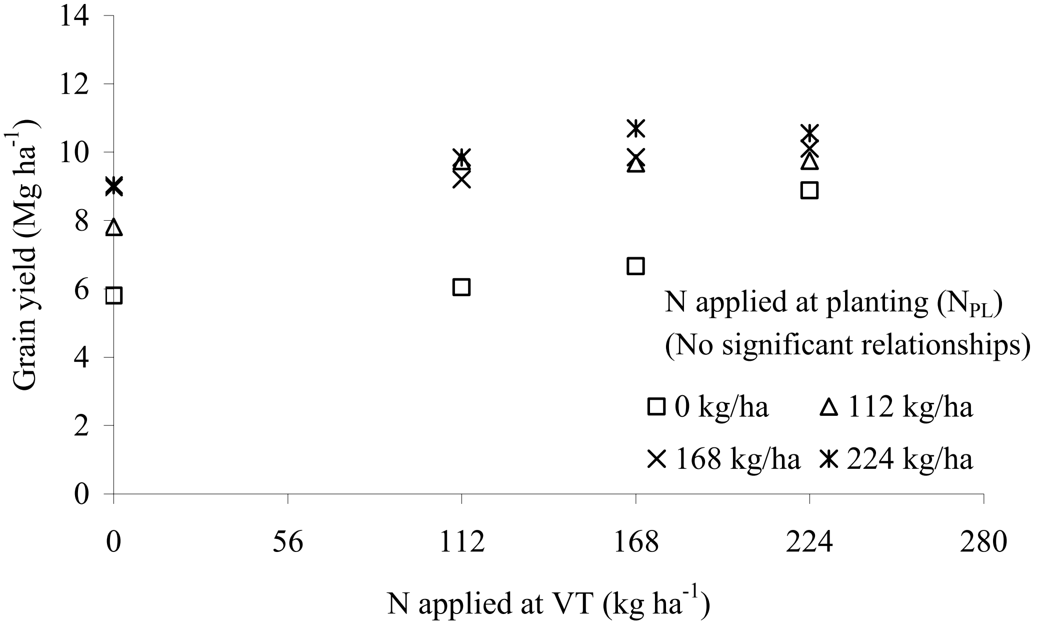
HSOR-2001-Non-Irrigated (Site 10)



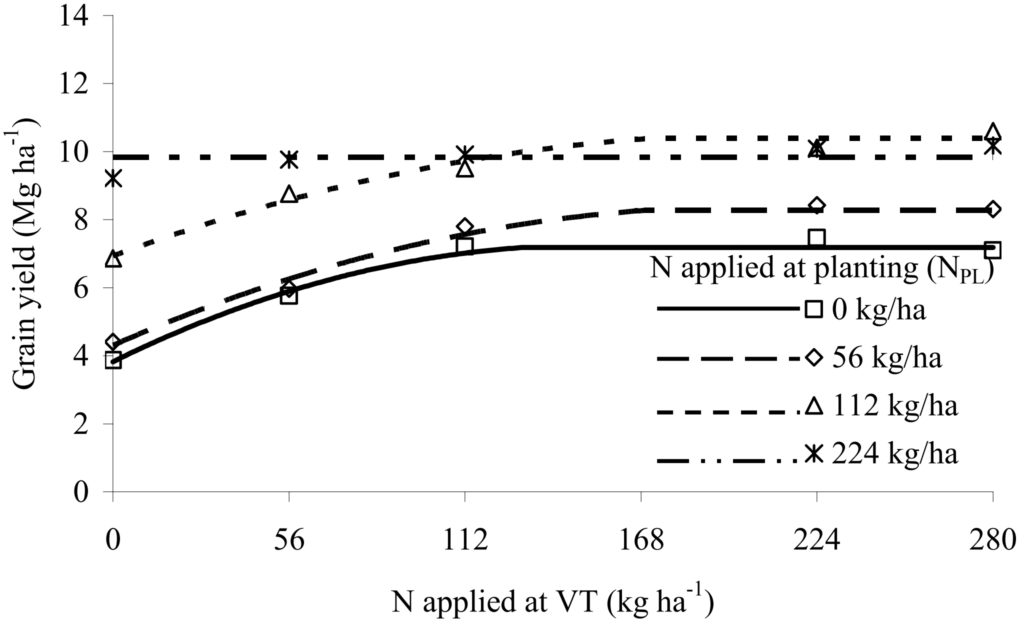
TRS-2001-Irrigated (Site 11)



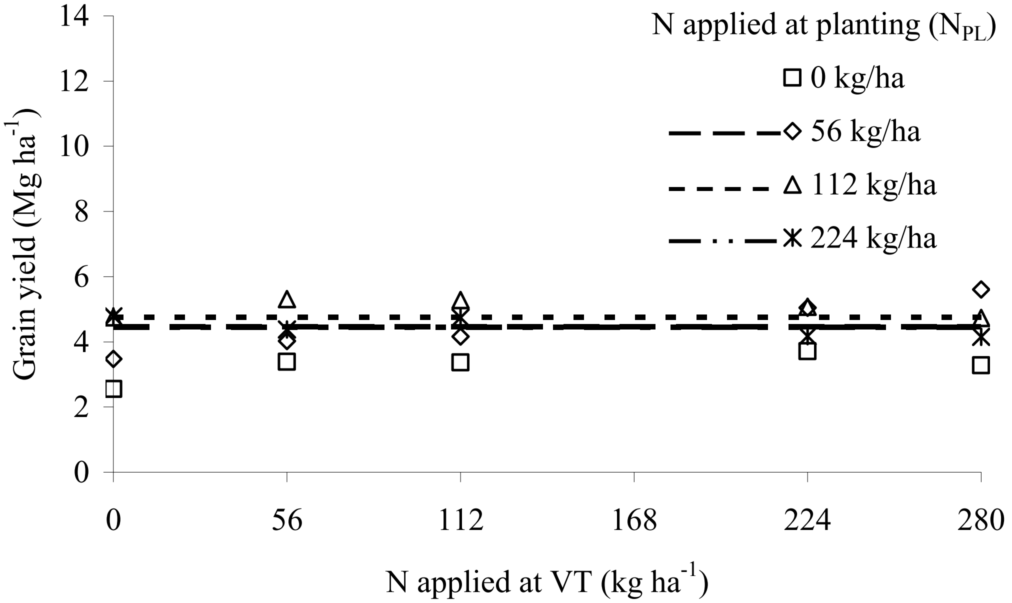
TRS-2001-Non-Irrigated (Site 12)



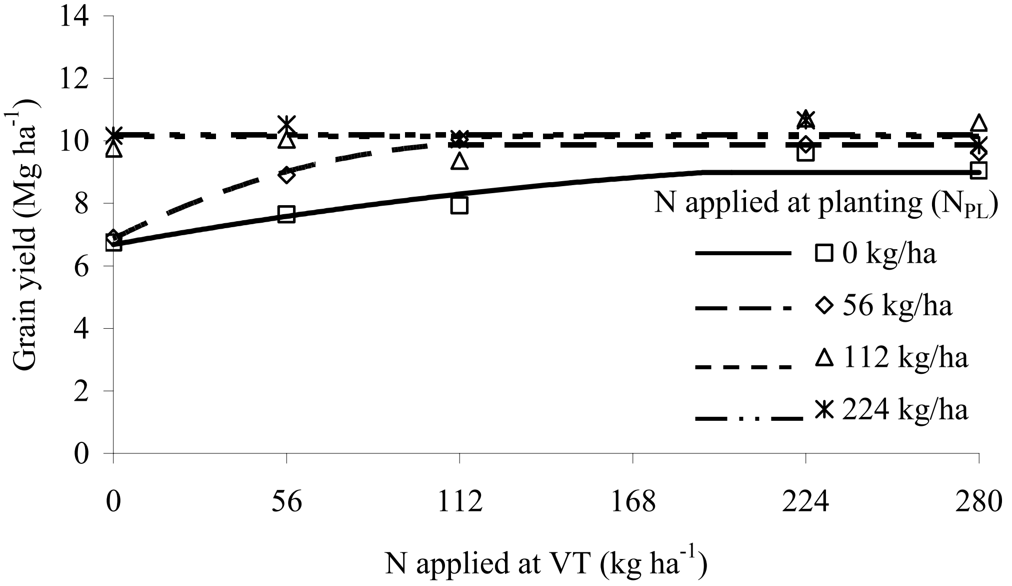
PBRS-2002-Irrigated (Site 13)



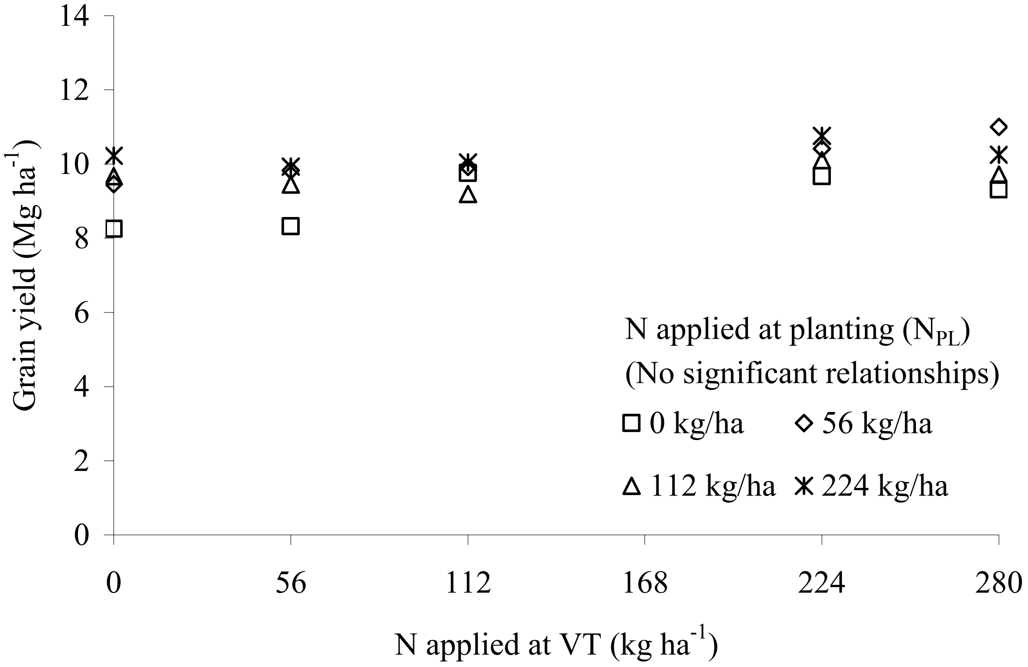
PBRS-2002-Non-Irrigated (Site 14)



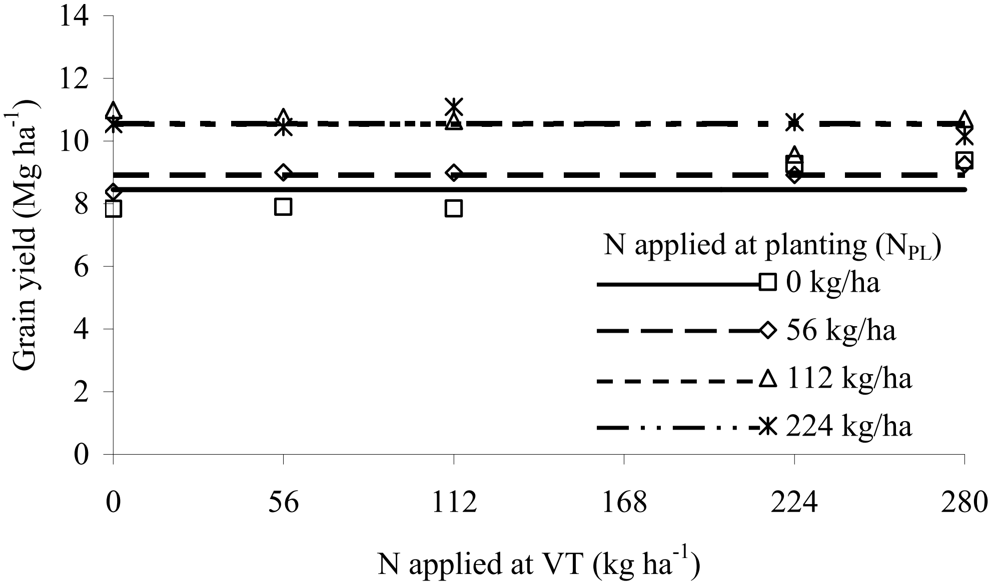
TRS-2002-Irrigated (Site 15)



TRS-2002-Non-Irrigated (Site 16)



TRS-2002-Irrigated (Site 17)



CHAPTER THREE

Field Validation of a Remote Sensing-Based Late-Season Nitrogen Application Decision System in Corn.

Field Validation of a Remote Sensing-Based Late-Season Nitrogen Application Decision System in Corn.

ABSTRACT

Previous research indicated that a linear-plateau function using relative green difference vegetation index (RGDVI) from aerial color-infrared (CIR) photography could be used to predict optimum N rates in corn (*Zea mays* L.) at tasseling (VT). The objective of this research was to validate this RGDVI-based remote sensing technique for determining in-season N requirements for corn at the VT growth stage, and to test the robustness of the model across years. A two-way factorial experimental design was implemented as a split-plot in randomized complete blocks with N at planting (N_{PL}) as main plot factor and sidedress N at VT (N_{VT}) as sub-plot factor at 10 irrigated and non-irrigated sites in North Carolina during 2003. Results indicate that the linear-plateau model describing the relationship between economic optimum N_{VT} rates and RGDVI was the best predictor and as observed in previous research appears robust over a variety of moisture regimes and years. The difference between predicted and observed optimum N_{VT} rates ranged from -30 to 90 kg N ha^{-1}. A greater difference between predicted and observed N rates was observed when N requirement was high and was attributed to lower yield potential observed in this study compared to model development years. Overall, the remote sensing technique was successful in predicting optimum N_{VT} rates ($r^2 = 0.85$) given the inherent constraints of predicting yield potential in a particular year. Although the model tended to over-predict N rates, it was able to capture changes in N requirements across the range of conditions tested. The results indicate that the RGDVI-based remote sensing technique can be used to adjust late in-season N rates.

Concerns with NO_3-N contamination of groundwater have led to increased efforts to improve management of N in corn production. The traditional practice in the Southeast has been to apply some N at the time of planting, supplemented with a sidedress application sometime between the V3 and V7 (Ritchie et al., 1993) growth stages. Recent research has shown that spectral reflectance can be used to determine N requirement just prior to VT (Sripada et al., 2005). While most growers in the Southeastern USA do not apply sidedress N as late as the VT stage, it might be possible to adjust grower practices if this method improved N management. A more accurate method of determining sidedress N requirements has the potential to improve N-use efficiency and minimize N losses to the environment.

Research has shown that approximately one-third of the total N uptake in corn occurs after the tassel has appeared (Crozier, 2002; Ritchie et al., 1993; Bigeriego et al., 1979). Therefore, there is an enormous potential to apply N as late as VT to meet some of the N requirements and minimize losses. In the Midwest, Blackmer and Schepers (1995) observed significant yield responses to N applied at the R4-R5 stage. Scharf and Lory (2002) and Sripada et al. (2005) demonstrated significant yield responses to N applied at V7 and VT, respectively.

The traditional methods of estimating the optimum N requirements for corn are based on soil testing (Magdoff, 1991), tissue N concentrations (Tyner and Webb, 1946), and chlorophyll concentration (leaf greenness). These methods are labor intensive, time consuming, and may not be economical for large fields. Remote sensing via aerial film or digital photography can provide valuable crop information in both space and time. Image-based remote sensing can be used to map crop yields (Shanahan et al., 2001) and to monitor seasonal variability of soil and crop-characteristics such as soil moisture, biomass production, crop evapo-transpiration, crop nutrient deficiencies (Blackmer et al., 1996), and weed or insect infestations. Scharf and Lory (2002) used relative green (G) from aerial color images to predict optimum sidedress N in corn at the V6-V7 stage. Sripada et al. (2005) developed an algorithm to estimate the economic optimum N rate at VT based on the RGDVI (Table 1) calculated from aerial CIR photographs. These and many other studies show that aerial color and/or CIR photographs taken between V7 and VT could be used to predict yield potential and N requirements.

There are a number of factors that can influence the apparent reflectance from a corn canopy in the near-infrared (NIR) and visible regions of the electromagnetic spectrum. The spectral reflectance of a crop canopy is a combination of the reflectance spectra of plant and soil components. Spectral reflectance in the red (R) region (600-700 nm) of the electromagnetic spectrum is inversely related to the *in situ* chlorophyll density, while spectral reflectance in the NIR (750-1350 nm) is directly related to the green leaf density (Gates et al., 1965). Further, it has been reported that vegetation under stress shows a decrease in reflectance in the NIR bands, a reduced R absorption in the chlorophyll active band (680 nm), and a consequent blue (B) shift on the R edge (Blackmer et al., 1996).

Because of the number of factors that can influence crop spectral characteristics, Blackmer and Schepers (1995) developed a N sufficiency index (NSI) relative to chlorophyll meter readings from a non-N-limited area to compare N status across fields and for fertigation in corn in the Great Plains. Similarly, Scharf and Lory (2002) used relative G to predict optimum sidedress N in corn at the V6-V7 stage. In a similar manner, the remote-sensing based in-season N-requirement prediction model for corn developed by Sripada et al. (2005) used within-field references in the form of high-N strips. Fertilizer N was applied to these high-N reference strips throughout the corn-growing season to maintain N sufficiency. Using data from two moisture regimes and across two years, a linear-plateau function of RGDVI with a negative slope was developed to estimate the economic optimal N requirements for corn at VT.

From a farmer's perspective, the adoption of a remote sensing technique to predict in-season N requirements in a corn production system would depend in part on the accurate prediction of that requirement. Therefore our objective was to validate the remote sensing-based in-season N requirement prediction model (linear - plateau) for corn developed by Sripada et al. (2005). In addition we wanted to determine if the RGDVI remote sensing model was robust across varying environments such as years and moisture regimes.

MATERIALS AND METHODS

Experimental Site Description

Field studies were conducted in North Carolina at two locations, the Peanut Belt Research Station (PBRS) near Lewiston-Woodville and the Tidewater Research Station (TRS) near Plymouth, with a total of 10 sites during the 2003 corn-growing season. Although both locations are in the Coastal Plain soil region of the soil systems of North Carolina, PBRS is located in the Large River Valleys and Flood Plain system and TRS in the lower Coastal Plain-Pamlico system. There were non-irrigated and irrigated sites at both locations. The soil classification data for the experimental sites is described in Table 2.

At each site, a two-way factorial experimental design was implemented as a split-plot in randomized complete blocks with two replications with the N applied at planting (N_{PL}) as the main plot factor and sidedress N applied at VT (N_{VT}) as the sub-plot factor. The main plots were 9.1-m long and 25.5-m wide with 0.91-m row spacing. The subplots were four rows wide at all sites. ‘Pioneer 31G98’ was planted at approximately 60,000 seeds ha^{-1} 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. The N_{PL} rates were 0, 56, 112, and 224 kg ha^{-1} and the N_{VT} rates were 0, 56, 112, 168, 224, and 280 kg ha^{-1}. With the exception of N management, standard management practices corresponding to the region were followed. Herbicides were applied based on weeds present and excellent weed control was obtained at all sites. Depending on the rainfall, water was applied to the irrigated plots at the rate of 25.4 mm a week. Weather data from 1971 – 2001 was used in calculating the 30 year average air temperature and precipitation values (Fig. 1). Planting, V7, VT, and harvest occurred on Julian days 93, 162, 185, and 247 at PBRS and Julian days 121, 167, 192, and 249 at TRS in 2003. For graphing purposes, planting, V7, VT and harvest dates at PBRS and TRS were assumed to occur at Julian days 96, 154, 181, and 251 days and 121, 169, 192, and 253 respectively.

Determining Response to N_{VT}

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 moisture content of 155 g kg^{-1}. For the combined yield analysis that encompassed all sites, site within a location and irrigation combination was considered as an individual experiment (IE). Location and its interactions with irrigation, N_{PL}, and N_{VT} were considered as random effects. The grain yield responses to IE, irrigation, and applied N (N_{PL} and N_{VT}) were analyzed using PROC GLM in SAS version 8 (SAS Institute, Cary, NC).

Determination of Economic Optimum N_{VT} 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_{VT} rates were calculated using the first derivative of the quadratic-plateau model 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_{VT} 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_{VT} rate was set equal to zero.

Image Acquisition and Conversion to Color Values

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 one-meter 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 such that the entire experimental field 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, Inc., 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.

The spectral properties of the CIR film used for obtaining images were described by Flowers et al. (2003). 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 represents 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 – 900 nm, band 2 (R) covered the wavelengths between ~490 – 700 nm, and band 3 (G) covered the wavelengths between ~490 – 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). Digital images were georegistered using ERDAS Imagine version 8.7 (ERDAS Inc. Atlanta, GA).

Areas of interest (AOI) corresponding to each individual plot were identified, which included an approximately equal number 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). To avoid working with negative values a constant value of 255 and 1 was added to DVI and GDVI, and all relative indices respectively. Relative bands (Rel NIR, Rel R, Rel G) and indices (Table 1) were calculated as the ratio of the spectral value of a particular plot to the spectral value for the plot (reference plot) that received the highest N_{PL} rate at a particular site. The digital counts for the NIR, R, and G bands and all of the indices were regressed against the economic optimum N_{VT} 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).

Validation of the Remote Sensing-Based In-season N Requirement Prediction Model

To test how robust the model parameters were across years, the observed economic optimum N_{VT} rates and the corresponding RGDVI values were fit to a linear-plateau model 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_{VT} 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_{VT} rate with change in the RGDVI values). The NLMIXED procedure was used to estimate the parameters for the linear-plateau model from the 10 sites examined in this study. Contrast statements were used to test the difference in the linear-plateau model parameters of the remote sensing-based in-season N requirement prediction model developed by Sripada et al. (2005) and those obtained in this validation study.

The predicted economic optimum N rates were calculated by using the model developed by Sripada et al. (2005) as follows:

$$\text{Economic Optimum } N_{VT} \text{ rate} = 184.7 + [-3477.5 \times (\text{RGDVI} - 0.9563)] \qquad [1]$$

To test the accuracy of this remote sensing-based in-season N requirement prediction model, the observed economic optimum N_{VT} rates were plotted against the predicted optimum N_{VT} rates. The residuals, that is, difference between the predicted and observed economic optimum N_{VT} rates, were calculated and plotted to quantify the under-and or over-prediction of the in-season N requirement.

RESULTS AND DISCUSSION

Grain Yield Responses to N Applications

Across the different sites, grain yields for the treatment means ranged from 2.1 Mg ha^{-1} to 12.9 Mg ha^{-1} (Table 3). All the 10 sites (Table 2) were used in the analysis to test the effects of location, irrigation, IE, (i.e., site [location × irrigation]), N_{PL} and N_{VT} on grain yield, resulting in an analysis of ten sites with five sites at two locations and two irrigation treatments. The three-way interactions of N_{PL} and N_{VT} and IE, (i.e., site [location × irrigation]) and irrigation were not significant (Table 4). Similarly, the two-way interactions of IE × $N_{PL,}$ Irrigation × N_{PL}, and IE × N_{VT} were not significant. However, there was a significant two-way interaction between irrigation and N_{VT}. Contrary to our expectation, the two-way interaction $N_{PL} \times N_{VT}$ was not significant as can be seen in the nearly parallel form of the response curves for N_{VT} in Fig. 2 & 3 showing the response curves obtained at sites CIR1 and TNI3 respectively. One possible explanation for this is the similar slope and varying intercept of the 0 kg ha^{-1} N_{PL} response curve compared to the 56 and 112 kg ha^{-1} N_{PL} response curves. The significance of the main effect IE (Table 4) can be attributed to differences in the soil series between the two locations and within each location used in this study (Table 2). The main effect N_{PL} was significant as seen by the different intercepts for the grain yield response to N_{VT} at different N_{PL} rates (Fig. 2 & 3; Table 4). The 0 kg ha^{-1} N_{PL} plots that did not receive any N up to VT stage appeared to have lost yield potential which was not regained even after high N_{VT} applications. This resulted in a lower maximum yield plateau and thus lower economic optimum N_{VT} rate compared to the 56 kg ha^{-1} response curve (Fig. 2 and 3). 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. When sidedress N is to be applied at or near tasseling (VT), adequate N must be applied at planting and/or at layby (e.g., V7-8) to maintain yield potential through VT (Crozier, 2002).

Predicting Economic Optimum N_{VT} Rates from Spectral Data

The different N_{PL} rates helped create a range of spectral variability among plots 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 150 kg N ha^{-1} with a mean of 68 kg N ha^{-1}. The spectral band G showed a significant linear relationship with economic optimum N_{VT} rates (Table 5) while the bands R and NIR were not significant. With the exception of DVI, the indices associated with NIR and G bands (GDVI, GRVI, GNDVI, GSAVI, and GOSAVI) showed significant linear relationships with economic optimum N_{VT} rates compared to the indices associated with NIR and R bands.

Better prediction of the economic optimum N_{VT} rates was observed with relative bands and indices (Table 5) than with individual spectral bands or absolute indices.

Overall in the present study, a linear-plateau model using RGDVI ($r^2 = 0.81$) was the best predictor of economic optimum N_{VT} rates, where a gradual increase in RGDVI values was observed with decreasing economic optimum N_{VT} rates (Fig. 4). Based on the statistical analysis (not shown), the linear-plateau model describing the relationship between economic optimum N_{VT} rates and RGDVI obtained in this study did not differ over a variety of moisture regimes, thus a combined model could be used to express the relationship between economic optimum N_{VT} rate and RGDVI. The narrow range of RGDVI values (0.9524 to 1.02) that is responsive to economic optimum N_{VT} rates is of particular importance because even very small variations in the RGDVI value can change the predicted economic optimum N_{VT} rate significantly (Fig. 4). These results were consistent with those obtained by Sripada et al. (2005) when developing the model being validated in this study. Scharf and Lory (2002) in similar work targeting much earlier in the corn growing season (V7), observed a linear relation between predicted economic optimum N_{VT} rates and G (R^2=0.70) or B (R^2=0.79) reflectance, after removal of soil pixels and only in the absence of significant prior N application.

Comparison of the Remote Sensing-Based In-season N-Requirement Prediction Model to the Model Obtained in this Validation Study

Mean treatment yield levels (Table 3) obtained in this validation study were lower than those obtained during the studies in which the original model was developed (Sripada et al, 2005). At PBRS, the treatment means for grain yield during the model development years were greater than 9 Mg ha^{-1} but less than 9 Mg ha^{-1} in this validation study. At TRS, the treatment means for grain yield were consistently higher in the model development years compared to the present validation study.

The results of the statistical tests to determine the differences in the linear plateau model parameters of the RGDVI-based remote sensing model developed by Sripada et al. (2005) and those obtained in this validation study are shown in Table 6. There was no significant difference in the slope (*b*) and inflection point (*x0*). However, the intercept *a* (the plateau for economic optimum N_{VT} rate) was significantly different for the two models (Table 6 and Fig. 5). This might have been due to greater loss of yield potential caused by delaying the second split N application untill VT in this validation study compared to the model development years (Sripada et al., 2005). Consistent with the generally lower yields observed in the present study, the plateau for the economic optimum N rate (Fig. 5) was substantially lower than in the model development study (Sripada et al., 2005), 128 versus 185 kg N ha^{-1}.

Based on the data used in model development by Sripada et al. (2005) providing sufficient N_{PL} so as to totally avoid N deficiency through VT, we would expect the linear portion of the linear-plateau-model to originate at RGDVI=1 and result in an economic optimum N_{VT} rate of 0 in both the present validation study and in the model developed by Sripada et al. 2005 (Fig. 5). However, the linear portion of the linear-plateau model describing the relationship between economic optimum N_{VT} rate and RGDVI in this validation study has a higher slope than the model developed by Sripada et al. (2005) (Fig. 5).

Validation of Remote Sensing-Based In-season Predicted Economic Optimum N_{VT} Rates

A linear regression of the observed and predicted economic optimum N_{VT} rates had an $r^2 = 0.85$ (Fig. 6). To further assess the accuracy of the predicted economic optimum N_{VT} rates, we examined them relative to the 1:1 line between the predicted and observed economic optimum N_{VT} rates (Fig. 6). In general, the model tended to overestimate economic optimum N_{VT} rates (Fig. 6). There was a consistent difference of 33 kg N ha^{-1} between the observed and predicted N requirements for the low-N requiring situations, that is, the plots that received 224 kg N ha^{-1} at planting (Fig. 7). Since the model calculates the predicted optimum N_{VT} rates using an index calculated relative to the highest N rate strip/plot available (RGDVI: Sripada et. al., 2005), the 224 kg N ha^{-1} plots had an RGDVI value equal to 1 resulting in a predicted economic optimum N_{VT} rate of 33 kg ha^{-1} for which the corresponding observed economic optimum N_{VT} rate was zero.

The high-to medium N requiring situations, that is, the plots that received N_{PL} of 0, 56, and 112 kg N ha^{-1}, had a greater range (-30 to 90 kg N ha^{-1}) in the difference between the predicted and observed economic optimum N_{VT} rates (Fig. 7). This is consistent with the narrower range of economic optimum N_{VT} rates observed in this study (0 to 150 kg N ha^{-1} with a mean of 68 kg N ha^{-1}) compared to those obtained in the model development study (0 to 220 kg N ha^{-1} with a mean of 104 kg N ha^{-1}: Sripada et al., 2005). The lower yield potential found during this validation study compared to the model development years and the tendency of the model to over predict optimum N_{VT} rate suggests that the remote sensing-based in-season N prediction model might be optimized by adjusting for yield potential of a given season.

CONCLUSIONS

At present, most corn growers do not apply sidedress N as late as the VT stage. However, the risk of N loss from the soil is increased when applications are made far in advance of the time they are used by the crop. Studies by Sripada et al. (2005) and the present validation study demonstrate significant yield responses to N_{VT}. Our objective was to validate the RGDVI-based model to predict economic optimum N_{VT} rates developed by Sripada et al., 2005. Tests showed that a linear-plateau function similar to that developed by Sripada et al., 2005 resulted in the best fit for the relationship between economic optimum N_{VT} rate and the RGDVI. Likewise, results indicate that this linear-plateau model relating the economic optimum N_{VT} rates with RGDVI did not differ across years similar to our earlier findings.

Overall the remote sensing technique was reasonably successful ($r^2 = 0.85$) in predicting the optimum N_{VT} rates. However, the model tended to over predict economic optimum N rates. The over estimation of 33 kg N ha^{-1} seen in this validation study may not be a major concern. When the economic optimum N_{VT} rates are based on a linear-plateau function, the plateau, which is the maximum optimum N_{VT} rate, can be expected to vary from year to year due to changes in yield potential caused by changes in weather and/or management. Even so, most growers would tolerate an over estimation up to 50 kg ha^{-1} as long as they were able to identify the relative amounts of N required based on the crop N status as seen in this study. The remote sensing-based in-season N prediction model can likely be further enhanced by an adjustment factor based on estimated yield potential.

In principle, by utilizing this technique, we hope that corn farmers will be able to maximize profitability by applying the right amounts of N. If realized by improving fertilizer N-use efficiency, this might translate into less excess N to pollute groundwater. There are several obstacles to adoption of this technique: unpredictability of yield potential, primarily due to unpredictability of available soil moisture in rain-fed situations; necessity for high-N reference strips in the field (Sripada et al. 2005); and the need for high-clearance applicators to apply N at VT. If these obstacles can be overcome, the remote sensing based technique may become an attractive method to estimate how in-season N rates should be adjusted from field to field and even within a field using site-specific, variable rate applicators. The grower can adjust N rates based on the season, with remote sensing providing valuable information on when, where, and how much N to apply.

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Table 1. 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)	$GOSAVI_{plot}/GOSAVI_{reference\ plot}$	-

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[†] NIR: near infrared; R: red; G: green.

[‡] A reference plot is one that received the highest N rate.

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

Site	Location[†]	Irrigation[‡]	Soil series	Soil taxonomic classification
CIR1	PBRS	IR	Norfolk sandy loam	Fine-loamy, siliceous, thermic Typic Paleudults
CIR3	PBRS	IR	Norfolk sandy loam	Fine-loamy, siliceous, thermic Typic Paleudults
CNI1	PBRS	NI	Rains sandy loam	Fine-loamy, siliceous, thermic Typic Paleaquults
CNI2	PBRS	NI	Rains sandy loam	Fine-loamy, siliceous, thermic Typic Paleaquults
CNI3	PBRS	NI	Rains sandy loam	Fine-loamy, siliceous, thermic Typic Paleaquults
TIR1	TRS	IR	Hyde loam	Fine-silty, mixed, thermic Typic Umbraquults
TIR2	TRS	IR	Hyde loam	Fine-silty, mixed, thermic Typic Umbraquults
TIR3	TRS	IR	Hyde loam	Fine-silty, mixed, thermic Typic Umbraquults
TNI2/ TNI3	TRS	NI	Portsmouth fine sandy loam	Fine-loamy over sandy or sandy skeletal, mixed, thermic Typic Umbraquults

[†] PBRS: Peanut Belt Research Station; TRS: Tidewater Research Station.

[‡] IR: Irrigated; NI: Non-irrigated.

Table 3. Minimum, maximum, mean, and standard deviation for corn grain yields obtained at different experimental sites.

	Grain yield			
Site	Minimum	Maximum	Mean	Std Dev
	------------------------------------Mg ha^{-1}--------------------------------			
CIR1	2.1	11.7	6.1	2.3
CIR3	2.2	10.9	6.4	2.3
CNI1	3.9	12.4	8.6	1.9
CNI2	4.5	12.5	8.9	1.8
CNI3	4.1	11.8	8.8	2.0
TIR1	2.7	12.9	8.3	2.2
TIR2	2.3	11.5	8.0	2.1
TIR3	2.1	11.6	7.5	1.9
TNI2	3.6	11.8	9.0	1.8
TNI3	3.5	11.4	8.6	1.7

Table 4. ANOVA for grain yield as affected by location, irrigation, individual experiment (IE), and fertilizer N at planting (N_{PL}) and at pretassel (VT: N_{VT}).

Source of variation[†]	df	Grain yield
Location	1	NS
Irrigation	1	NS
IE	6	**
N_{PL}	3	*
Irrigation × N_{PL}	3	NS
IE × N_{PL}	18	NS
N_{VT}	5	**
Irrigation × N_{VT}	5	*
N_{PL} × N_{VT}	15	NS
IE × N_{VT}	30	NS
Irrigation × N_{PL} × N_{VT}	15	NS
IE × N_{PL} × N_{VT}	87	NS

*, **, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

[†] IE: Individual experiment. Site within a location and irrigation combination was considered as an individual experiment.

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

	Model			
Vegetation Index	Linear	Linear-Plateau	Quadratic	Quadratic-Plateau
	r^2	----------------------------	R^2	----------------------------
NIR	NS	NS	NS	NS
Red	NS	NS	NS	NS
Green	0.32**	NS	NS	NS
Norm NIR	0.35**	NS	NS	NS
Norm R	NS	NS	NS	NS
Norm G	NS	NS	NS	NS
Rel NIR	0.46**	NS	NS	NS
Rel R	0.56**	NS	0.65**	NS
Rel G	0.74**	NS	0.82**	0.83**
DVI	0.15*	NS	NS	NS
RDVI	0.57**	NS	0.64**	NS
GDVI	0.20*	NS	NS	NS
RGDVI	0.67**	0.81**	0.80**	NS
RVI	NS	NS	NS	NS
RRVI	0.61**	0.69**	NS	NS
GRVI	0.20*	NS	NS	NS

RGRVI	0.72**	0.76**	0.80**	NS
NDVI	NS	NS	NS	NS
RNDVI	0.57**	0.69**	0.67**	NS
GNDVI	0.22**	NS	NS	NS
RGNDVI	0.67**	0.78**	0.78**	NS
SAVI	NS	NS	NS	NS
RSAVI	0.56**	0.68**	0.67**	NS
GSAVI	0.22**	NS	NS	NS
RGSAVI	0.67**	0.78**	0.78**	NS
OSAVI	NS	NS	NS	NS
ROSAVI	0.57**	NS	0.67**	NS
GOSAVI	0.22**	NS	NS	NS
RGOSAVI	0.67**	0.78**	0.78**	NS

*, **, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

Table 6. Tests of differences in linear-plateau model parameters between the linear-plateau model derived from the present validation study and the remote sensing-based in-season N requirement prediction model being validated (Sripada et al., 2005).

Parameter[†‡]	Estimate	Standard error	Lower limit, 95% confidence interval	Upper limit, 95% confidence interval	p-value
a_1	185	11	161	208	***
a_2	128	113	102	156	***
b_1	-3477	450	-4416	-2538	***
b_2	-2413	580	-3624	-1202	***
$x0_1$	0.9563	0.005	0.9452	0.9680	***
$x0_2$	0.9524	0.01	0.9298	0.9747	***
Contrasts					
a_1 Vs. a_2	-	-	-	-	**
b_1 Vs. b_2	-	-	-	-	NS
$x0_1$ Vs. $x0_2$	-	-	-	-	NS

, *, NS Significant at the 0.01 and 0.001 probability levels and not significant, respectively.

[†] The parameters of a linear plateau model are the intercept a, slope b, and x_0 the inflection point.

[‡] Parameters a_1, b_1, and $x0_1$ correspond to the linear – plateau model parameters for the model being validated (Sripada et al., 2005) and a_2, b_2, and $x0_2$ correspond to the and the validation dataset parameters.

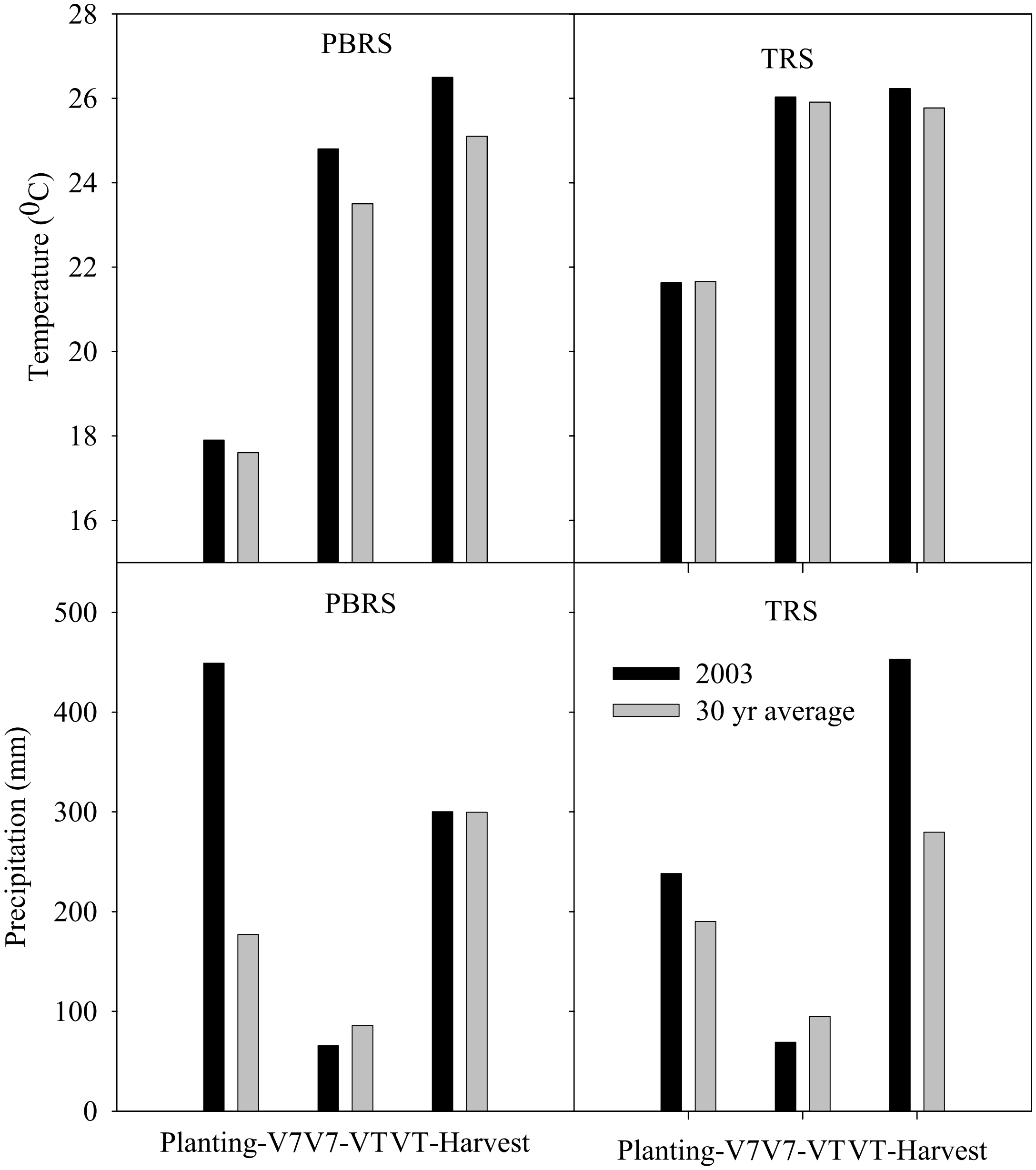


Fig. 1. Mean air temperature and cumulative precipitation from planting to V7, V7 to VT, and VT to harvest growth stages of corn at the Peanut Belt Research Station (PBRS) and the Tidewater Research Station (TRS) during 2003 compared to the 30-year average.

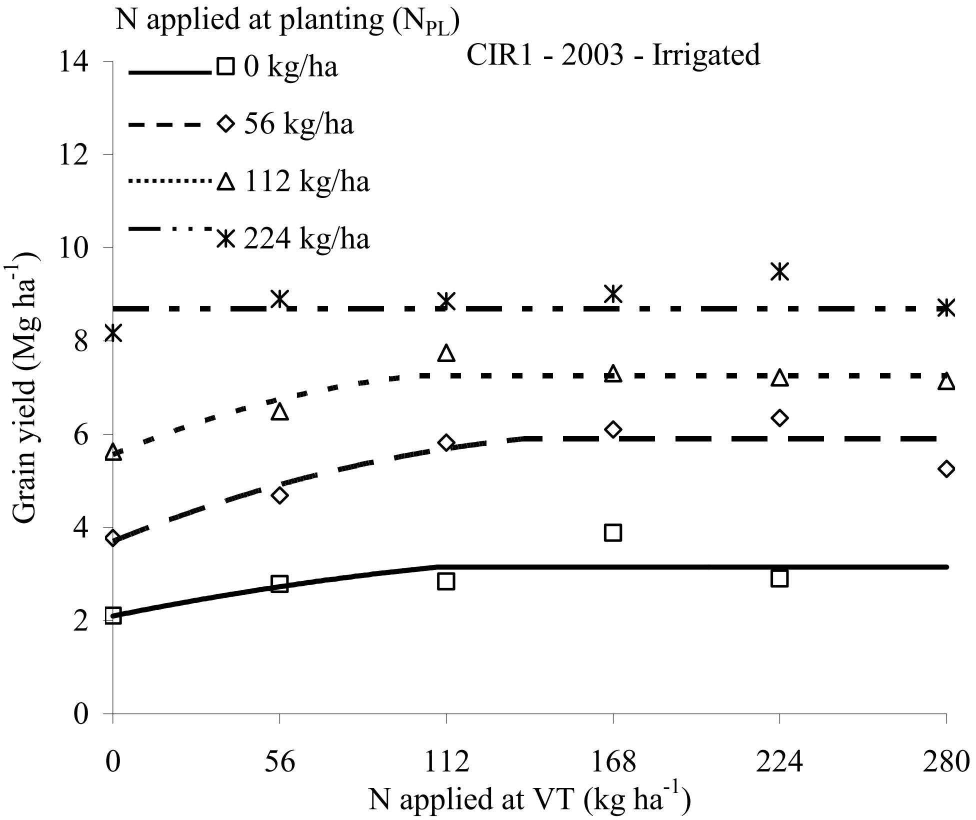


Fig. 2. Quadratic-plateau fit of corn grain yield response to N applied at VT (N_{VT}) for different rates of N applied at planting (N_{PL}) at the Peanut Belt Research Station site CIR1 in 2003.

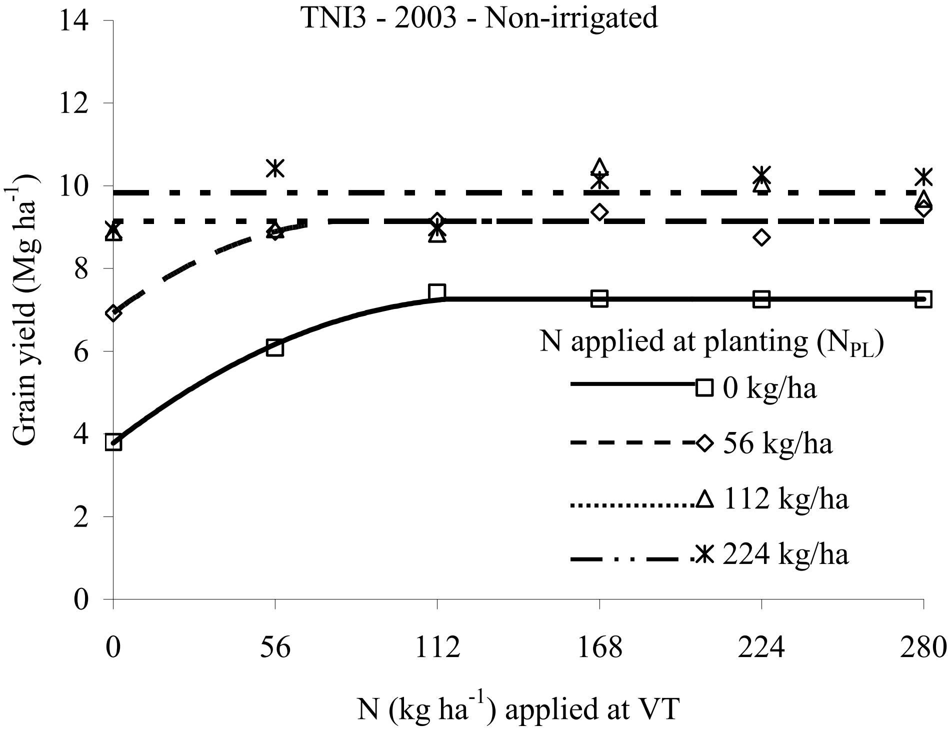


Fig. 3. Quadratic-plateau fit of corn grain yield response to N applied at VT (N_{VT}) for different rates of N applied at planting (N_{PL}) at the Tidewater Research Station site TNI3 in 2003.

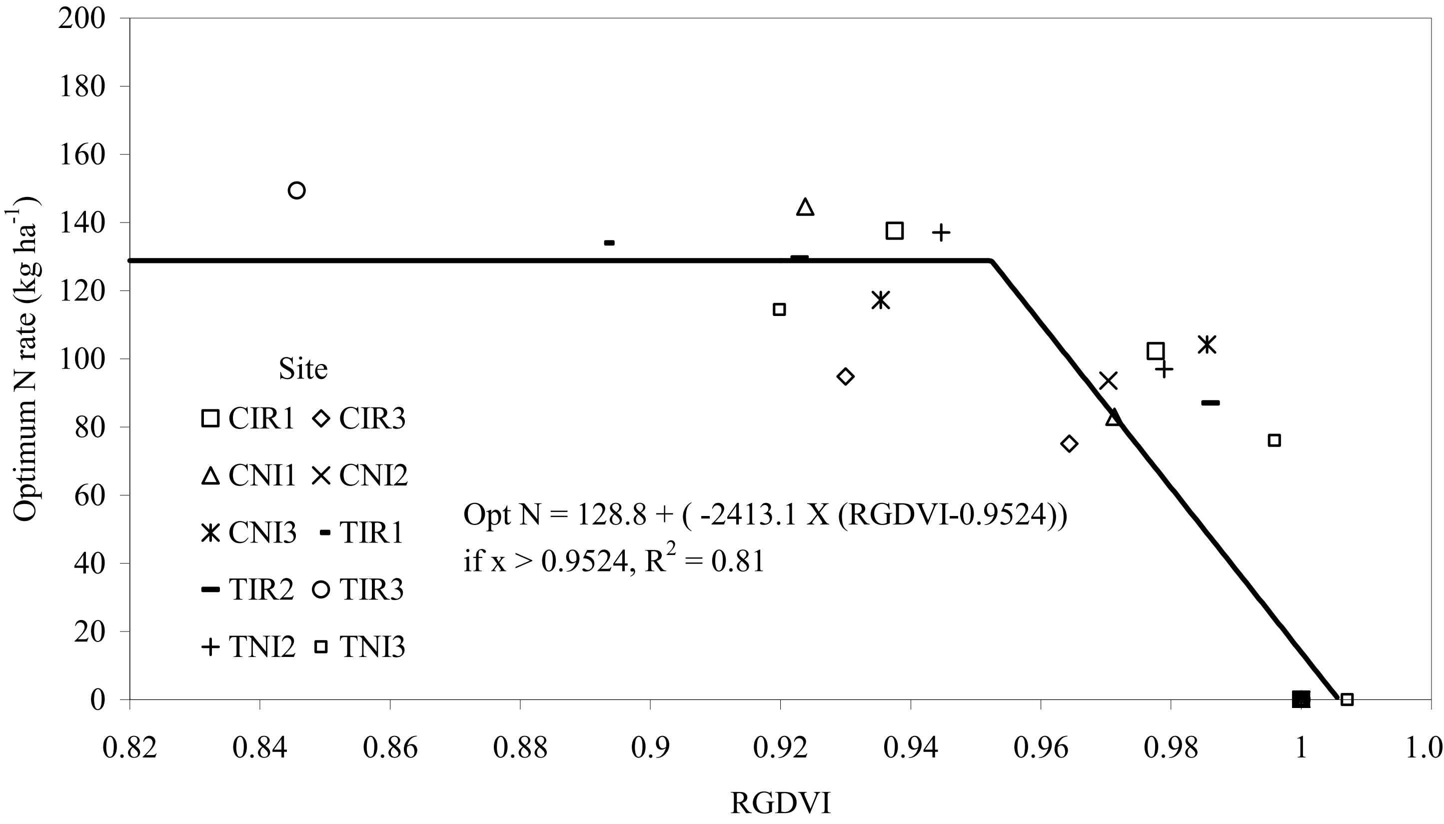


Fig. 4. Linear-plateau model showing the relationship between economic optimum N rate at VT (N_{VT}) and RGDVI in the present validation study. Different symbols represent different sites, except for the symbol at (1, 0) which represents 10 individual data points.

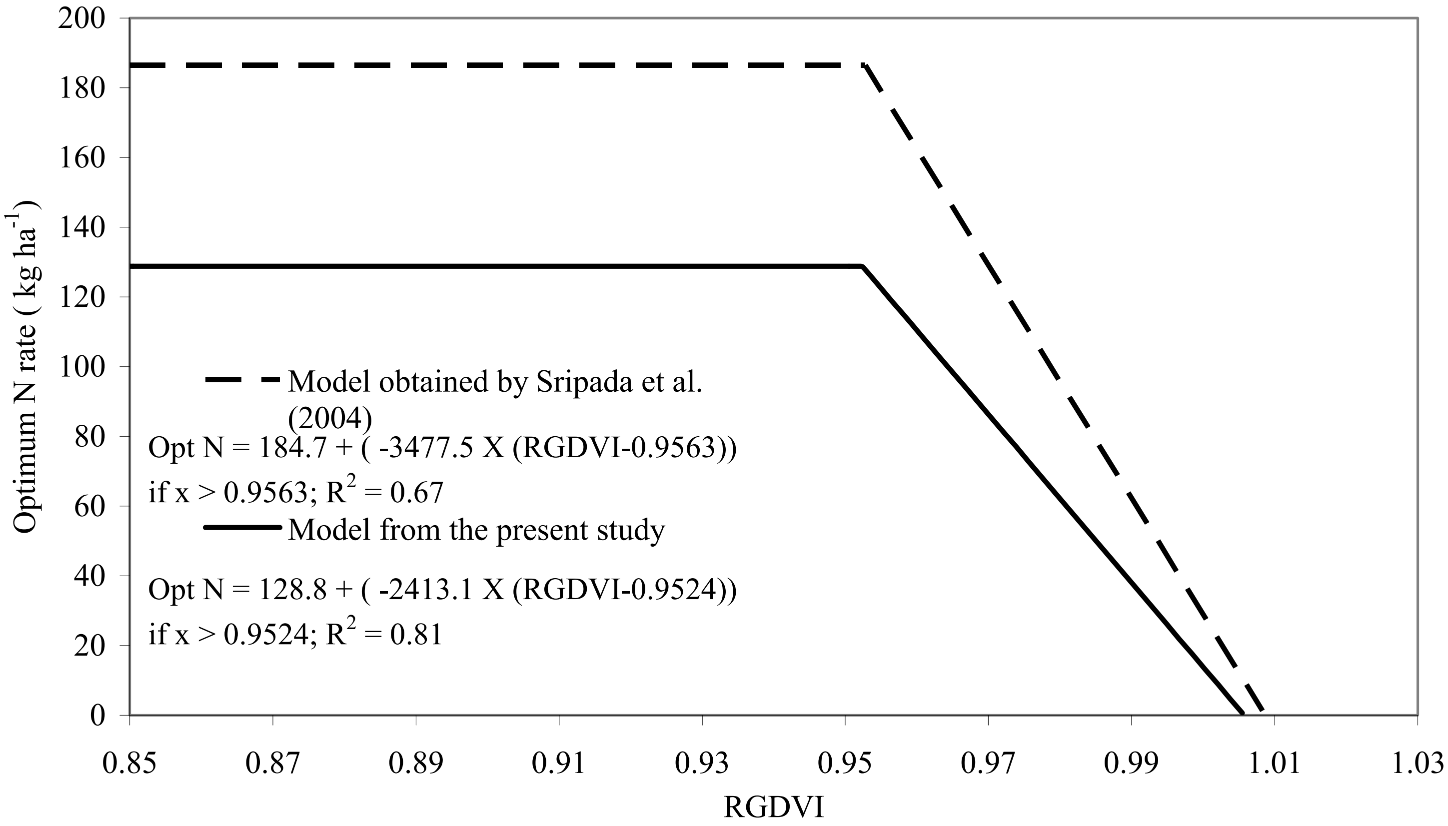


Fig. 5. Comparison of the remote sensing-based in-season N-requirement prediction model to the model obtained in this validation study.

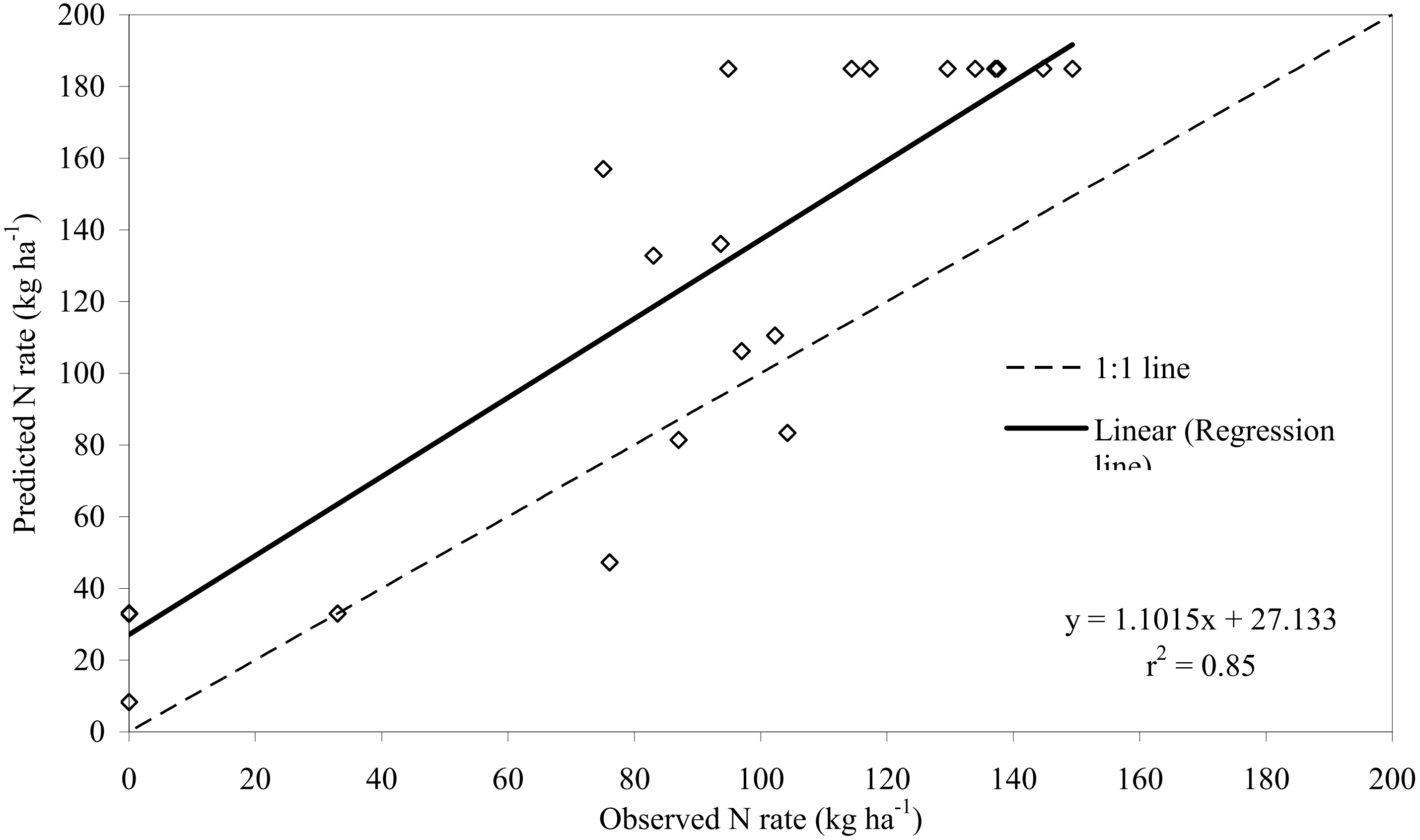


Fig. 6. Relationship between the predicted economic optimum N rates at VT (N_{VT}) using the model developed by Sripada et al. (2005) and the observed economic optimum N rates during the 2003 growing season.

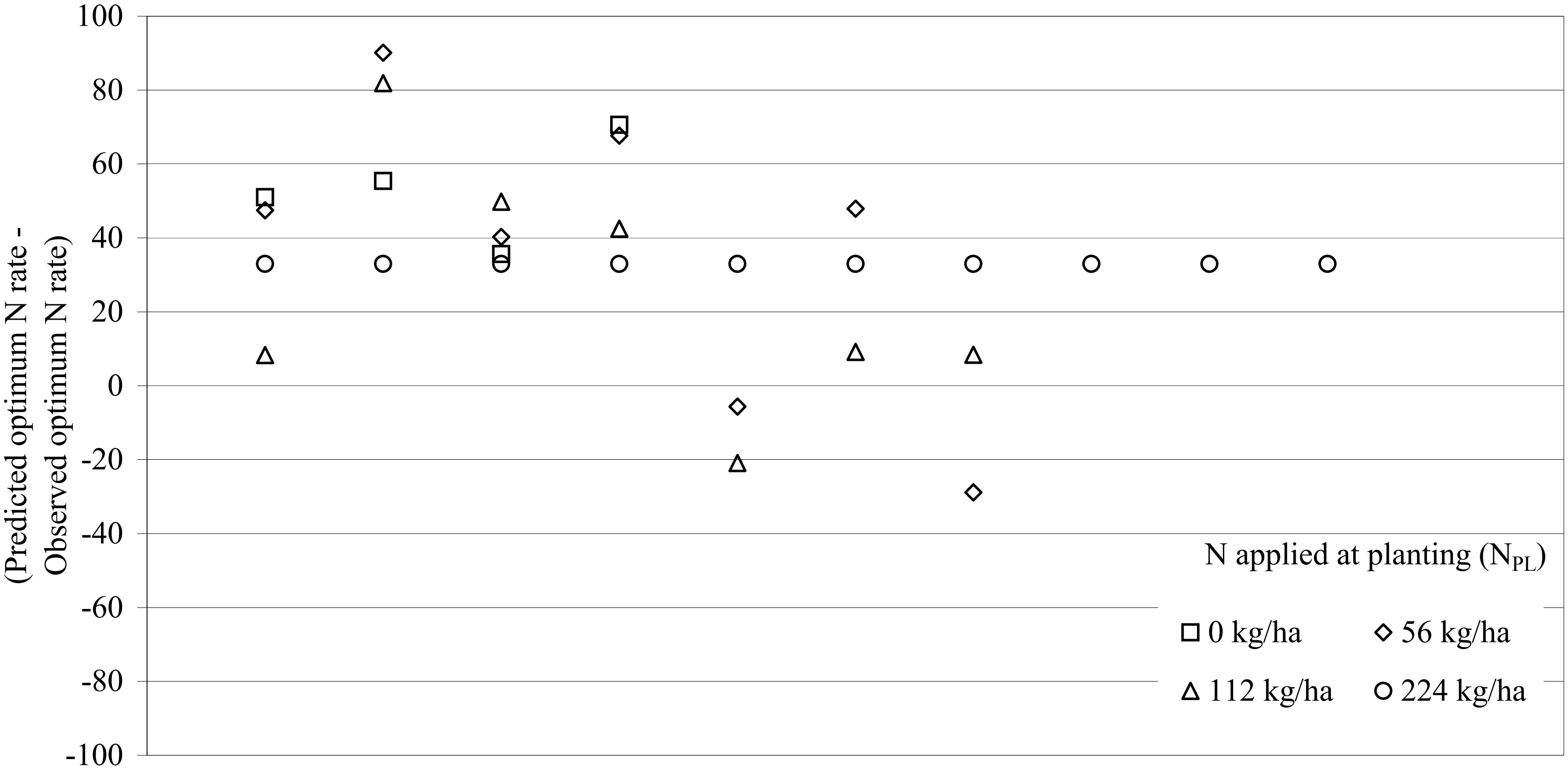


Fig. 7. Scatter plot of the residuals of the predicted economic optimum N rates at VT (N_{VT}) using the model developed by Sripada et al. (2005) and the observed economic optimum N rates during 2003 corn growing season. Each different symbol represents amount of N applied at planting.

APPENDICES

Appendix –A. Table of the minimum, maximum, mean, and standard deviation (SD), for grain yields and economic optimum N rate at VT (N_{VT}) and the source of N_{VT} obtained for different N rates at planting (N_{PL}) at the different the experimental sites.

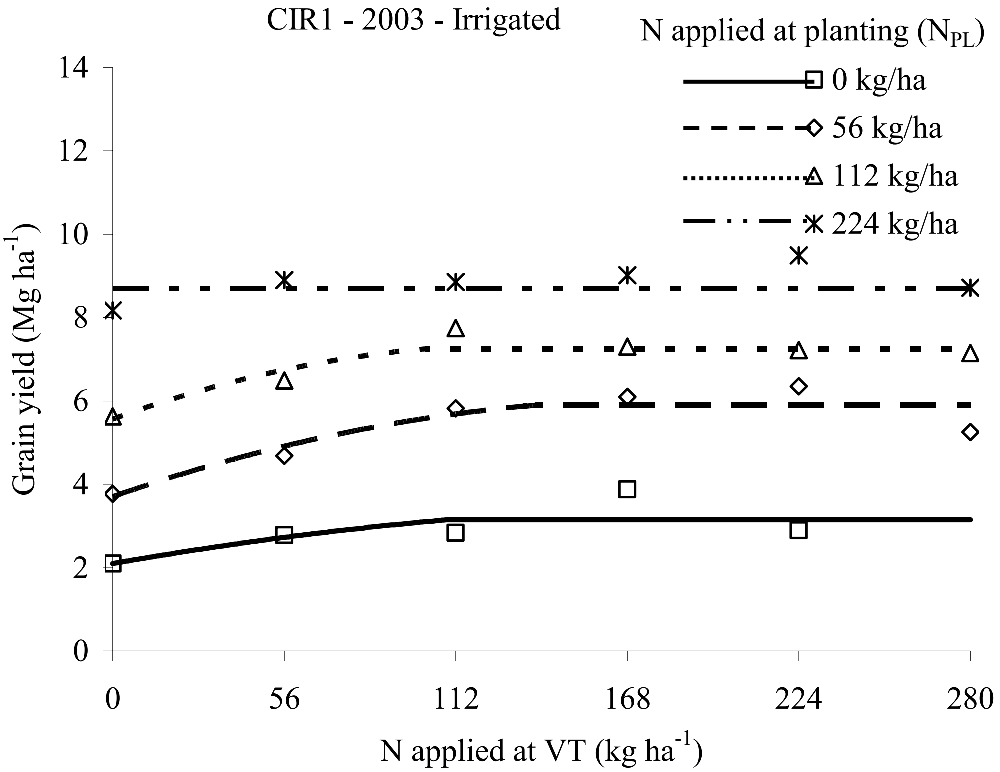
Site	N_{PL}	n	Min	Max	Mean	SD	Optimum N_{VT}	Source of optimum N_{VT} [†]
	kg ha^{-1}		--------------Mg ha^{-1}-------------				kg ha^{-1}	
CIR1	0	10	2.01	3.91	2.90	0.62	109	QP
	56	12	3.74	6.68	5.33	0.98	137	QP
	112	12	5.05	8.10	6.92	0.91	102	QP
	224	12	5.51	11.74	8.69	1.78	0	MS
CIR2	0	12	2.59	4.76	3.49	0.59	NA	NA
	56	12	2.66	7.23	4.28	1.27	NA	NA
	112	11	6.49	9.89	7.65	0.98	NA	NA
	224	12	4.53	11.55	8.87	1.96	NA	NA
CIR3	0	10	2.17	4.41	3.39	0.59	NA	NA
	56	12	3.41	7.01	5.50	1.01	95	QP
	112	10	5.61	9.48	7.59	1.14	75	QP
	224	11	6.79	10.99	9.05	1.30	0	MS
CNI1	0	11	3.93	8.22	6.66	1.24	NA	NA
	56	12	5.18	8.93	7.62	1.18	145	QP
	112	12	7.69	10.74	9.23	0.96	83	QP
	224	12	9.89	12.40	10.90	0.77	0	MS
CNI2	0	12	4.47	8.16	6.80	1.15	NA	NA

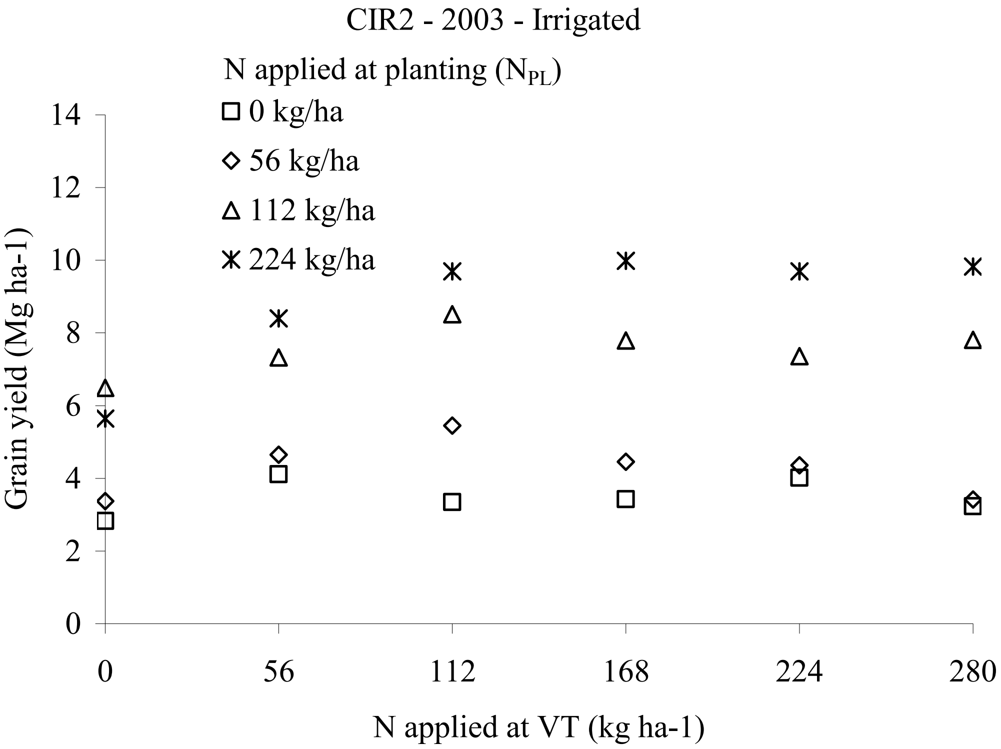
	56	12	5.04	9.78	8.71	1.36	NA	NA
	112	12	8.19	11.00	9.41	1.00	94	QP
	224	12	10.09	12.57	10.97	0.74	0	MS
CNI3	0	12	4.05	8.25	6.17	1.22	NA	NA
	56	12	6.10	9.95	8.51	1.05	117	QP
	112	12	8.27	11.82	10.30	1.14	104	QP
	224	12	9.48	11.51	10.56	0.71	0	MS
TIR1	0	12	2.75	9.98	6.26	2.11	134	QP
	56	12	3.98	10.01	7.66	1.73	NA	NA
	112	12	6.07	11.02	9.22	1.36	NA	NA
	224	12	7.47	12.95	9.96	1.80	0	MS
TIR2	0	10	2.36	7.71	5.94	1.68	129	QP
	56	12	3.57	10.38	7.49	2.31	87	QP
	112	12	7.10	10.97	9.28	1.09	NA	NA
	224	12	6.01	11.52	8.84	1.95	0	MS
TIR3	0	12	2.09	7.08	5.23	1.47	149	QP
	56	12	6.15	9.59	7.64	1.23	NA	NA
	112	12	5.40	8.91	7.99	0.95	48	QP
	224	12	7.03	11.58	9.24	1.62	0	MS
TNI1	0	12	3.26	9.25	7.00	1.80	NA	NA
	56	12	4.37	10.15	8.15	1.64	NA	NA
	112	12	8.02	11.54	9.67	1.07	NA	NA
	224	12	5.99	11.02	9.52	1.38	NA	NA

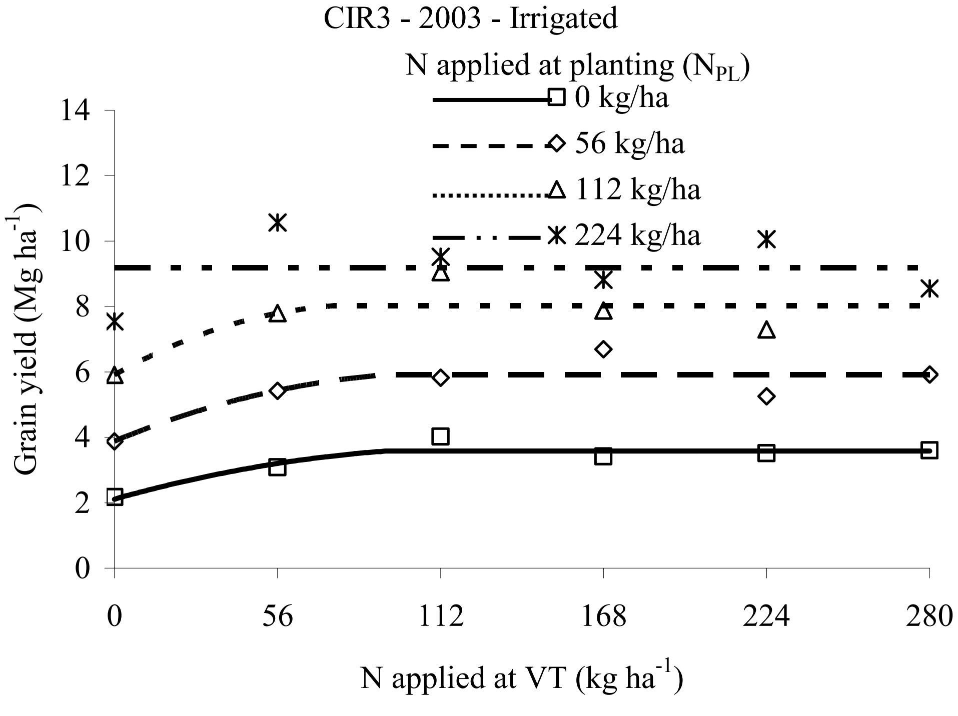
TNI2	0	12	3.65	8.71	6.85	1.67	NA	NA
	56	12	6.81	10.28	8.71	1.15	137	QP
	112	12	7.63	11.86	10.14	1.22	97	QP
	224	12	9.91	10.83	10.28	0.34	0	MS
TNI3	0	12	3.56	8.23	6.51	1.51	114	QP
	56	12	6.55	9.87	8.75	1.01	76	QP
	112	11	6.88	10.48	9.36	1.25	0	MS
	224	12	7.94	11.37	9.83	0.95	0	MS

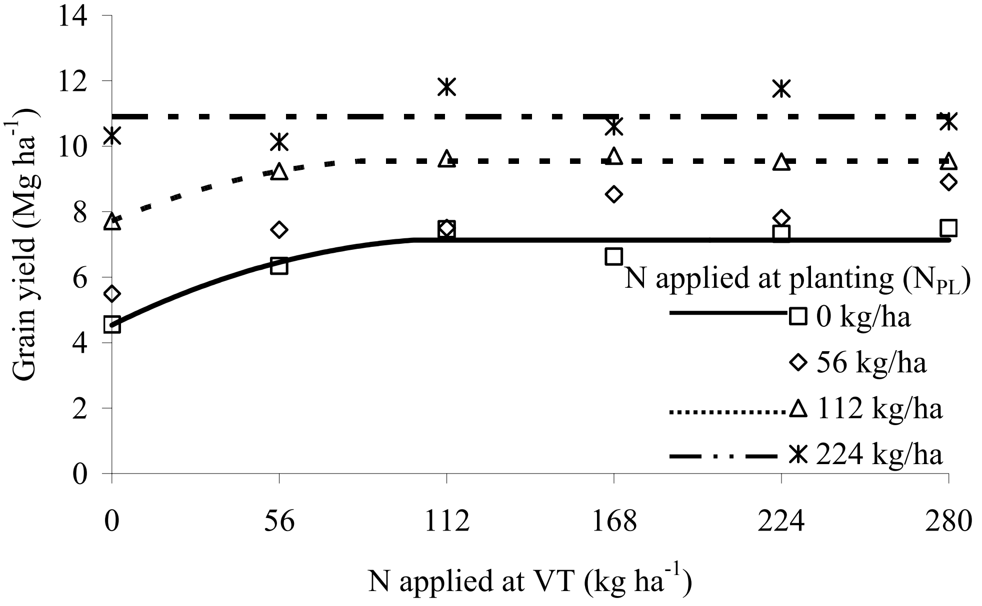
[†] QP: Quadratic –plateau function; MS: Mean separation via Fisher’s protected LSD; NA: Not available.

Appendix B. Quadratic plateau fit of grain yield response to N applied at VT (N_{VT}) for different rates of N applied at planting (N_{PL}) at the different experimental sites during 2003. Each point represents mean of two replications. Absence of a line indicates that optimum N rates were derived using Fisher's protected Least Square mean separation.

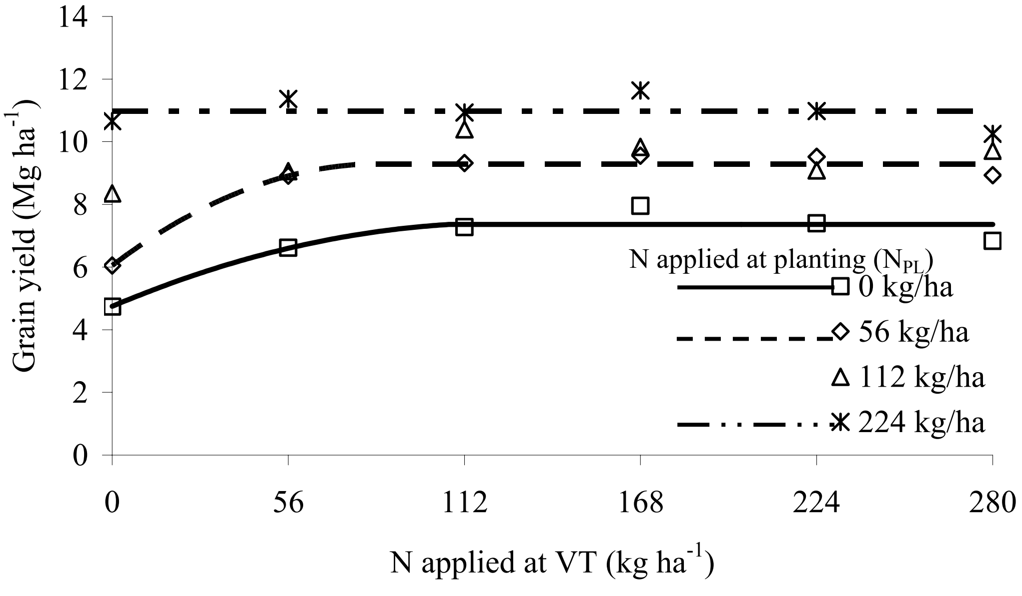



CIR2 - 2003 - Irrigated
N applied at planting (N_PL)
0 kg/ha
56 kg/ha
112 kg/ha
224 kg/ha
Grain yield (Mg ha-1)
0
2
4
6
8
10
12
14
0
56
112
168
224
280
N applied at VT (kg ha-1)

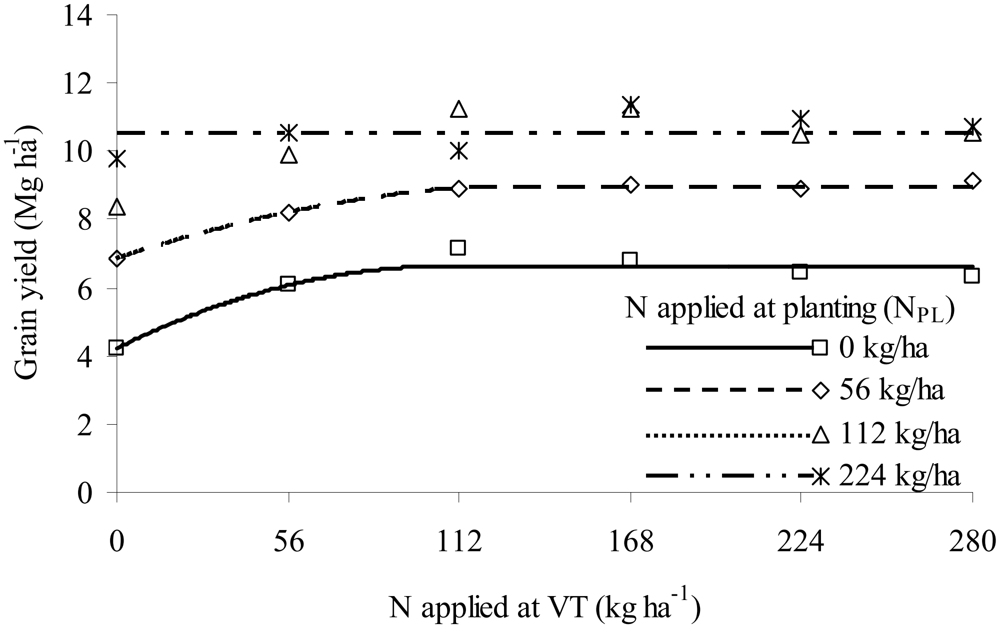

CIR3 - 2003 - Irrigated
N applied at planting (N_PL)
0 kg/ha
56 kg/ha
112 kg/ha
224 kg/ha
Grain yield (Mg ha-1)
0
2
4
6
8
10
12
14
0
56
112
168
224
280
N applied at VT (kg ha-1)



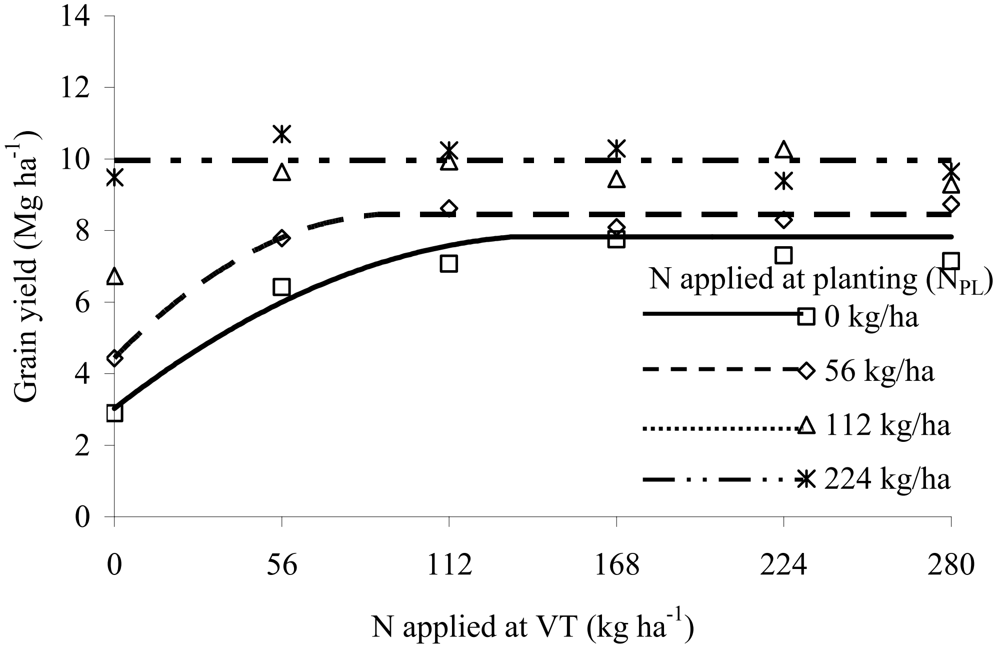
CNI1 - 2003 - Non-Irrigated



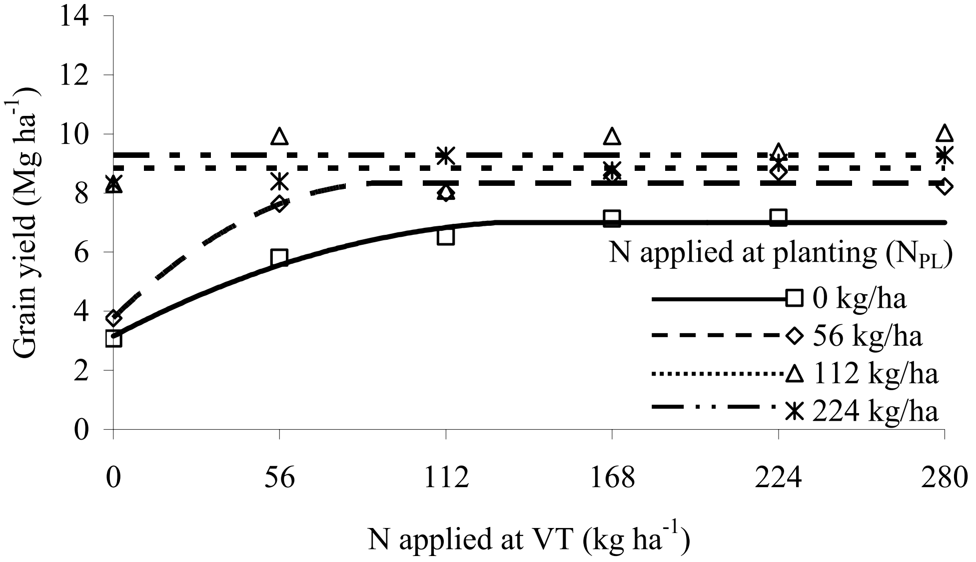
CNI2 - 2003 - Non-Irrigated



CNI3 - 2003 - Non-Irrigated



TIR1 - 2003 - Irrigated



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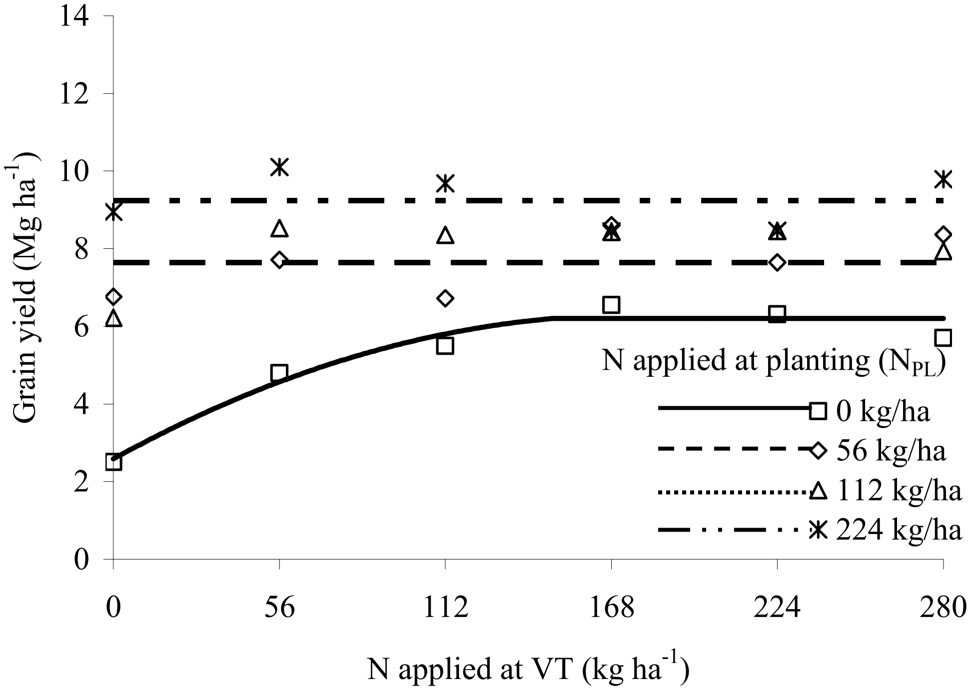

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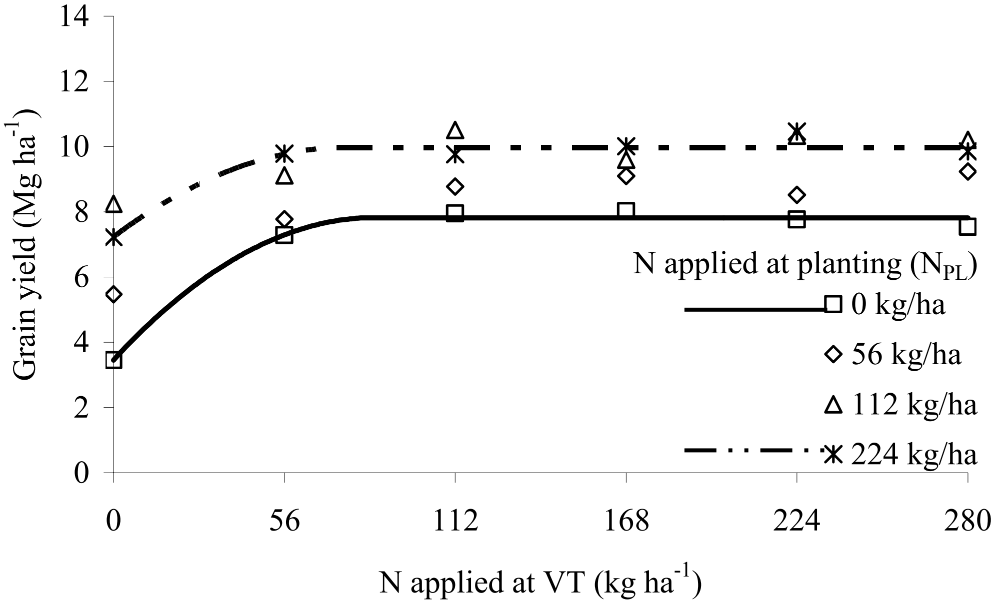
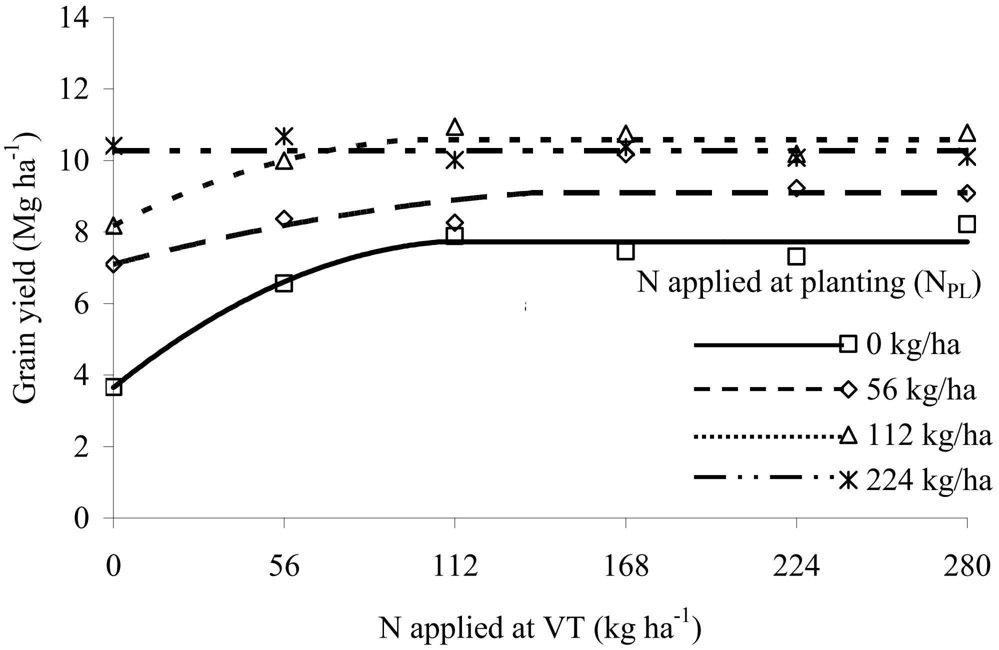
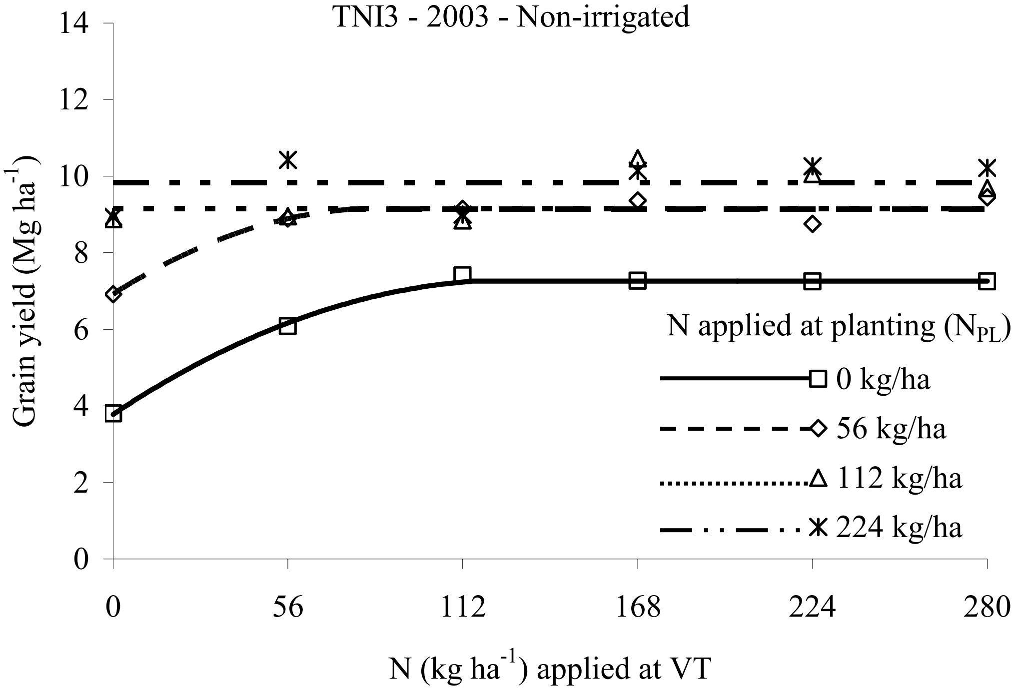


TNI1 - 2003 - Non-Irrigated



TNI2 - 2003 - Non-Irrigated

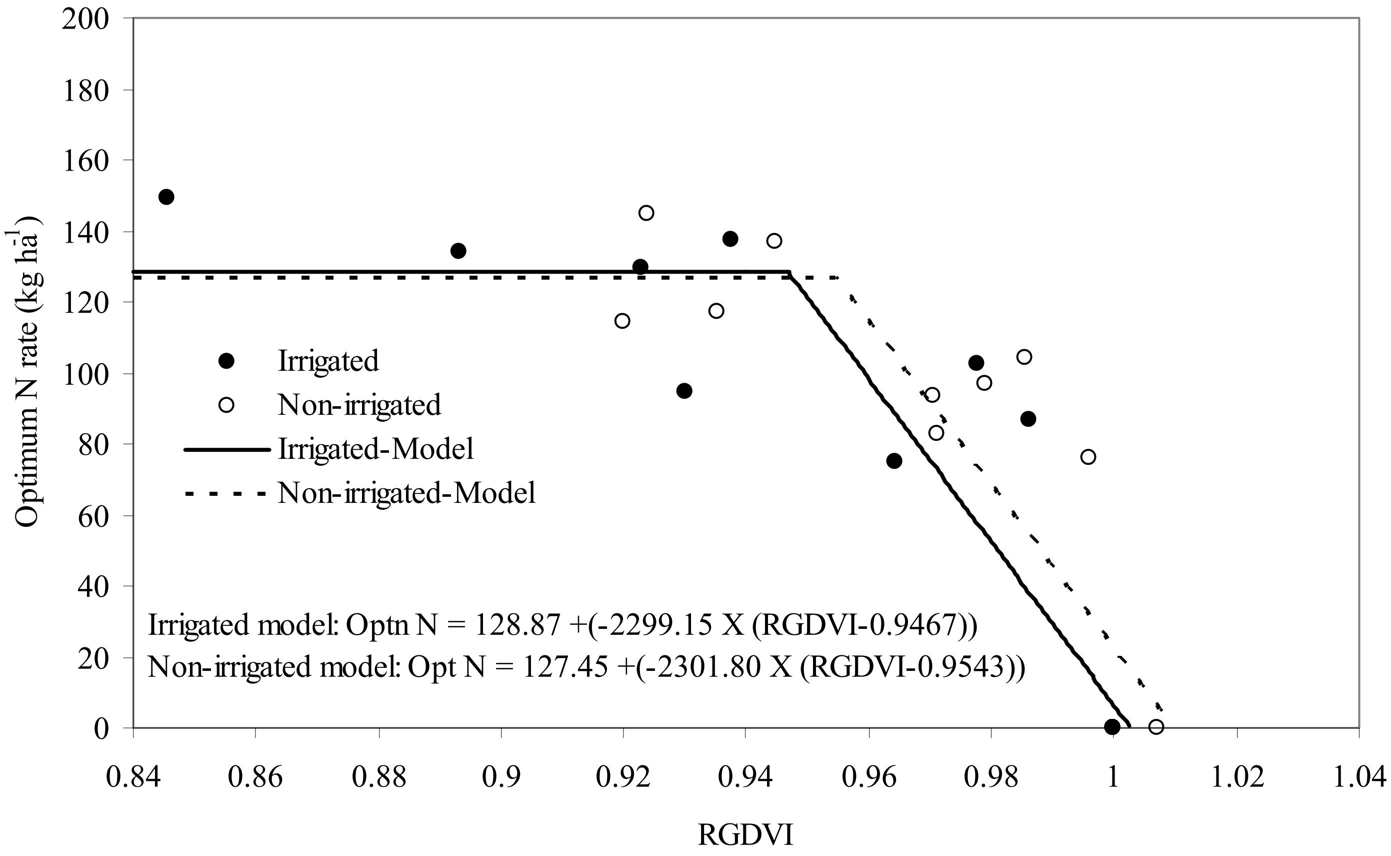

TNI3 - 2003 - Non-irrigated
Grain yield (Mg ha^{-1})
14
12
10
8
6
4
2
0
0
56
112
168
224
280
N (kg ha^{-1}) applied at VT
N applied at planting (N$_{PL}$)
0 kg/ha
56 kg/ha
112 kg/ha
224 kg/ha

Appendix C. Model tests for differences in linear-plateau model parameters between irrigation treatments for the validation dataset.

Parameter[†]	Estimate	Standard error	Lower limit, 95% confidence interval	Upper limit, 95% confidence interval	p-value
a_{IR}	128.87	10.83	104.38	153.37	***
a_{NI}	127.45	12.11	100.06	154.85	***
b_{IR}	-2299.15	534.55	-3508.40	-1089.91	**
b_{NI}	-2301.80	640.76	-3751.29	-852.31	***
$x0_{IR}$	0.9467	0.01	0.9214	0.9721	***
$x0_{NI}$	0.9543	0.01	0.9270	0.9816	***
Contrasts					
a_{IR} Vs. a_{NI}	-	-	-	-	NS
b_{IR} Vs. b_{NI}	-	-	-	-	NS
$x0_{IR}$ Vs. $x0_{NI}$	-	-	-	-	NS

, *, NS Significant at the 0.01 and 0.001 probability levels and not significant, respectively.

[†] The parameters of a linear plateau model are the intercept a, slope b, and the inflection point, x_0.



Appendix D. Relationships between economic optimum N rate and RGDVI and the best-fit linear-plateau models separated by irrigation treatment.

CHAPTER FOUR

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

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

ABSTRACT

Remote sensing has enormous potential to help optimize nitrogen (N) application decisions in crop production. The objective of this study was to use aerial color infrared (CIR) photography as a remote sensing technique to develop a methodology for predicting in-season N requirements for corn (*Zea mays* L.) at the V7 growth stage. Field studies were conducted for two years over a wide range of soil conditions and water regimes in the North Carolina Coastal Plain. Aerial CIR photographs were taken at each of the locations at V7 prior to N application. Optimum N rates at V7 (N_{V7}) ranged from 0 to 207 kg N ha^{-1} with a mean of 67 kg N ha^{-1}. Significant but very weak correlations were observed between optimum N rates at V7 and band combinations with significant correlations for relative green (Rel G), relative green difference vegetation index (RGDVI), and relative difference vegetation index (RDVI). High proportions of soil reflectance in the images early in the corn growing season (V7) likely confounded our attempts to relate spectral information to optimal N rates. The primary agronomic obstacle to applying this technique early in the season is the unpredictability of available soil moisture in rainfed situations and the use of relative digital counts or indices, which requires the availability of high N reference strips in the field. When treatments with high preplant N applications were removed from the analysis, the indices Norm NIR, GDVI, GRVI, and GNDVI 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, and quantifying the optimum in-season N requirement is an important step towards an economically and environmentally viable corn production system. 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 (NO_3-N) 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.

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) digital counts early in the corn-growing season (Scharf and Lory, 2002). These studies showed that color and/or CIR photographs obtained between growth stages V7 and VT (Ritchie et al., 1993) could be used to predict N deficiency and corn N requirements. One of the problems with using the spectral reflectance of the corn canopy at V7 to determine yield potential or N requirement is the interference of the soil background.

The spectral reflectance of a crop canopy is a combination of the reflectance spectra of plant and soil components as governed by the optical properties of these elements and radiant energy exchange within the canopy. 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 green band (in combination with NIR band) is more highly associated than the red band with variability in leaf chlorophyll, N content, and final grain yield. Walburg et al. (1982) also indicated that spectral measurements of corn canopies could be used to detect N treatment differences.

Linear combinations or some transformation of the spectral data from two or more radiometric wavebands may be more sensitive to certain agronomic variables than single waveband spectral data (Bausch and Duke, 1996). Vegetation indices developed from spectral observations in the R and NIR wavelengths have shown strong correlations with plant variables such as green leaf area in tropical rain forest (Jordan, 1969), winter wheat (Wiegand et al., 1979), and soybean (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, Table 1; Rouse et al., 1973) has been the most widely used spectral vegetation index. The NDVI is a good indicator of crop stress and has been considered as an indirect measure of crop yield (Tucker et al., 1980, Pinter et al., 1981).

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 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 green normalized difference vegetation index (GNDVI, Table 1) might prove to be useful for assessing canopy variation in biomass. Later, Shanahan et al. (2001) found 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.

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; Huete, 1987). 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, Table 1; Tucker, 1979), and the soil adjusted vegetation index (SAVI, Huete, 1988; Table 1) have been developed to correct for soil influences.

Though the ability to predict yield 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 side-dress 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) used corn color in the form of relative G from aerial images to predict optimum sidedress N in corn at the V6-V7 stage. They found that the relationship did not hold under conditions where N was applied at or prior to planting or where there were confounding effects of soil reflectance in the aerial images. However, they were able to use corn color with reasonable success in predicting optimum N rates when soil pixels were removed from the image and when the corn color was expressed relative to the color of well-fertilized corn in the same field. The relationship did not hold when N was applied at or prior to planting. The removal of soil pixels requires very high resolution aerial images, which may be cost prohibitive in practical application. Sripada et al. (2004) used a linear-plateau function of the relative green difference vegetation index (RGDVI) to predict optimum N rates for corn at the VT stage with reasonable success. 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 objective was to develop a similar in-season model to predict the amount of side dress N required by corn at an early stage (V7) which could be used under different initial N levels and that could simultaneously account for any confounding soil reflectance.

MATERIALS AND METHODS

Field studies were conducted with irrigated and non-irrigated experiments over two years, 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. 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 applied at planting (N_{PL}) as the main plot factor and sidedress N applied at V7 (N_{V7}) as the sub-plot factor. 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 (30% UAN) 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 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. Herbicides were applied based on weeds present and excellent weed control was obtained at all sites. 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 were analyzed using PROC MIXED in SAS Version 8 (SAS Institute, Cary, NC). For the yield analysis, year, irrigation, N_{PL}, and N_{V7} were considered as fixed effects and site as a random effect. Planting, V7, VT, and harvest occurred on days 99, 147, 175, and 254 of the year, respectively, at PBRS in 2002, days 93, 162, 185, and 247 in 2003; days 122, 173, 189, and 256 at TRS in 2002, and days 121, 167, 192, and 249 in 2003. For graphing purpose, weather data from 1971 – 2001 was used in calculating the 30 year normal values; planting, V7, VT, and harvest at PBRS and TRS were assumed to occur at days 96, 154, 181, and 251 days and 121, 169, 192, and 253 days, respectively.

Determination of Optimum N Rates

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 Institute, Cary, NC). The linear-plateau function was used for further analysis as it was consistently significant across years and sites. When using a linear-plateau function, the optimum N rate is 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 alpha of 0.05, then 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 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 one-meter accuracy (Trimble AG 132, Trimble Navigation, Sunnyvale, CA) was used to geo-reference the targets. Aerial CIR photographs were taken at V7 prior to

N application at each of these sites using the technique described by Flowers et al. (2001). The aerial CIR images were obtained at altitudes such that the entire experimental field was covered in a single image and under as cloud-free conditions as possible using a belly mounted platform with 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 (Eastman Kodak Co., Rochester, NY) was used for obtaining the CIR images. The film was AR-5-processed to obtain false-color 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 Syst., San Jose, CA), resulting in a ground resolution of 0.43 to 0.55 m. Differences in ground resolution were due to the different altitudes at which the images were obtained. The spectral properties of the CIR film used for obtaining images were described by Flowers et al. (2003). 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 red [R], 8 bit green [G], and 8 bit blue [B]). At each pixel in the image, the primary 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 – 900 nm, band 2 (R) covered the wavelengths between 490 – 700 nm, and band 3 (G) covered the wavelengths between 490 – 620 nm. While these bands overlap, differences in spectral sensitivity exist between them. 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 (EastmanKodak, 1996).

Digital image data were georegistered using ERDAS Imagine version 8.7 (ERDAS Inc., Atlanta, GA) image processing software. Areas of interest (AOI) corresponding to individual plots were identified, which included approximately the same number of pixels for each plot. The AOI included both the corn plants and any soil that was visible between adjacent rows and plants, i.e., 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 2). 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 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).

RESULTS AND DISCUSSION

Yield Responses to N Applications

Yield levels of non-irrigated corn in 2003 were much lower than in 2002 at PBRS. Yield levels at TRS were higher in 2002 compared to 2003 under irrigated and non-irrigated conditions (Table 3). This was mainly attributed to the near-drought conditions with very low rainfall early in the 2002 season coupled with high temperatures (Fig. 1), which likely resulted in loss of yield potential. In contrast, during the 2003 growing season, there was adequate and timely rainfall that likely fostered efficient N utilization.

Environmental and water stresses can influence the spectral response of the corn canopy and thereby influence the relationship 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 years and/or water regimes. The four-way and three-way interactions involving year, irrigation, $N_{PL,}$ and N_{V7} were not significant (Table 4). Similarly the two-way interactions involving N_{PL} with year and with site were not significant, but the two-way interactions of irrigation with both N_{PL} and N_{V7}, of N_{V7} with year, and of N_{PL} with N_{V7} were also significant. However, the two-way interaction of site with N_{V7} was not significant (Table 4).

The significance of the two-way interactions of year and irrigation with N_{V7} was 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. 2), which was an irrigated site in an exceptionally dry year (Fig. 1) compared to site 10 (Fig. 3), a non-irrigated site with adequate rainfall (Fig. 1). An additional application of almost 100 kg N ha^{-1} was needed in 2002 to reach similar yield levels compared to 2003 (Fig. 2 & 3), which is an indicator of the different N requirements and N-use efficiencies 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 can be seen in Fig. 2 and 3, which show the N_{V7} responses obtained at Sites 1 & 10. The quantity of N_{V7} needed for grain yield response to reach a plateau was greater for plots receiving 0 and 56 kg ha^{-1} N at planting than plots receiving 112 and 224 kg ha^{-1}. Under low initial N conditions, the N_{V7} applications resulted in the recovery of yield potential evident by the near similar yield plateaus (Fig. 2). These results indicate that grain yield optimization can be achieved by using an in-season N application at the V7 stage. These results further demonstrate that there is an enormous potential for determining an in-season N_{V7} rate appropriate for the current season.

Optimum N_{V7} Rates

The different N_{PL} rates helped create a range of optimum N_{V7} rates. The range of optimum N_{V7} rates was 0 to 207 kg N ha^{-1} with a mean of 67 kg N ha^{-1}. There were three sites in 2002 (sites 3, 4, 5) and one site in 2003 (site 8) that were non-responsive to N_{V7}; this may have been due to the extreme rainfall conditions, with low rainfall in 2002 and excessive rainfall at the beginning of the season in 2003, respectively. Our interpretation for such low optimum N rates is the significance of the irrigation and N_{V7} interaction (Table 4), and the relatively high levels of readily labile soil N at sites 3, 4, and 5 compared to other sites as determined by amino sugar N test (Khan et al., 2001; Williams et al., 2004) from soil samples taken at planting (not shown).

Predicting Optimum N Rates from Spectral Data

The coefficient of determination values (r^2 or R^2) of the relationship 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 model the relationship between optimum N_{V7} rates and spectral indices, only the linear model showed consistently significant relationships. 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 were significant year × N_{V7} and irrigation × N_{V7} interactions for yield, we analyzed the same spectral indicators separately for each year and irrigation treatment. The coefficients of determination (r^2) for the linear relationships between optimum N_{V7} rates and different spectral bands and indices separated by individual years and irrigation treatments are shown in Table 6. The individual absolute spectral bands (NIR, R, and G) were not correlated with optimum N rate when analyzed across all years and irrigation treatments (Table 5). However, when these relationships were examined for individual years and irrigation treatments, optimum N_{V7} rates showed significant relationships ($r^2 = 0.25$) with NIR in 2002 (Fig. 4), with G in both 2002 and 2003 ($r^2 = 0.25$ and 0.26, respectively; Table 6; Fig. 5) and with R in 2002 ($r^2 = 0.24$) and under irrigation ($r^2 = 0.29$). In contrast to the absolute spectral bands, the relative R and G bands showed a significant relationship with optimum N_{V7} rates, though Rel NIR remained non-significant (Table 5) when analyzed across years and irrigation treatments.

Normalized spectral bands often can correct for different levels of illumination when compared to absolute bands. Across years and irrigation treatments, the Norm NIR and Norm R showed significant but weak relationship with optimum N rates (Table 5). When separated by year, Norm NIR and Norm R showed significant relationship 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 are 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: Table 5) when analyzed across years and irrigation treatments. 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 indices showed significant relationships with optimum N_{V7} rates in 2003 nor 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).

Most indices showed stronger relationships when expressed relative to a high-N reference strip (RDVI, RGDVI, GRVI, RGNDVI, RGSAVI, and RGOSAVI), although several (RRVI, RNDVI, and ROSAVI) weakened. However, the strength of the relationship of RSAVI with optimum N_{V7} was same as with SAVI. When analyzed separately for each year and irrigation treatment, none of the relative indices showed a significant relation ship with optimum N_{V7} rates in 2003 or without irrigation, with the exception of RDVI and RGDVI which showed a significant relationship without irrigation. With the exception of RRVI, all the relative indices showed a significant relationship with optimum N_{V7} rates either with or without irrigation. However, with irrigation, RDVI and RGDVI were the only relative indices that were significant. Using indices computed relative to high N reference strips in fields can help reduce potential sources of variation that may occur due to using images captured at different times and/or places, and help account for differential response to N from field to field (Schepers et al., 1992). Our results are in agreement with those of Scharf and Lory (2002), which suggested that a high-N reference was necessary to accurately predict N need from aerial photographs.

CONCLUSIONS

Among the different spectral bands and indices examined in this study, 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). At a later stage in corn development (VT), Sripada et al. (2004) developed a linear plateau model using RGDVI that explained 67% of the variability in economic optimum N rates. To illustrate the effects of year and irrigation in influencing the relationship between RGDVI and optimum N_{V7} rates, RGDVI was plotted against optimum N_{V7} separated by year (Fig. 6) and irrigation (Fig. 7). RGDVI had a significant linear relationship with optimum N_{V7} rates in 2002 and when separated by irrigation treatment (Fig. 7 & Table 6). However, the linear model did not have a significant relationship in 2003 (Fig. 6 & Table 6). While RGDVI had a significantly stronger relationship, unfortunately, most of the relative index values were close to 1 and did not vary much.

The large levels of unexplained variability in the relationships between spectral indicators and optimum N rate at V7 compared to those reported at VT (Sripada et al., 2004) are probably due to the influence of soil reflectance. Scharf and Lory (2002) observed improved relationships between economic optimum N rates and relative corn color from aerial photographs by removing soil pixels from the images in similar work done at the same growth stage (V7). 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. 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 us from attempting to separate soil from plant pixels. The minimum resolution of the aerial color infrared 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. 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 data points for which the predicted optimum N_{V7} rate was 0 kg ha^{-1} (Table 6), that is, the non-responsive data points. 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} rate when the data points for which the predicted optimum N_{V7} rate was 0 kg ha^{-1} were eliminated from analysis (r^2 of 0.33: Table 6 & Fig. 8).

Practical Implications

The currently recommended practice for determining N rates for corn in North Carolina is based on “realistic 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 Southeast 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, there was limited success relating in-season optimum N_{V7} rates to corn canopy color (NIR, R, and G) or any of the indices derived from mathematical combinations of the different spectral bands. Green, DVI, and GDVI, expressed relative to a high N reference plot, showed a modest increase in the strength of relationships with optimum N_{V7} rates. However, these indices were able to explain only 22% of the variability in changing optimum N_{V7} rates.

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 the field 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 can limit the use of this technique in precise application of N. Eliminating the sites where yield did not respond to N_{V7}, indices such as Norm NIR, GDVI, GRVI, and GNDVI were able to describe 28% of the variability in optimum N rates. However, the primary agronomic obstacle to removing non-responsive sites is the unpredictability of available soil moisture in rainfed situations and the difficulty in determining non-responsive sites. The major technical obstacle in applying this technique at V7 is probably the influence of soil pixels on the spectral characteristics of the image and thus on the spectral index values. At the V7 growth stage, the groundcover was not complete, and therefore there was significant interference from soil in pixels in aerial images at the resolution that we used. This may have contributed to the lack of strong relationships between optimum N rates and spectral radiance. Further research is needed to improve the relationship obtained in this study by developing a protocol for a more reliable N_{V7} rate estimation; perhaps by using high resolution images which can facilitate the removal of soil pixels from the image as did Scharf and Lory (2002).

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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.

Table 2. Soil type, classification, and cultural practices 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: Non-irrigated.

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

				Grain yield			
Site	Location[†]	Year	Irrigation[‡]	Minimum	Maximum	Mean	Std Dev
				------------------------Mg ha^{-1}----------------------			
1	PBRS	2002	IR	2.88	11.92	8.47	2.55
2	PBRS	2002	NI	1.98	8.45	4.63	1.10
3	TRS	2002	IR	6.28	11.49	9.47	1.18
4	TRS	2002	NI	6.92	11.46	10.02	0.94
5	TRS	2002	IR	6.19	11.99	10.15	1.13
6	TRS	2002	NI	2.19	6.73	4.16	0.88
7	PBRS	2003	IR	1.74	11.86	8.26	2.32
8	PBRS	2003	NI	4.74	12.83	9.64	1.47
9	TRS	2003	IR	2.86	12.20	9.54	1.92
10	TRS	2003	NI	4.19	12.25	9.41	1.87
11	TRS	2003	IR	2.78	11.07	7.74	1.75
12	TRS	2003	NI	1.80	11.08	7.49	1.96

[†] PBRS: Peanut Belt Research Station, Lewiston-Woodville, NC; TRS: Tidewater Research Station, Plymouth, NC.

[‡] IR: Irrigated; NI: Non-irrigated.

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

Source of Variation	df	Grain yield
Year	1	NS
Site	2	NS
Irrigation	1	NS
N_{PL}	3	**
Year × N_{PL}	3	NS
Site × N_{PL}	6	NS
Irrigation × N_{PL}	3	**
Year × Irrigation × N_{PL}	3	NS
Site × Irrigation × N_{PL}	6	NS
N_{V7}	4	**
Year × N_{V7}	4	**
Site × N_{V7}	8	NS
Irrigation × N_{V7}	4	**
N_{PL} × N_{V7}	12	**
Year × N_{PL} × N_{V7}	12	NS
Site × N_{PL} × N_{V7}	24	NS
Irrigation × N_{PL} × N_{V7}	12	NS
Year × Irrigation × N_{PL} × N_{V7}	16	NS

*, **, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

Table 5. Regression analysis of optimum N rate (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.

	Model			
Vegetation Index	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

*, **, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

Table 6. Regression analysis of optimum N rate (kg ha^{-1}) versus near infrared (NIR), red (R), green (G), and the various spectral indices separated by year and irrigation and when non-responsive treatments were eliminated.

Vegetation Index	2002	2003	Irrigated	Non-Irrigated	Eliminating non-responsive 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

*, **, NS Significant at the 0.05 and 0.01 probability levels and not significant, respectively.

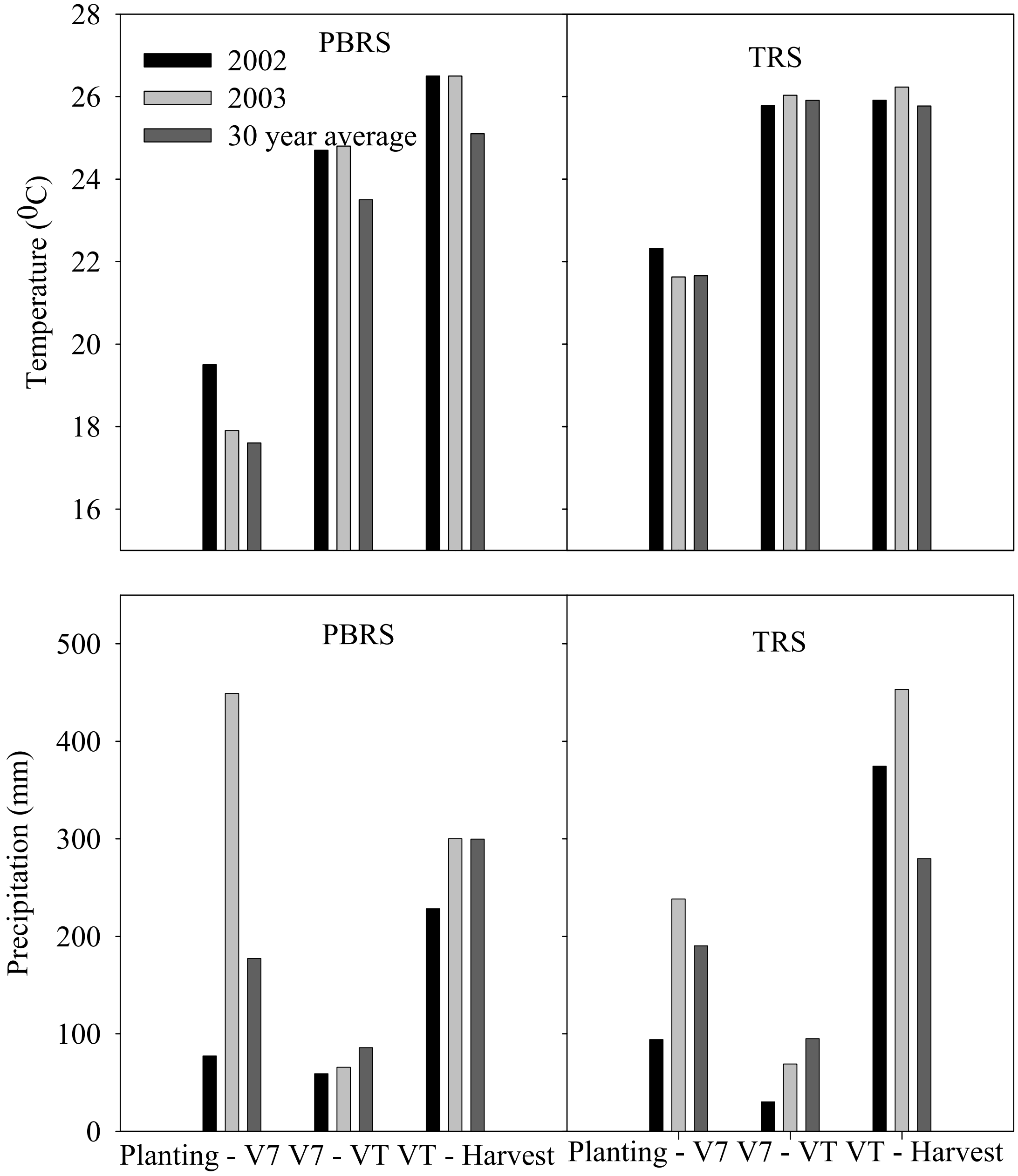


Fig. 1. Mean air temperature and cumulative precipitation from the planting to V7, V7 to VT, and VT to harvest growth stages of corn at the Peanut Belt Research Station (PBRS) and the Tidewater Research Station (TRS) experimental sites during 2002 and 2003 compared to 30-year average.

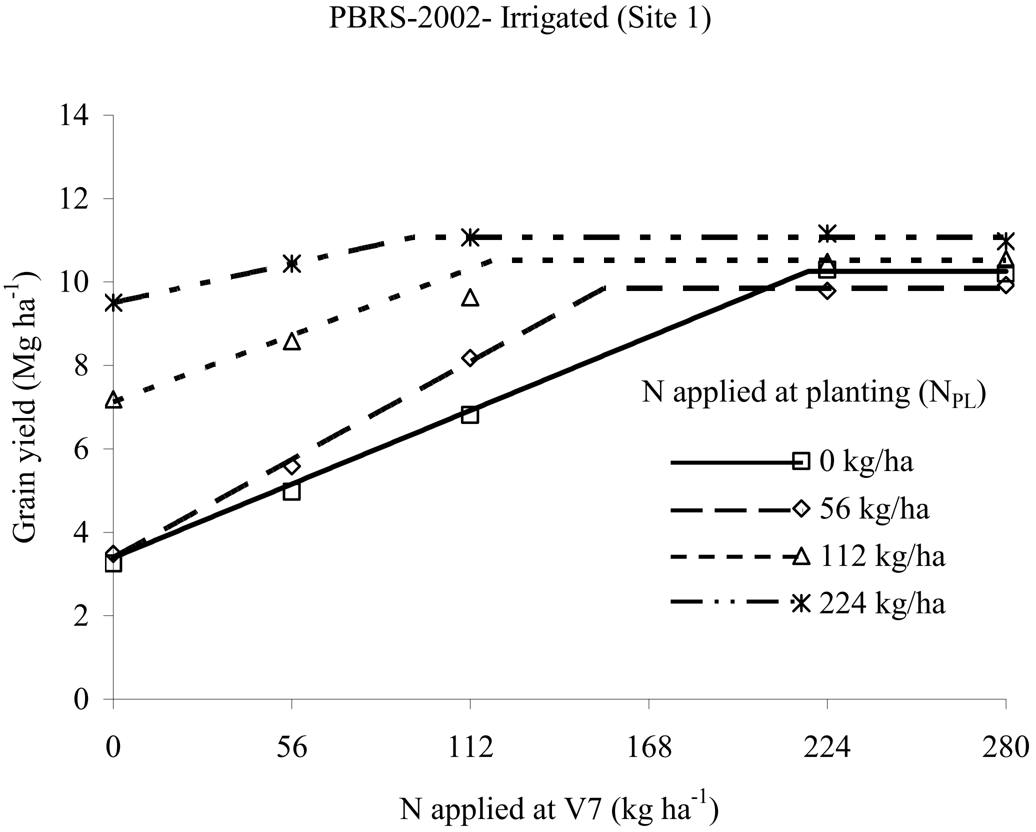


Fig. 2. Linear-plateau fit of grain yield response to N applied at V7 (N_{V7}) for different rates of N applied at planting (N_{PL}) at the Peanut Belt Research Station (PBRS: Site 1) during 2002.

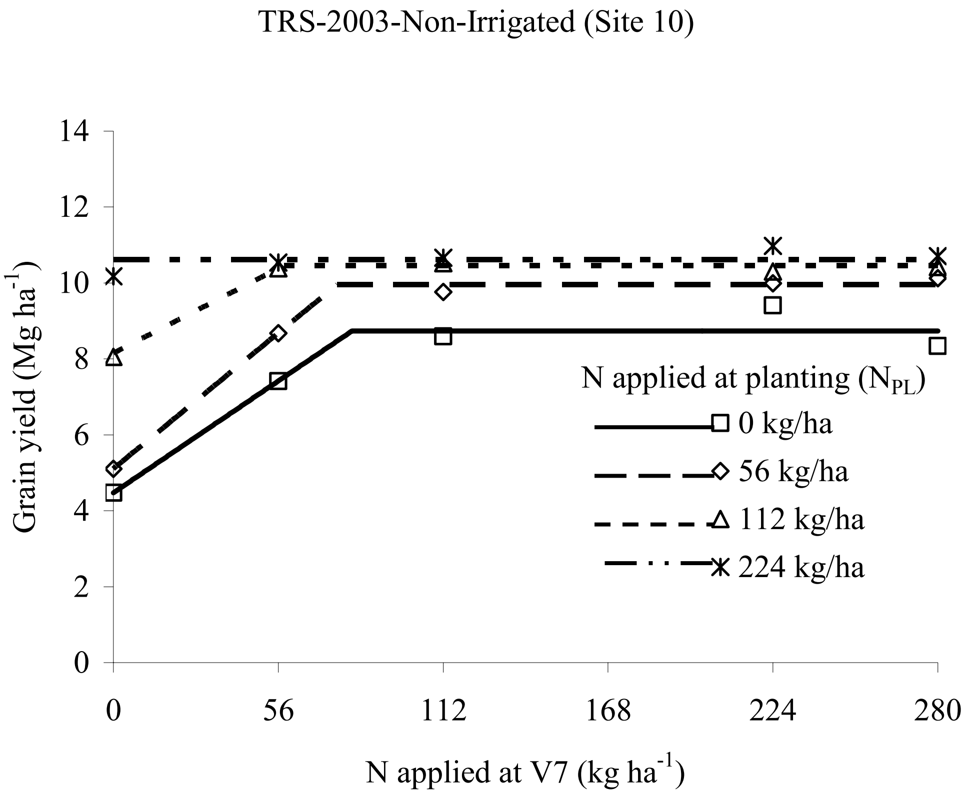


Fig. 3. Linear-plateau fit of grain yield response to N applied at V7 (N_{V7}) for different rates of N applied at planting (N_{PL}) at Tidewater Research Station (TRS: Site 10) during 2003.

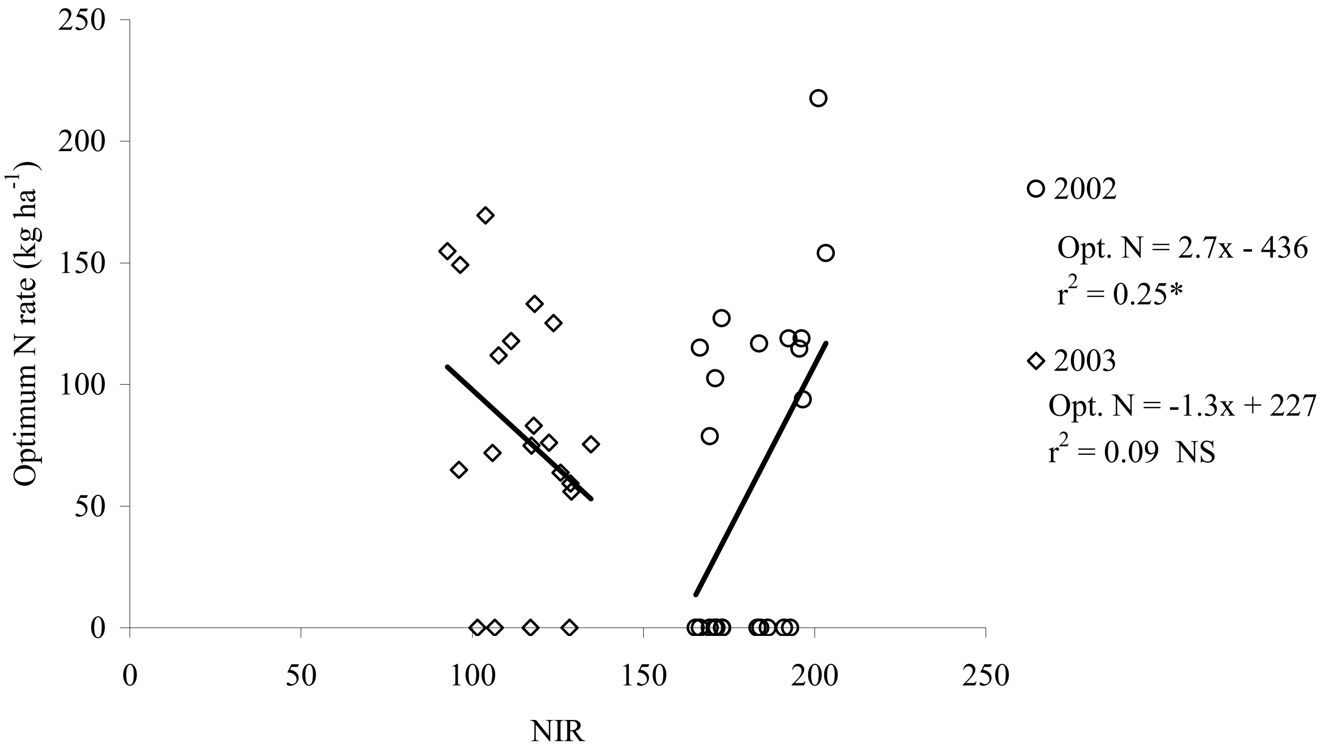


Fig. 4. Relationship between optimum N rate at V7 (N_{V7}) and Near-infrared (NIR) Digital Number (DN) separated by year.

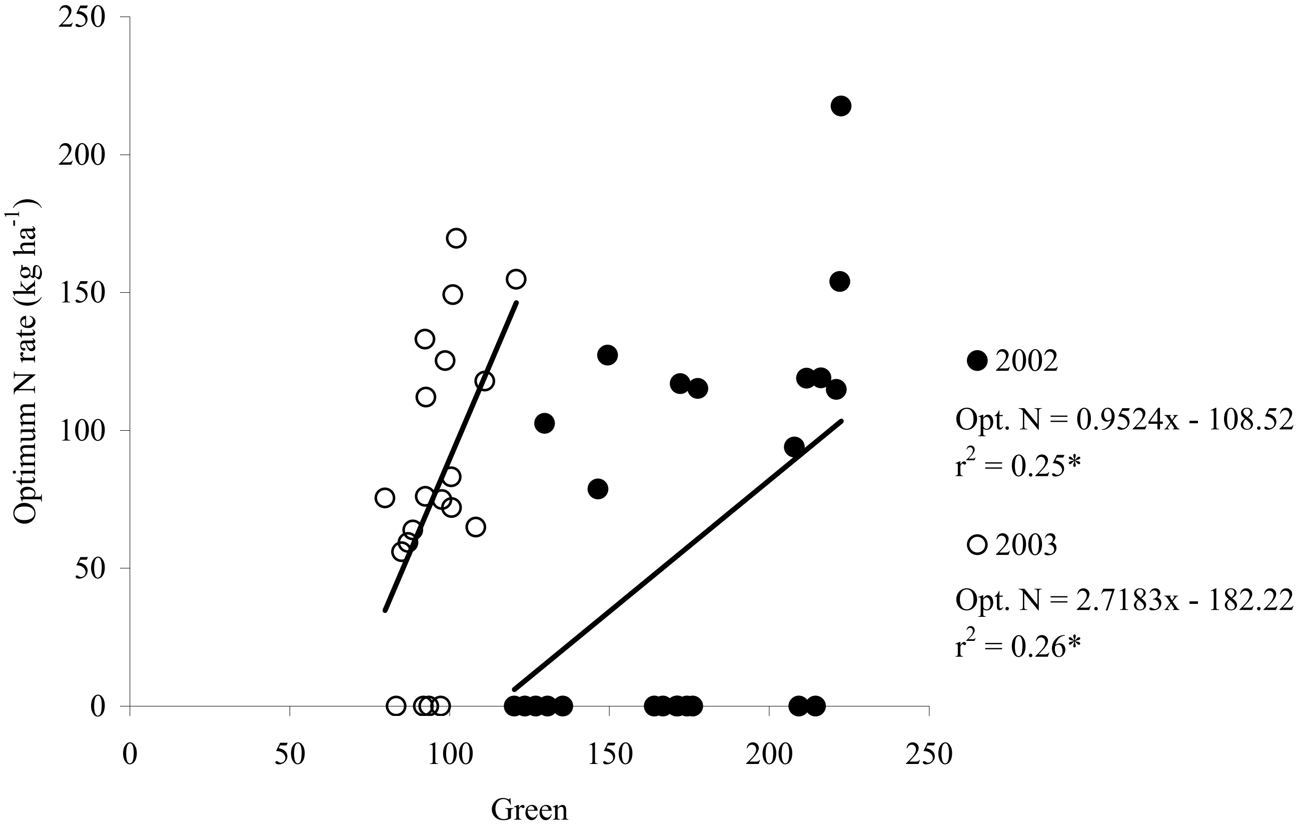


Fig. 5. Relationship between optimum N rate at V7 (N_{V7}) and Green (G) Digital Number (DN) separated by year.

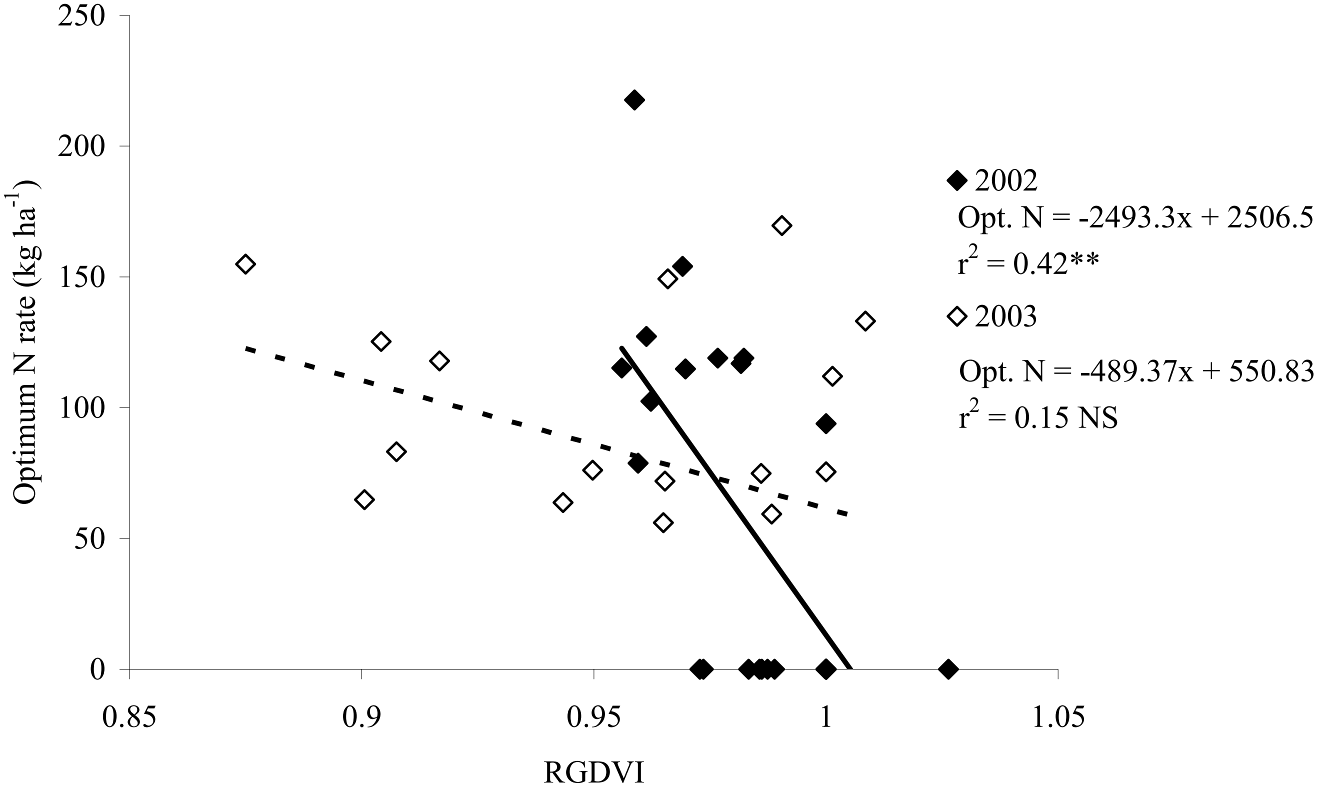


Fig. 6. Relationships between optimum N rate at V7 (N_{V7}) and Relative Green Difference Vegetation Index (RGDVI) separated by year.

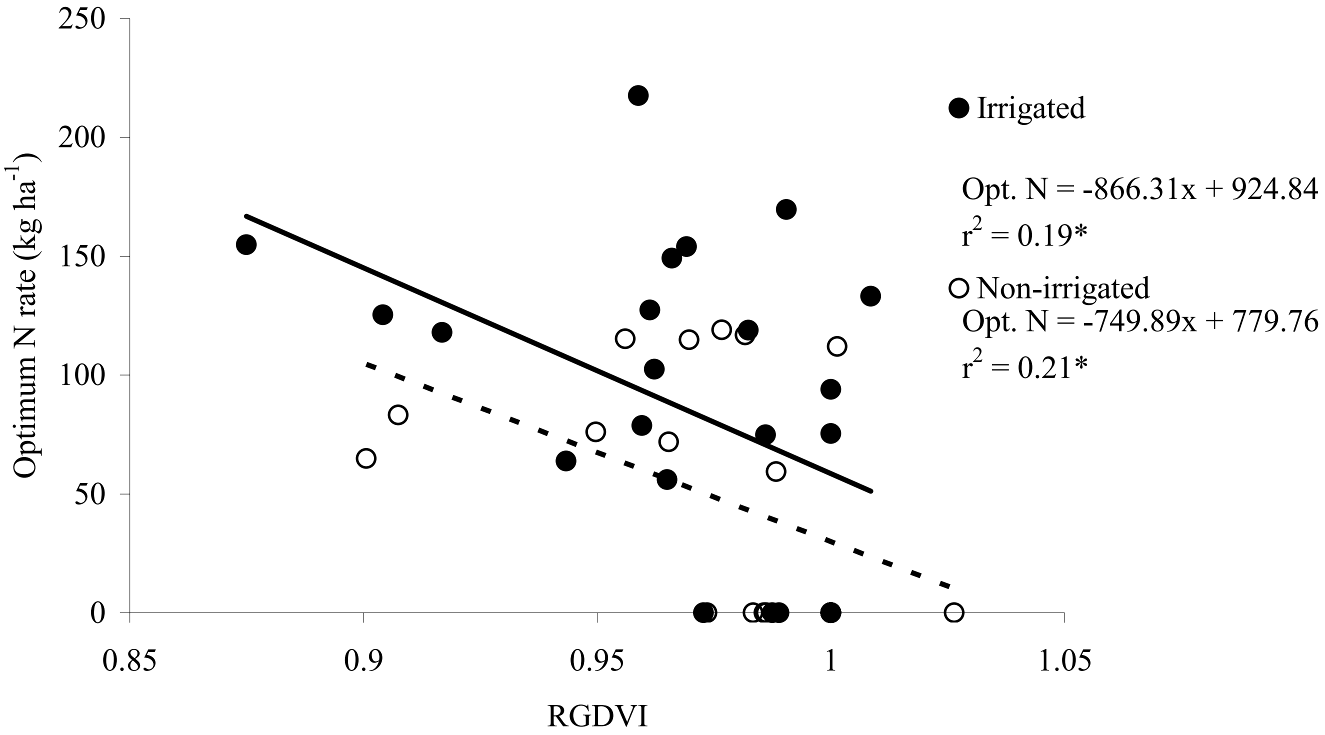


Fig. 7. Relationships between optimum N rate at V7 (N_{V7}) and Relative Green Difference Vegetation Index (RGDVI) separated by irrigation.

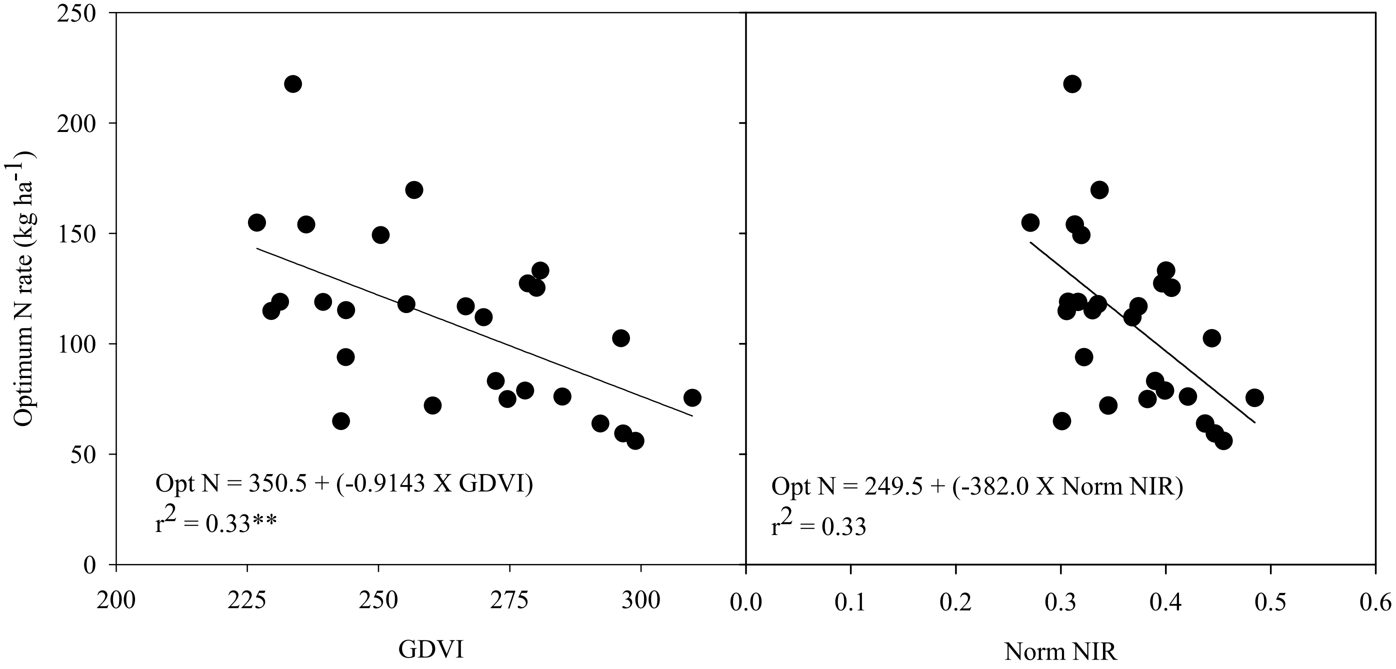


Fig. 8. Models showing the relationships of optimum N rate at V7 (N_{V7}) with Green Difference Vegetation Index (GDVI) and normalized NIR (Norm NIR), excluding the treatments which had a predicted optimum N_{V7} rate of 0 kg ha^{-1}.

APPENDICES

Appendix A. Table of the minimum, maximum, mean, and standard deviation for grain yields obtained for different N rates at planting (N_{PL}) at different experimental sites.

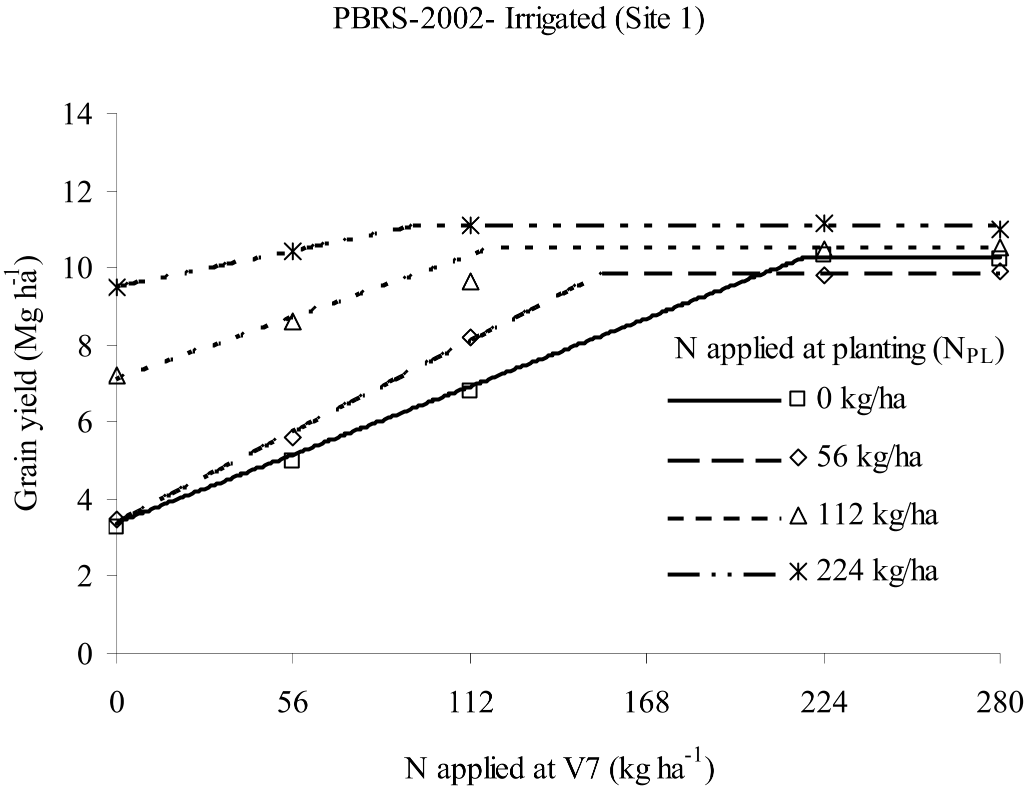
Site	N_{PL}	n	Min	Max	Mean	SD	Optimum N rate	Source of optimum N rate[†]
	kg ha^{-1}		--------------Mg ha^{-1}-------------				kg ha^{-1}	
1	0	24	2.88	11.00	7.27	2.91	217	LP
	56	25	3.02	10.57	7.39	2.62	154	LP
	112	25	6.27	11.72	9.29	1.59	119	LP
	224	17	8.53	11.92	10.55	0.90	94	LP
2	0	23	1.98	5.99	4.12	0.95	115	LP
	56	20	3.59	6.88	5.16	0.92	119	LP
	112	25	3.00	8.45	4.89	1.09	0	MS
	224	20	2.56	6.50	4.36	1.17	0	MS
3	0	19	6.61	10.26	8.45	1.08	79	LP
	56	20	6.28	10.76	9.19	1.20	127	LP
	112	20	7.91	10.87	9.96	0.77	0	MS
	224	19	9.20	11.49	10.29	0.67	0	MS
4	0	19	6.92	11.38	9.38	1.34	117	LP
	56	17	9.24	10.98	10.26	0.49	0	MS
	112	19	8.77	11.31	9.96	0.75	0	MS
	224	19	9.55	11.46	10.50	0.51	0	MS
5	0	18	6.19	10.90	9.30	1.45	103	LP
	56	18	8.50	11.08	9.89	0.81	0	MS
	112	19	9.75	11.99	10.81	0.65	0	MS

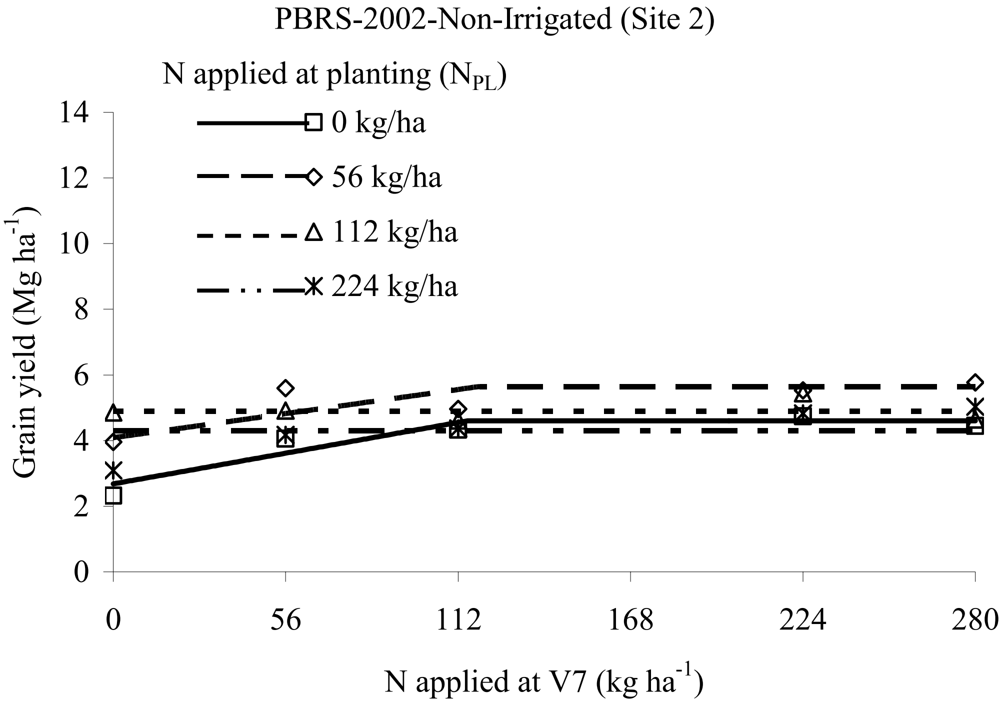
	224	18	8.95	11.80	10.55	0.86	0	MS
6	0	15	2.28	4.97	4.06	0.72	115	LP
	56	15	2.56	4.77	3.93	0.63	0	MS
	112	15	3.47	6.23	4.65	0.90	0	MS
	224	14	2.19	6.73	3.98	1.10	0	MS
7	0	19	1.74	8.18	5.75	2.21	155	LP
	56	19	3.93	11.05	7.93	2.10	149	LP
	112	20	7.20	10.84	9.11	1.27	170	LP
	224	20	8.98	11.86	10.09	0.81	0	MS
8	0	20	8.83	12.83	10.55	1.00	NA	NA
	56	20	4.87	11.82	9.64	1.75	NA	NA
	112	20	5.85	11.38	9.18	1.26	NA	NA
	224	20	4.74	10.83	9.20	1.40	NA	NA
9	0	17	2.86	9.87	7.60	2.12	125	LP
	56	20	5.38	10.73	8.98	1.51	64	LP
	112	20	7.10	11.97	10.30	1.28	56	MS
	224	20	9.26	12.20	11.01	0.72	75	LP
10	0	17	4.19	10.02	7.74	1.77	83	LP
	56	19	4.71	11.82	8.92	2.03	76	LP
	112	19	7.45	11.91	10.19	1.17	59	LP
	224	19	8.92	12.25	10.61	0.95	0	MS
11	0	19	2.78	7.80	6.14	1.74	118	LP
	56	19	4.37	10.22	7.49	1.70	75	LP

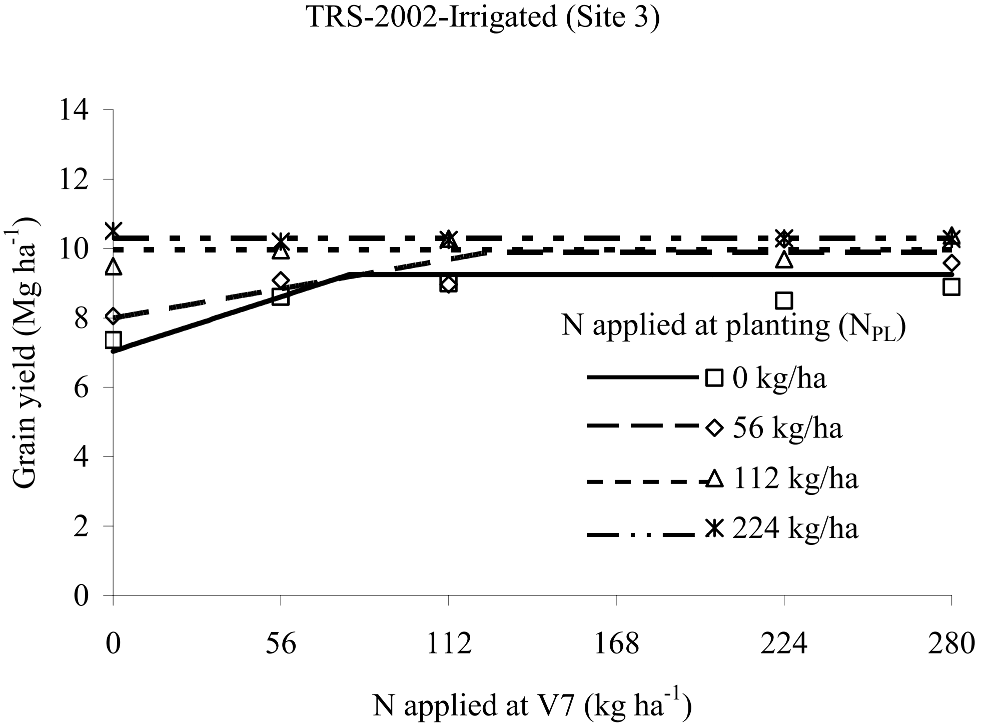
	112	19	6.62	10.76	8.67	1.07	133	LP
	224	20	6.38	11.07	8.61	1.16	0	MS
12	0	17	1.80	9.31	6.50	2.20	72	LP
	56	18	2.91	9.25	6.54	1.80	65	LP
	112	17	6.48	11.08	8.67	1.33	112	MS
	224	20	6.02	10.80	8.20	1.56	0	MS

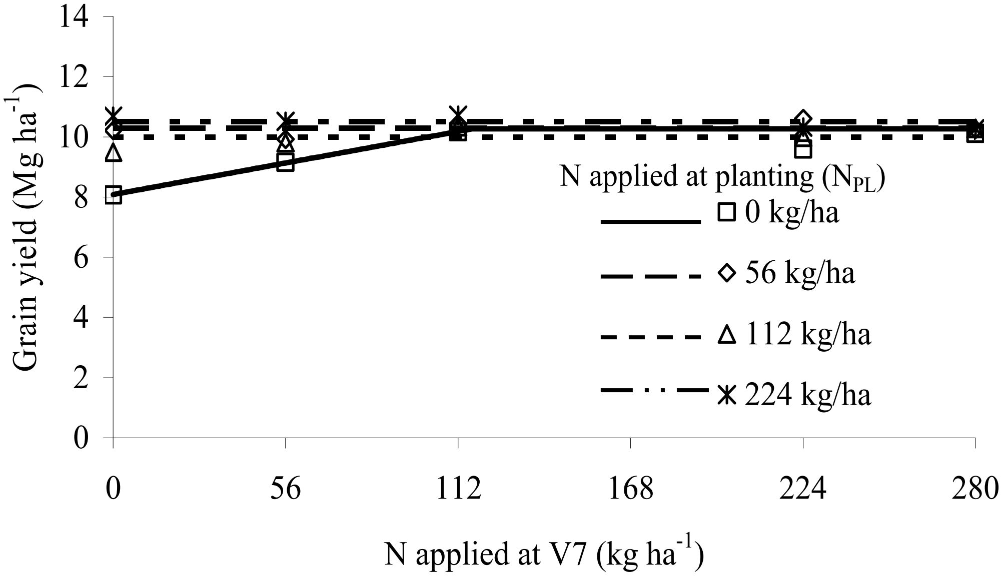
[†] LP: Optimum N rate derived using Linear–plateau function; MS: Mean separation via Fisher’s protected LSD; NA: Not available.

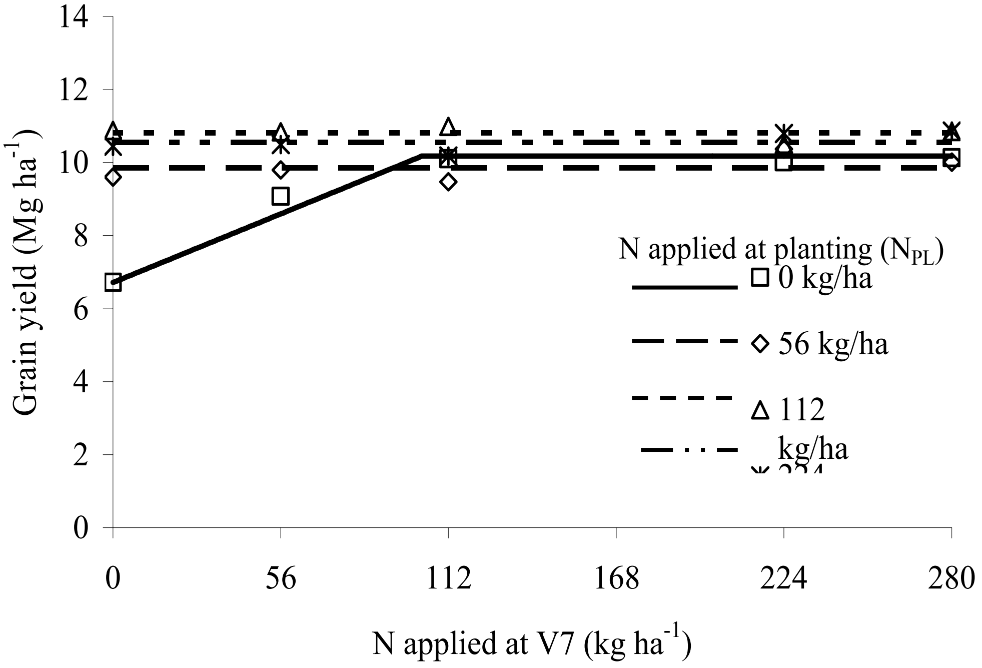
Appendix B. Linear-plateau fit of grain yield response to N applied at V7 (N_{V7}) for the different rates of N applied at planting (N_{PL}) at the different experimental sites during 2002 and 2003. Absence of a line indicates that optimum N rates were derived using Fisher's protected Least Square mean separation.

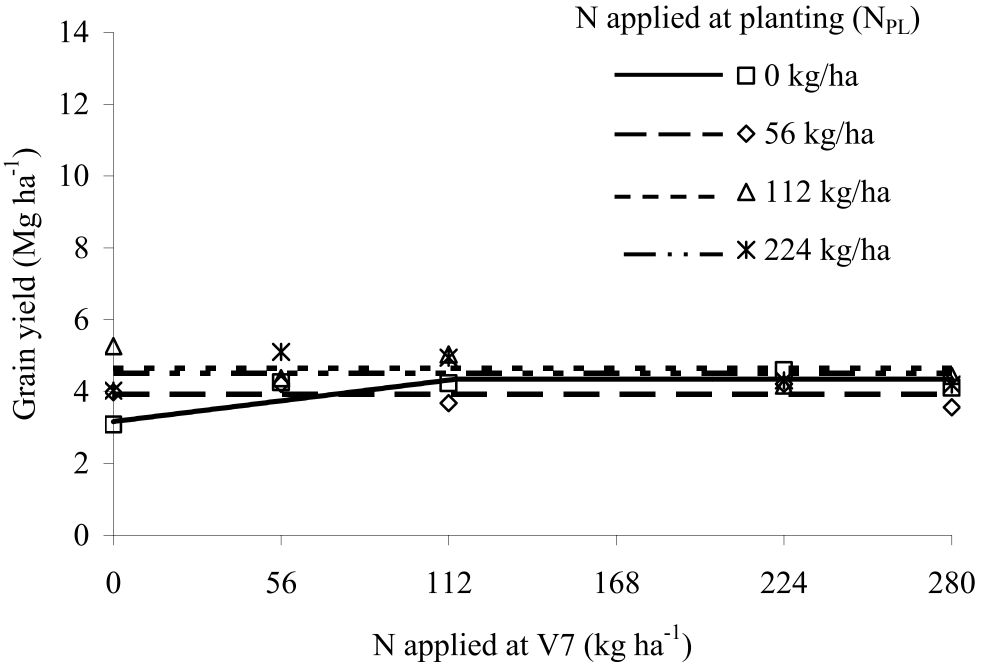


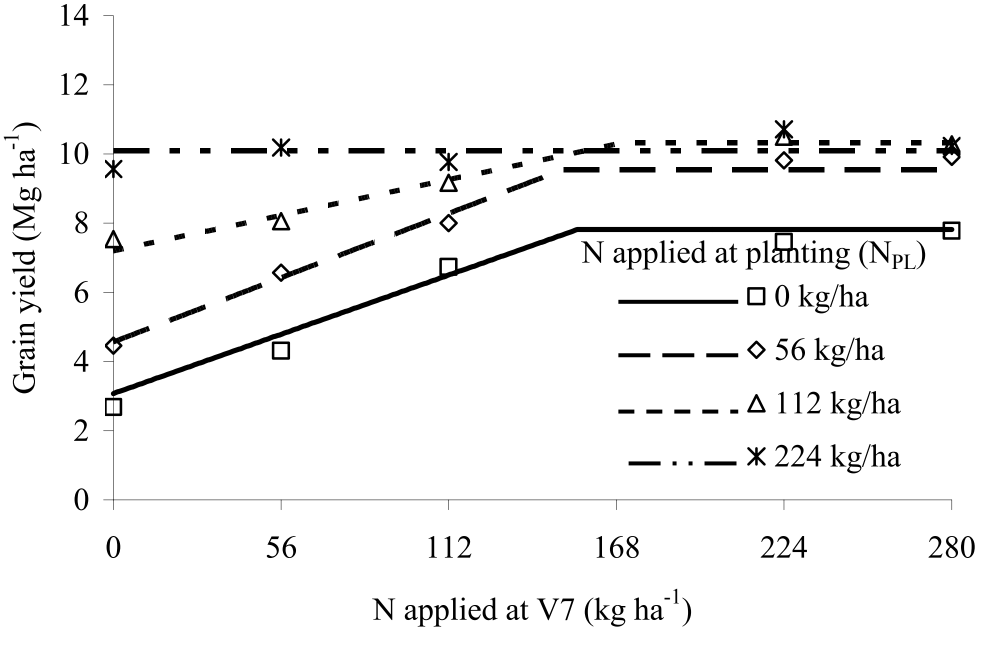

PBRS-2002-Non-Irrigated (Site 2)
N applied at planting (N_{PL})
0 kg/ha
56 kg/ha
112 kg/ha
224 kg/ha
Grain yield (Mg ha^{-1})
14
12
10
8
6
4
2
0
0
56
112
168
224
280
N applied at V7 (kg ha^{-1})


TRS-2002-Irrigated (Site 3)
Grain yield (Mg ha^{-1})
14
12
10
8
6
4
2
0
N applied at planting (N_{PL})
0 kg/ha
56 kg/ha
112 kg/ha
224 kg/ha
0
56
112
168
224
280
N applied at V7 (kg ha^{-1})

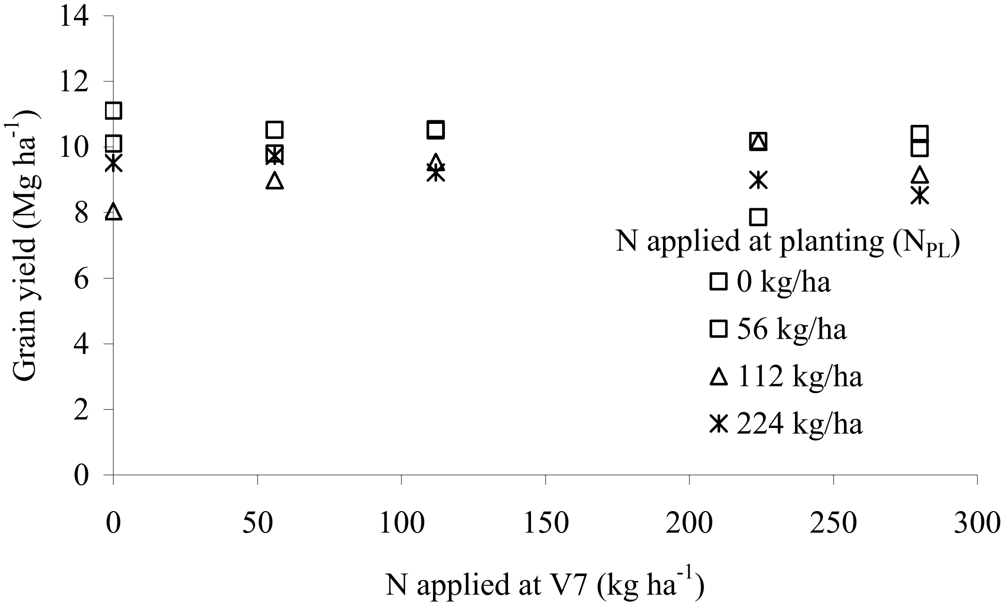

TRS-2002-Non-Irrigated (Site 4)


TRS-2002-Irrigated (Site 5)

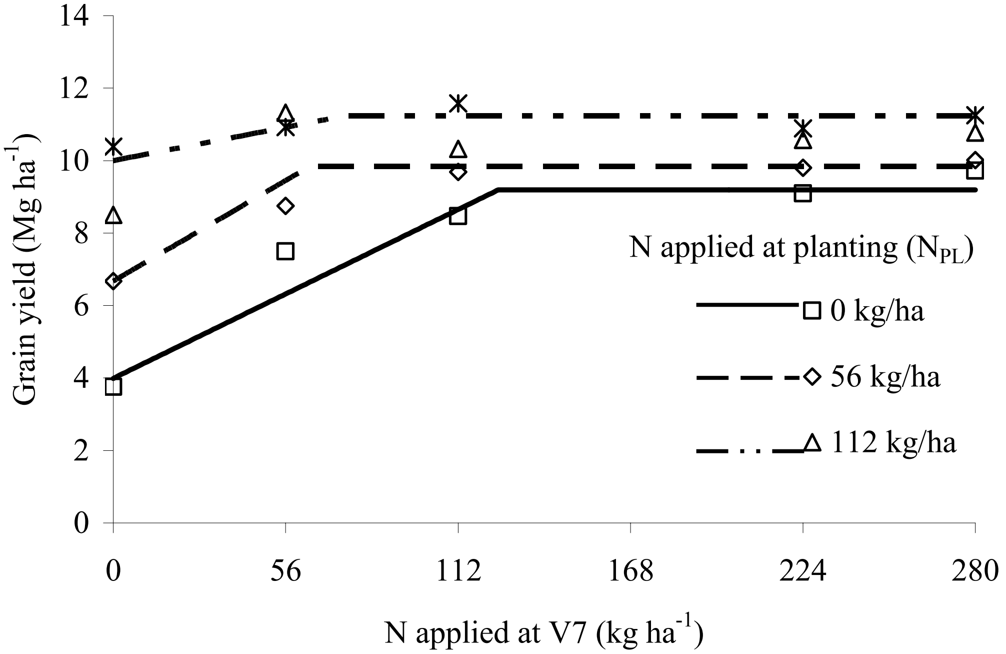

TRS-2002-Non-Irrigated (Site 6)

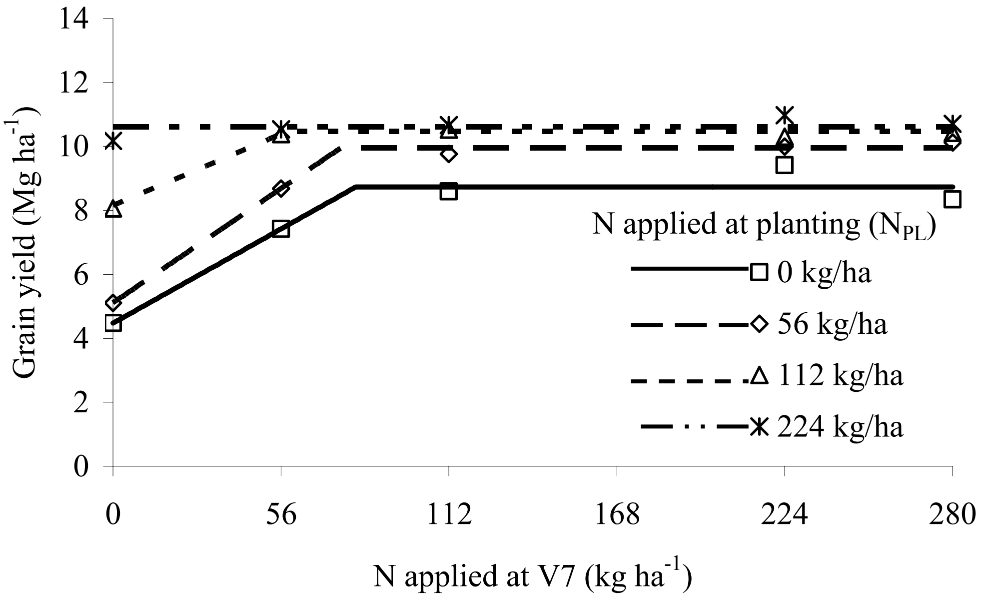

PBRS-2003-Irrigated (Site 7)

PBRS-2003-Non-Irrigated (Site 8)

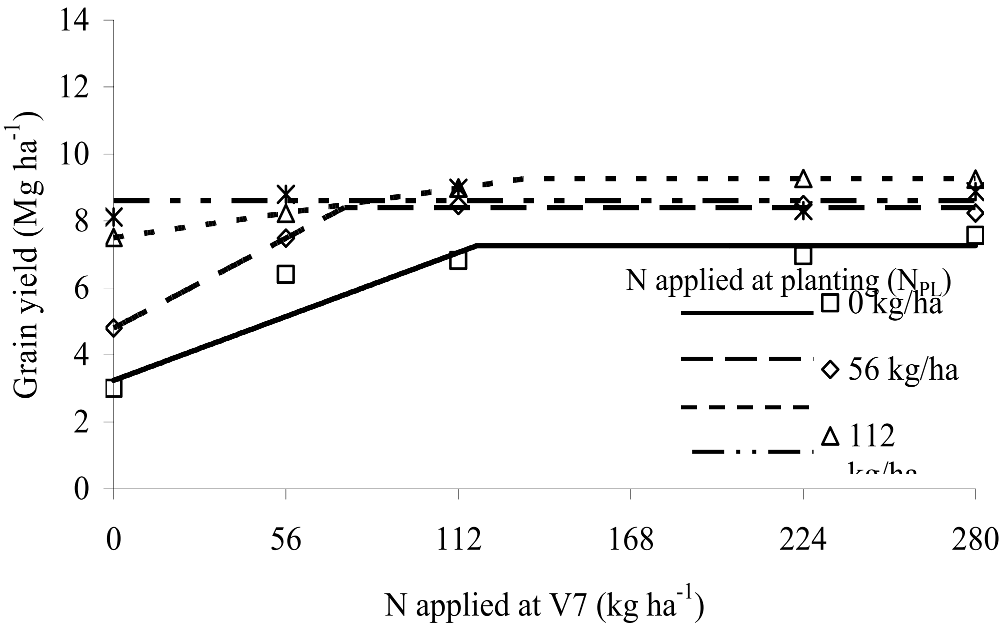


TRS-2003-Irrigated (Site 9)

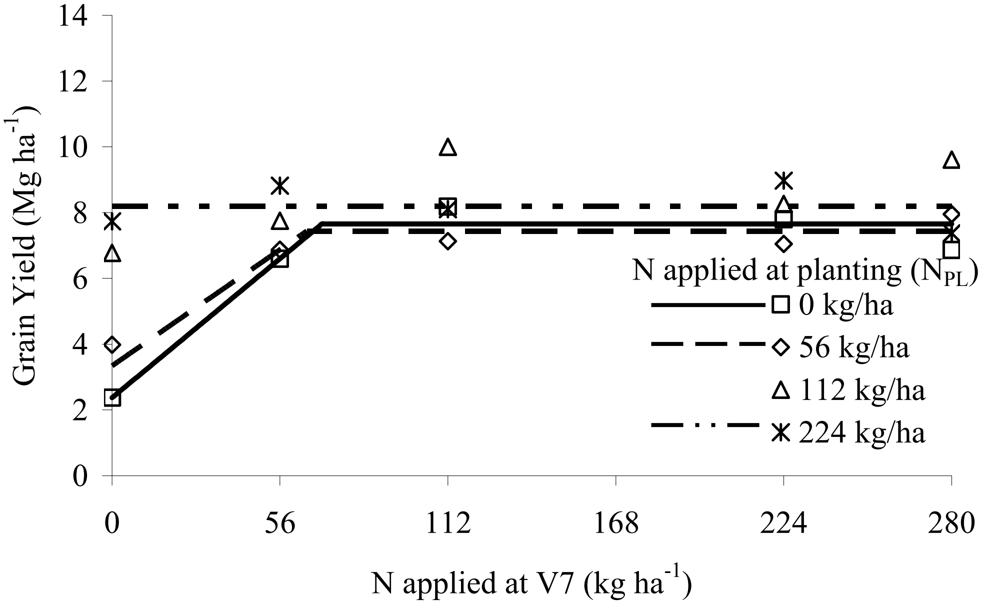




TRS-2003-Non-Irrigated (Site 10)



TRS-2003-Irrigated (Site 11)



TRS-2003-Non-Irrigated (Site 12)

CHAPTER FIVE

Biophysical Basis for the Use of Aerial Color Infrared Photography in Determining In-Season Nitrogen Requirements in Corn

Biophysical Basis for the Use of Aerial Color Infrared Photography in Determining In-Season Nitrogen Requirements in Corn

ABSTRACT

Very few studies have attempted to understand the bio-physical basis for the use of aerial color infrared (CIR) photography to quantify in-season corn (*Zea mays* L.) nitrogen (N) requirements. The objectives of this research were to: i) examine the response of corn agronomic parameters (biomass, plant N concentration, and total N uptake) and spectral parameters (near-infrared [NIR], red [R] and green [G]) from CIR measured at the V7 and VT growth stages to changing environments (year), irrigation, and N applications at planting (N_{PL}); and ii) determine the relationships between corn agronomic parameters and spectral parameters that influence the prediction of optimum N rates at growth stages V7 and VT. Research was conducted during the 2000-2003 corn growing seasons in North Carolina under irrigated and non-irrigated conditions with different N_{PL} rates as the main plot factor. Corn agronomic parameters were measured and aerial CIR photographs were obtained at each site at V7 or at VT. Results indicate that N_{PL} significantly influenced corn agronomic parameters measured at V7 and VT. Corn spectral parameters measured at V7 and VT varied with year and N_{PL}. Green and NIR were significantly correlated with biomass and total N uptake. Relative indices using G and NIR were related to plant N concentration. Among the different indices, relative green difference vegetation index (RGDVI) was the best predictor of corn N status (plant N concentration) at V7 and VT. RGDVI showed consistently significant relationships with corn agronomic parameters measured at VT when analyzed across irrigated and non-irrigated experiments.

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., 1997a). Macy (1936) recognized that the concentration of a nutrient in plant tissue is a function of the sufficiency of that nutrient, and his work laid the foundations for the current ideas regarding use of tissue analysis to diagnose nutrient deficiencies. In his work, nitrate (NO_3-N) concentration, and total N concentration measured in reference to individual leaves or the entire plant were used as indicators of crop N status.

The leaf opposite and below the primary ear at silking ("ear leaf") frequently is used to determine the N status of corn (Tyner and Webb, 1946). Critical N concentrations in the ear leaf between tasseling and silking range from 26 to 36 g N kg^{-1} in the dry matter (Soltanpour et al., 1995). Cerrato and Blackmer (1991) pointed out that critical N concentrations are often overestimated due to the use of incorrect regression models. They concluded that corn could be considered non-responsive to N above an ear-leaf N concentration of 21 g kg^{-1} and that the variation within and across sites is too large to use ear leaf N as a practical diagnostic tool. These variations in total N concentrations caused by factors other than N probably stem in part from the crop-stage dependent nature of N concentration (Greenwood et al., 1990).

End-of-season cornstalk N content has been used as an indicator tool for determining N status in corn at harvest. Stalk sample NO_3-N concentrations have been classified into four categories: low (< 0.25 g N kg^{-1}), marginal (0.25 - 0.70 g N kg^{-1}), optimal (0.70 - 2.0 g N kg^{-1}), and excess (> 2.0 g N kg^{-1}). Within the optimal range, yield may increase without a change in stalk sample NO_3-N concentration. Luxury consumption (when an increase in N uptake does not result in an increase in yield) occurs in the excess category (Blackmer and Mallarino, 1996).

The relationship between the availability of soil N and NO_3–N concentration of a crop is complex, and it is often difficult to translate observations on NO_3-N concentration into quantitative estimates of N deficiency or excess. In an effort to address these difficulties, total N concentration has been evaluated for its potential as an indicator of the N status of corn. Unfortunately, because total N concentration reaches a plateau with increasing N supply, total N has proved to be an unsuitable indicator for detection of excess N in corn (Cerrato and Blackmer, 1991).

The SPAD-502 chlorophyll meter (Minolta Camera Co., Ltd., Japan) measures relative chlorophyll concentration by measuring the light transmittance through the leaf at 650 and 940 nm. Wood et al. (1992) found a high correlation between SPAD-502 chlorophyll meter readings and corn tissue N concentrations between the stage when the tassel begins to develop rapidly (VT) and the mid-silk growth stage (R1 – R2). Nitrogen deficiency is quickly reflected in a low chlorophyll concentration, which is accurately registered by the SPAD meter. However, SPAD meter readings are poor predictors of excess N because not all N is converted into chlorophyll when the availability of N is large (Wood et al., 1992; Blackmer and Schepers, 1995). Additionally, hybrid (Schepers et al., 1996; Waskom et al., 1996), planting time (Jemison and Lytle, 1996), and site-year effects in general (Blackmer and Schepers, 1995; Varvel et al., 1997a) have been reported to impact SPAD readings.

Recently, the development of indicators for N status in crops has focused on the use of color. These indicators either refer to the color of individual leaves (leaf greenness) or to the color of the entire crop (field or canopy greenness). The pigments involved in photosynthesis (chlorophyll) absorb visible light (400–700 nm) selectively. Chlorophyll absorbs mainly blue (~ 450 nm) and red (~ 660 nm) wavelengths and reflects green (~ 550 nm) wavelengths. Reflectance measurements at these wavelengths, therefore, can be good indicators of leaf chlorophyll content. Healthy green plant vegetation is strongly reflective in the NIR (700–1400 nm), and soil tends to absorb these wavelengths more strongly than do plants, so reflectance measurement at these wavelengths provides information on the amount of leaf relative to the amount of bare soil (Lilleseater, 1982).

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. The use of reflectance or radiance as indicators of crop N status is still in its infancy (Bausch et al., 1996; Bausch and Duke, 1996; Schepers et al., 1996) relative to the other indicators discussed above. Bausch and Duke (1996) observed a near one-to-one relationship between relative Ratio Vegetation Index (ratio of NIR/G of a particular treatment to the NIR/G of a reference area) and the N sufficiency index (ratio of SPAD data for a particular area to the SPAD data for a reference area) and plant tissue total N concentration for corn growth stages between V11 and R4. 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 and Sripada et al. (2005a & b) used relative green difference vegetation index (RGDVI) to predict corn optimum sidedress N at V6-V7 and at VT, respectively.

While it would seem intuitive to compare the bio-physical techniques of measuring crop N status with the techniques using crop color, to date there have been very few studies attempting to understand the relationships between corn agronomic parameters (biomass, plant N concentration, and total N uptake) and spectral parameters. Therefore, the objectives of this research were to i) examine the response of corn agronomic parameters (biomass, plant N concentration, and total N uptake) and spectral parameters (near-infrared [NIR], red [R] and green [G] and the vegetation indices derived from these bands) from CIR measured at the V7 and VT growth stages to changing environments (year), irrigation, and N applications at planting (N_{PL}); and ii) determine the relationships between corn agronomic parameters and spectral parameters that influence the prediction of optimum N rates at growth stages V7 and VT.

MATERIALS AND METHODS

Field studies were conducted in North Carolina during the 2000 – 2003 growing seasons, with irrigated and non-irrigated sites at the Peanut Belt Research Station (PBRS) near Lewiston-Woodville, the Tidewater Research Station (TRS) near Plymouth, and several farmers' fields. Soil classification and site identification are described in Table 1. Pre-plant N (N_{PL}) application rates and the experimental layout for the V7 and VT studies were reported by Sripada et al. (2005a) and Sripada et al. (2005b) respectively. Sites 1 – 10 were used for the VT study and Sites 11 – 22 were used for the V7 study.

Treatments and Experimental Design

At each site a two-way factorial experimental design was implemented as a split-plot in randomized complete blocks with three replications in 2000 and 2001, five replications in 2002, and four replications in 2003. The N applied at planting (N_{PL}) was the main plot factor and the sub-plot factors were either sidedress N applied at V7 (N_{V7}) or at VT (N_{VT}). For the V7 study, the N_{PL} rates were 0, 56, 112, and 224 kg ha^{-1}, and the N_{V7} rates were 0, 56, 112, 224, and 280 kg ha^{-1}. For the VT study, N rates varied among years. 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. The hybrid 'Pioneer 31G98' was planted at approximately 60,000 seeds ha^{-1} across all sites and years. Herbicides were applied based on weeds present, and excellent weed control was obtained at all sites. Depending on the rainfall, water was applied to the irrigated plots at the rate of 25.4 mm a week.

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 V7 or VT using the technique described by Flowers et al. (2001). The aerial CIR images were obtained at altitudes such that the entire experimental field was covered in a single image and under conditions as cloud-free as possible using a belly mounted platform with 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) were used for obtaining the CIR images. 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 Syst., San Jose, CA), resulting in a ground resolution of 0.43 to 0.55 m. Differences in ground resolution were due to the different altitudes at which the images were obtained. The spectral properties of the CIR film used for obtaining images were described by Flowers et al. (2003). 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 red (R), 8-bit green (G), and 8-bit blue (B). For each pixel in the image, the primary color value represents 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 – 900 nm, band 2 (R) covered the wavelengths between ~490 – 700 nm, and band 3 (G) covered the wavelengths between ~490 – 620 nm. While these bands overlap, differences in spectral sensitivity exist between them. 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. Digital image data were georegistered using ERDAS Imagine (ERDAS Inc. Atlanta, GA) image processing software.

Areas of interest (AOI) corresponding to individual plots were identified, which included approximately equal numbers of pixels for each plot. The AOI included both the corn plants and any soil that was visible between adjacent rows, i.e. 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 2). Relative bands

(Rel NIR, Rel R, Rel G) and indices (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.

Biomass, Tissue Sampling and Grain Yield Determination

At all sites, plant biomass samples were collected at V7 or at VT from three 0.91-m sections of a row within each plot that received no further N applications. These samples consisted of all the tissue above the soil surface. For each sample, dry biomass was determined by drying the samples at 65^{o}C for 72 h. For the samples taken at VT, the leaves were separated from stalks, dried, weighed, and N concentration determined separately. Tissue N concentration (g kg^{-1}) was determined using a CHN analyzer (McGeehan and Naylor, 1988). Nitrogen uptake (kg N ha^{-1}) at V7 was determined by multiplying dry biomass (kg ha^{-1}) by whole-plant N concentration (g N kg^{-1}). For the samples taken at VT, N uptake (kg N ha^{-1}) was determined by the sum of leaf and stalk N uptake obtained by multiplying dry biomass (kg ha^{-1}) of leaf and stalk with the leaf and stalk N concentrations (g N kg^{-1}), respectively. 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 moisture content of 155 g kg^{-1}.

Data Interpretation and Statistical Analysis

Statistical analysis including ANOVA and linear regression were performed with SAS Version 8 (SAS Institute, Cary, NC). Since the objective of this research was to determine the responses to year, irrigation, and N_{PL} of corn agronomic and spectral parameters at V7 and VT and of grain yield, the N_{V7} and N_{VT} treatments were not considered in the analysis. The response of corn biomass, plant N concentration, and total N uptake at V7 and of grain yield to year, irrigation, and N_{PL} were analyzed using PROC MIXED in SAS Version 8 (SAS Institute, Cary, NC) with year, irrigation, and N_{PL} considered fixed effects and site a random effect. Due to the confounded nature of site and irrigation for the VT study, a separate analysis was performed for the irrigated and non-irrigated VT experiments. The responses to year and N_{PL} of VT corn biomass, plant N concentration, and N uptake, as well as grain yield were analyzed using PROC MIXED in SAS Version 8 (SAS Institute, Cary, NC) with year and N_{PL} as fixed effects and site as a random effect. The digital counts for the NIR, R, and G bands and all of the spectral indices (Table 2) were regressed against corn biomass, plant N concentration, and total N uptake using linear and quadratic models. These models were fit using PROC REG in SAS Version 8 (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

V7 Study

Response of V7 Corn Biomass, Plant N Concentration, Total N Uptake, and Grain Yield to Year, Irrigation, and N_{PL}

For all corn agronomic parameters, there were no significant interactions between the treatment factors (Table 3). Among the main effects, only N_{PL} was significant (Table 3). Biomass, plant N concentration, and total N uptake at V7 and grain yield increased with increasing rates of N_{PL} (Table 4). The highest grain yields were associated with higher levels of V7 biomass, N concentration, and N uptake. At the highest level of N_{PL}

(224 kg ha^{-1}), significant increases in plant N concentration and total N uptake were not accompanied by a significant increase in grain yield.

Response of V7 NIR, R, and G to Year, Irrigation, and N_{PL}

The three-way interaction of year × irrigation × N_{PL} was significant for R and G but was not significant for NIR. The two-way interaction of Year × N_{PL} was significant for NIR, R, and G. The main effect of N_{PL} was consistently significant for each of the three spectral bands. This response was expected based on the differential N uptake of corn under differing N availability situations and is similar to what has been found in previous research (Iversen et al., 1985a; Fox et al., 1989; Bindford et al., 1990; Bindford et al., 1992). Among the three spectral bands used in this study, only NIR was significantly affected by year (Table 3). The significance of year may have been the result of differences in the illumination conditions when the images were captured and differences in vegetation cover from year-to-year.

When analyzed separately by year, digital counts representing the NIR band did not vary significantly with changes in N_{PL} in 2002 (Table 5). However, in 2003 the NIR values increased with increasing N_{PL} applications, a trend similar to that observed with NIR and biomass (Fig. 1). This suggests that changes in NIR values can be attributed to the changes in biomass, a response to the N applications (Fig. 1; Table 5). The DN values for R and G decreased with increases in N_{PL} (Table 5; Fig. 1). As chlorophyll content increases in the leaf more light is absorbed, especially in the red (and blue), but also in the G band. The increasing amount of absorbed light results in the leaf becoming a darker green and hence lower DN values.

Relating Corn Biomass, Plant N Concentration, and Total N Uptake with Spectral Bands and Indices

Between the two models (linear and quadratic) that were used to relate the spectral bands and indices with corn agronomic parameters, a linear model was always a better fit than a quadratic model to the relationships tested. Therefore, further discussion will focus on the linear model. Across years, with the exception of R, G, Normalized G, and GRVI all the spectral bands and indices tested showed significant linear relationships with biomass at V7 (Table 6). Absolute indices associated with NIR and R bands (DVI, RVI, NDVI, SAVI, and OSAVI) had stronger relationships with biomass than the indices associated with NIR and G bands (GDVI, GRVI, GNDVI, GSAVI, and GOSAVI) (Table 6). Compared to the absolute indices, the relative indices were not as good at describing changes in biomass. When analyzed by year, all bands and indices (absolute and relative) had significant linear relationships with biomass in 2003. In 2002, only the absolute bands (Fig. 1) and absolute indices (Table 6) had significant relationships with biomass. With the exceptions of Norm G, Rel R, Rel G, and RDVI, none of the relative indices were linearly related to biomass. When considered over both years, DVI showed the highest r^2 (0.47) with biomass and was significantly and positively correlated across both years (Table 6, Fig. 2).

With the exceptions of R, G, Norm R, DVI, and GDVI, all the indices tested had significant relationships with changes in plant N concentration at V7 (Table 6). Compared to indices that combined NIR and R bands (DVI, RVI, NDVI, SAVI, and OSAVI), indices calculated from NIR and G bands (GDVI, GRVI, GNDVI, GSAVI, and GOSAVI) had stronger relationships with plant N concentration. Overall, relative indices showed a consistently stronger relationship compared to the corresponding absolute indices. When analyzed separately by year, in 2002, Rel G, RGDVI, RGRVI, RGSAVI, and RGOSAVI were all significantly correlated while the other absolute and relative indices were not. However, in 2003 all the indices showed a significant relationship. Overall, RGDVI showed the highest r^2 (0.44) and was consistently and positively correlated with plant N concentration across both years (Table 6; Fig. 2).

With the exception of the R and G bands and Normalized G, all of the absolute and relative indices tested had significant relationships with changes in total N uptake at V7. Absolute indices combining the NIR and R bands (DVI, RVI, NDVI, SAVI, and OSAVI) were more strongly related than the absolute indices combining the NIR and G bands (GDVI, GRVI, GNDVI, GSAVI, and GOSAVI) (Table 6). In comparison to all the absolute indices, all the relative indices had weaker relationships to total N uptake at V7. When analyzed separately by year, all the absolute bands (Fig. 1) and absolute indices (Table 6) were significantly related to N uptake in 2002. However, with the exception of RDVI, none of the other relative indices were significantly related to N uptake. In 2003, all the bands and indices, both absolute and relative, had significant relationships with total N uptake. Overall, DVI was the measure that best described changes in total N uptake at V7 (r^2=0.48), and was consistently and positively correlated across years (Table 6; Fig. 2).

Association of Corn V7 Agronomic and Spectral Parameters with Optimum N Rate (N_{V7})

In this study, RGDVI was the best predictor of plant N concentration at V7 (Table 6; Fig. 2; r^2 = 0.44). Using data from the same experiments as those in the present study, Sripada et al. (2005a) found that the RGDVI was also the best predictor of optimum N rate at V7 for corn, albeit with a low coefficient of determination ($r^2 = 0.21$). Consistent with the fact that plant N concentration showed a positive slope with RGDVI measured at V7 (Fig. 2); optimum N rates showed a negative slope with RGDVI (Sripada et al., 2005a). Plots with low RGDVI and plant N concentrations were those that had high in-season N requirements determined at V7 (N_{V7}). The RGDVI values measured at V7 were successful in detecting the variation in plant N concentration which probably contributed to this index to predict different optimum N rates as shown by Sripada et al. (2005a).

VT Study: Non-Irrigated

Response of VT Corn Biomass, Plant N Concentration, Total N Uptake, and Grain Yield to Year and N_{PL}

The two-way interaction of year × N_{PL} and the main effect year were not significant for any of the corn agronomic parameters. In contrast, N_{PL} had a significant effect on biomass, plant N concentration, and total N uptake (Table 7). In general, applications of 112 kg N ha^{-1} or more did not result in increased VT biomass, or total N uptake (Table 8). However, plant N concentrations continued to increase up to the maximum N_{PL} rate of 224 kg N ha^{-1}. Grain yields were significantly influenced by N_{PL} and followed a trend similar to plant N concentration.

Response of VT NIR, R, and G Bands to Year and N_{PL}

There was no significant interaction of year × N_{PL} for the DN values of NIR, R, and G bands (Table 7). However, they were significantly affected by year. The mean DN values representing NIR, R, and G were 116, 65, and 81, respectively, in 2000, and 193, 157, and 181, respectively, in 2001. The difference in the DN values for the three bands over years was probably due primarily to differences in the illumination (higher in 2001 compared to 2000) and/or exposure when the images were captured. The DN values for NIR were not significantly affected by N_{PL} but R and G were significantly effected (Table 7 & 8). Consistent with general expectation, the DN values for R and G values tended to decrease with increasing rates of N_{PL} (Table 8). As chlorophyll content becomes denser in the leaves, more light is absorbed especially in the R and B, but also in the G band. The increasing amount of absorbed light results in the leaf becoming a darker green and hence lower DN values. Overall, the different N_{PL} rates helped create a range of values in the R and G spectral radiance, while NIR did not vary significantly.

Relating Corn VT Biomass, Plant N Concentration, and Total N Uptake with Spectral Bands and Indices

Across years, all the absolute bands and indices had significant linear relationships with VT biomass and total N uptake (Table 9). While the spectral bands R and G and the agronomic parameters biomass, plant N concentration, and total N uptake were significantly influenced by varying amounts of N_{PL} (Table 7), NIR did not differ with N_{PL}. Across years, R had a stronger relationship with agronomic parameters when compared to G (Table 9), suggesting that indices associated with R and NIR have the potential to describe changes in agronomic parameters compared to indices associated with G and NIR. Consistent with previous findings, indices formed from NIR and R bands (NDVI, SAVI, and OSAVI) were more strongly related with agronomic parameters than the indices formed from NIR and G bands (GNDVI, GSAVI, and GOSAVI) (Table 9).

One method of adjusting for the effect of year on spectral values is to use indices relative to a high N plot in the field. However, contrary to our expectations and with the exception of the RDVI which showed a significant relationship with biomass and plant N concentration, none of the relative bands or indices showed a significant relationship with agronomic parameters when analyzed across years (Table 9). Overall, across years R showed the strongest relationship ($r^2 = 0.65$; Fig. 3) with biomass, RGDVI with plant N concentration ($r^2 = 0.15$; Fig. 4), and NDVI with total N uptake ($r^2 = 0.57$; Fig. 4) (Table 9).

VT Study: Irrigated

Response of VT Corn Biomass, Plant N Concentration, Total N Uptake, and Grain Yield to Year and N_{PL}

The two-way interaction of year × N_{PL} and the main effect year were not significant for any of the VT corn agronomic parameters. In contrast to this, N_{PL} had a significant effect on all of them (Table 7). In general, applications of 112 kg N ha^{-1} or more did not result in increased biomass or total N uptake (Table 8). However, plant N concentrations continued to increase with N_{PL} up to 168 kg ha^{-1}. Grain yields were significantly influenced by N_{PL} applications and followed a trend similar to biomass. Across years, the different N_{PL} applications helped create a range of biomass, plant N concentration, and total N uptake levels.

Response of VT NIR, R, and G Bands to Year and N_{PL}

The DN values for NIR were significantly influenced by the two-way interaction of year × N_{PL}, while R and G were not (Table 7). Within each year, the NIR values did not vary with varying rates of N_{PL} in 2000, while in 2001, NIR values increased with N_{PL}

applications up to 112 kg ha^{-1}(not shown). The mean DN values for NIR were 132 and 187 in 2000 and 2001, respectively. The difference between years was probably due to difference in illumination (or exposure) when the images were taken. The DN values for R and G varied significantly with N_{PL} with lower DN values with increasing rates of N_{PL} (Table 8).

Relating Corn VT Biomass, Plant N Concentration, and Total N Uptake with Spectral Bands and Indices

Across years, DN values for R and G had significant relationships with biomass while NIR was not significant. None of the three bands showed a significant linear relationship with either plant N concentration or total N uptake when analyzed across years (Table 10). Across years, the absolute indices associated with the NIR and G bands showed stronger relationships with agronomic parameters compared to those associated with the NIR and R bands. As previously discussed, the corn agronomic parameters and R and G spectral bands were significantly influenced by N_{PL} applications. The DN values for NIR were significantly influenced by the two-way interaction of year × $N_{PL.}$ Therefore, the predictive ability of the spectral bands and indices might be enhanced by the use of relative bands and indices which adjust for the differences in spectral radiance over years as observed with NIR in this study. Contrary to our expectation, with the exceptions of Rel R, RDVI, and RRVI, relative indices did not show any stronger relationships with biomass in comparison to the absolute indices. All the relative bands and indices with the exception of Rel NIR showed stronger and significant relationships with plant N concentration in comparison to their corresponding absolute indices when analyzed across years. While the Rel NIR was not significant, the Rel R and Rel G showed significant relationships with total N uptake.

The DN values representing NIR did not show significant relationships with corn agronomic parameters in either 2000 or 2001. However, the DN values representing R and G spectral bands were significantly and strongly correlated with corn agronomic parameters in 2000, while all of them were non significant in 2001. Considering only spectral indicators that were significant in both years, GDVI showed the strongest relationship with biomass ($r^2 = 0.69$; Table 10; Fig. 6), RGDVI with plant N concentration ($r^2 = 0.46$; Table 10; Fig. 6) and RDVI with total N uptake ($r^2 = 0.64$; Table 10; Fig. 6).

Association of Corn VT Agronomic and Spectral Parameters with Economic Optimum N Rate (N_{VT})

One of the objectives of this study was to identify and characterize any relationships between corn agronomic parameters and spectral bands and indices measured at VT that can help support the relationship between economic optimum N predicted at VT (N_{VT}) using spectral indices (Sripada et al., 2005b) Unfortunately, the large number of spectral indices calculated and the complex relationships between the agronomic and spectral parameters and optimum N rates make it difficult to identify the key relationships among these data. Since all indices used in this study are calculated from the three primary spectral bands (NIR, R, G), we examined the key relationships for these bands as a prerequisite for an examination of the spectral indices. As discussed above, there were significant effects of year and N_{PL} on the three primary spectral bands. However, none of the three bands (NIR, R, and G) had consistent significant linear relationships in each year with corn agronomic parameters measured at VT under either non-irrigated (Table 9) or irrigated conditions (Table 10). When analyzed across years, R was related to biomass while G tended to be related to plant N concentration (Table 9 & 10).

The fact that year had a significant effect on the spectral bands (Table 7) indicates a potential limitation in using them effectively to predict corn agronomic parameters and economic optimum N_{VT} rates. Relative bands and indices have been used to adjust for inherent differences in spectral radiance values when using data collected across years (Blackmer and Schepers, 1995; Bausch and Duke, 1996; Scharf and Lory, 2002). A similar approach was used in this study. Among the different relative indices used, RDVI, RGDVI (Fig. 7), RNDVI, RSAVI, and ROSAVI showed consistently significant linear relationships with biomass, plant N concentration, and total N uptake measured at VT (Table 11). Using the data from this study and additional data, Sripada et al. (2005b) found that RDVI and RGDVI showed the highest R^2 in describing the changes in economic optimum N_{VT} rates. However, only the model using RGDVI was consistently significant when analyzed separately by year and irrigation treatments. In this study, the relationship of plant N concentration and RGDVI showed a slightly higher coefficient of determination ($r^2 = 0.31$) than RDVI ($r^2 = 0.29$), suggesting that RGDVI was more successful in predicting economic optimum N_{VT} rates in part because it was effective in detecting VT plant N concentration at VT.

A lower RGDVI value indicates that green tissue of the canopy is not as saturated with green chlorophyll pigments (measured as plant N concentration and total N uptake) as the high N reference plot. The chlorophyll pigment saturation of the high N reference plot is assumed to be high enough to not warrant any further N applications. Since plots with color similar to reference plots result in an RGDVI value of 1 these plots would not require additional N. Therefore the lower the RGDVI values, the lower the plant N concentration and total N uptake and the higher the economic optimum N_{VT} rate.

CONCLUSIONS

This study demonstrated that corn agronomic parameters measured at V7 and VT responded to a wide range of N fertility levels at planting. The corresponding spectral parameters at V7 and VT were influenced both by year and the N fertility levels at planting. Except in 2002, all three spectral bands showed significant relationships in each year with corn agronomic parameters measured at V7. RGDVI was the best predictor of plant N concentration measured at V7 and was consistently significant in individual years. Overall across years, DVI was the best predictor of biomass and total N uptake, and RGDVI was the best predictor of plant N concentration at V7.

None of the three spectral bands (NIR, R, and G) showed a consistently significant relationship with corn agronomic parameters measured at VT in each year neither in irrigated nor non-irrigated experiments. The indices RDVI and RGDVI were the best predictors of corn agronomic parameters at VT across years and irrigation experiments. The effectiveness of RGDVI in detecting changes in plant N concentration is probably the principle factor influencing the strong relationship between RGDVI and economic optimum N_{VT} rates.

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

Site[†]	Location[‡]	Year	Irrigation[§]	Soil series	Soil Taxonomic Classification
1	PBRS	2000	IR	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
2	DEN	2000	NI	Kirskey clay loam	fine-silty, siliceous, thermic, Aquic Hapludults
3	HSOR	2000	NI	Arapohoe coarse loam	coarse-loamy, mixed, nonacid, thermic, Typic Humaquepts
4	HSSR	2000	NI	Dragston sandy loam	coarse-loamy, mixed, thermic, aeric Ochraquults
5	TRS	2000	IR	Cape Fear loam	clayey, mixed, thermic, Typic Umbraquults
6	PBRS	2001	IR	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
7	PBRS	2001	NI	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
8	HSOR	2001	NI	Arapohoe coarse loam	coarse-loamy, mixed, nonacid, thermic, Typic Humaquepts
9	TRS	2001	IR	Cape Fear loam	clayey, mixed, thermic, Typic Umbraquults

10	TRS	2001	NI	Cape Fear loam	fine-silty, mixed, thermic Typic Umbraquults
11	PBRS	2002	IR	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
12	PBRS	2002	NI	Norfolk loamy sand	fine-loamy, siliceous, thermic, Typic Paleudults
13	TRS	2002	IR	Cape Fear loam	clayey, mixed, thermic Typic Umbraquults
14	TRS	2002	NI	Cape Fear loam	clayey, mixed, thermic Typic Umbraquults
15	TRS	2002	IR	Hyde clay loam	fine-silty, mixed, thermic Typic Umbraquults
16	TRS	2002	NI	Hyde clay loam	fine-silty, mixed, thermic Typic Umbraquults
17	PBRS	2003	IR	Norfolk loamy coarse sand	fine-loamy, siliceous, thermic, Typic Paleudults
18	PBRS	2003	NI	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
19	TRS	2003	IR	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults

20	TRS	2003	NI	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
21	TRS	2003	IR	Portsmouth fine sandy loam	fine-loamy, over sandy or sandy skeletal, mixed, thermic, Typic Umbraquults
22	TRS	2003	NI	Hyde loam	fine-silt, mixed, thermic, Typic Umbraquults

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[†] Sites1-10 were used for VT study and sites 11-21 were used for V7 study.

[‡] PBRS, Peanut Belt Research Station; HSOR, Haslin Farms-Organic Ridge; HSSR, Haslin Farms-Sandy Ridge; TRS, Tidewater Research Station; DEN, Denton.

[§] IR: Irrigated; NI: Non-irrigated.

Table 2. Spectral band combinations and vegetation indices studied.

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)	$[(NIR – R)/(NIR + R + 0.5)] \times 1.5$	Huete, 1988
Relative Soil Adjusted Vegetation Index (RSAVI)	$SAVI_{plot}/SAVI_{reference\ plot}$	-
Green Soil Adjusted Vegetation Index (GSAVI)	$[(NIR – G)/(NIR + G + 0.5)] \times 1.5$	-
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.

Table 3. ANOVA for V7 corn biomass, plant N concentration, total N uptake, near-infrared (NIR), red (R), and green (G), and grain yield as affected by year, irrigation, and N applied at planting (N_{PL}).

						Digital Number (DN)		
Source of Variation	df	Biomass	Plant N Conc.	Total N uptake	Grain yield	NIR	Red	Green
Year	1	NS	NS	NS	NS	**	NS	NS
Irrigation	1	NS	NS	NS	NS	NS	NS	NS
N_{PL}	3	*	**	**	**	*	**	**
Year × Irrigation	1	NS	NS	NS	NS	NS	NS	NS
Year × N_{PL}	3	NS	NS	NS	NS	**	*	**
Irrigation × N_{PL}	3	NS	NS	NS	NS	NS	NS	NS
Year × Irrigation × N_{PL}	3	NS	NS	NS	NS	NS	*	*

*, **, NS Significant at the 0.05, and 0.01probability levels and not significant, respectively.

Table 4. Response of V7 corn biomass, plant N concentration, total N uptake, and grain yield to N applied at planting (N_{PL}) across two years (2002 and 2003).

N_{PL}	Biomass	Plant N concentration.	Total N uptake	Grain yield
kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	Mg ha^{-1}
0	1586a†	21.1a	34.5a	4.46a
56	1797ab	23.3b	42.0a	6.28b
112	2013bc	25.6c	51.4b	7.88c
224	2306c	28.2d	64.6c	8.85c

†Within a column, means followed by the same letter are not significantly different at P= 0.05 level.

Table 5. Response of near-infrared (NIR), red (R), and green (G) bands measured at V7 to N applied at planting (N_{PL}) analyzed by year.

N_{PL}	Digital Number (DN)		
	NIR	Red	Green
kg ha^{-1}			
	2002		
0	181a†	157a	179a
56	182a	157a	178a
112	181a	149b	171b
224	180a	147b	170b
	2003		
0	110a	105a	108a
56	114b	94b	99b
112	117bc	86c	92c
224	118c	83c	90c

†Within a column, means followed by the same letter are not significantly different at P= 0.05 level.

Table 6. Regression analysis of V7 plant biomass, plant N concentration, and total N uptake versus near-infrared (NIR), red (R), green (G), and various spectral indices. The model significance and the coefficients of determination (r^2 or R^2) for the linear (L) and quadratic (Q) models are given.

	Biomass						Plant N concentration						Total N uptake					
	All data		2002		2003		All data		2002		2003		All data		2002		2003	
Indices	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q
	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2
NIR	0.24**	0.57**	0.67**	0.76**	0.40**	NS	0.14*	NS	NS	NS	0.42**	NS	0.27**	0.56**	0.48**	NS	0.45**	NS
Red	NS	0.15*	0.85**	NS	0.58**	NS	NS	0.21**	NS	NS	0.55**	NS	NS	NS	0.75**	NS	0.57**	NS
Green	NS	0.55**	0.82**	0.90**	0.77**	NS	NS	NS	NS	NS	0.69**	NS	NS	0.40**	0.73**	NS	0.75**	NS
Norm NIR	0.21*	NS	0.70**	0.79**	0.57**	NS	0.12*	NS	NS	NS	0.55**	NS	0.25*	NS	0.69**	NS	0.59**	NS
Norm Red	0.42**	NS	0.75**	0.83**	0.47**	NS	NS	NS	NS	NS	0.47**	NS	0.43**	NS	0.71**	NS	0.49**	NS
Norm Green	NS	NS	NS	0.42**	0.76**	NS	0.12*	NS	NS	NS	0.72**	NS	NS	NS	0.18*	0.45**	0.76**	NS
Rel NIR	0.10*	0.20*	0.21*	NS	0.34**	NS	0.21**	NS	NS	NS	0.36**	NS	0.13*	0.23*	0.19*	NS	0.35**	NS
Rel Red	0.15*	NS	NS	NS	0.54**	NS	0.39**	NS	NS	NS	0.50**	NS	0.21**	NS	NS	NS	0.52**	NS
Rel Green	0.16**	NS	NS	NS	0.57**	NS	0.40**	NS	0.17*	NS	0.50**	NS	0.22**	NS	NS	NS	0.55**	NS
DVI	0.47**	NS	0.80**	0.86**	0.52**	NS	NS	NS	NS	NS	0.51**	NS	0.48**	NS	0.75**	NS	0.53**	NS
RDVI	0.23**	NS	0.20*	NS	0.57**	NS	0.41**	NS	NS	NS	0.55**	NS	0.30**	NS	0.28**	0.44**	0.55**	NS
GDVI	0.20**	NS	0.73**	0.82**	0.61**	NS	NS	NS	NS	NS	0.60**	NS	0.23**	NS	0.72**	NS	0.62**	NS
RGDVI	0.18**	NS	NS	NS	0.56**	NS	0.44**	NS	0.23*	NS	0.52**	NS	0.25**	NS	NS	NS	0.54**	NS
RVI	0.31**	NS	0.65**	0.76**	0.52**	NS	0.10*	NS	NS	NS	0.49**	NS	0.35**	NS	0.65**	NS	0.55**	NS
RRVI	0.14*	NS	NS	NS	0.48**	NS	0.38**	NS	NS	NS	0.49**	NS	0.20**	NS	NS	NS	0.49**	NS
GRVI	NS	0.17*	0.63**	0.73**	0.63**	NS	0.14**	NS	NS	NS	0.60**	NS	0.11*	NS	0.65**	NS	0.65**	NS
RGRVI	0.16**	NS	NS	NS	0.51**	NS	0.40**	NS	0.22*	NS	0.49**	NS	0.22**	NS	NS	NS	0.51**	NS
NDVI	0.32**	NS	0.73**	0.82**	0.52**	NS	0.10*	NS	NS	NS	0.51**	NS	0.35**	NS	0.71**	NS	0.53**	NS

RNDVI	0.19**	NS	NS	NS	0.57**	NS	0.43**	NS	NS	NS	0.56**	NS	0.25**	NS	NS	NS	0.55**	NS
GNDVI	0.10*	NS	0.67**	0.77**	0.62**	NS	0.13*	NS	NS	NS	0.61**	NS	0.13*	NS	0.67**	NS	0.64**	NS
RGNDVI	0.17	NS	NS	NS	0.57**	NS	0.43**	NS	0.23	NS	0.53**	NS	0.24**	NS	NS	NS	0.55**	NS
SAVI	0.32**	NS	0.73**	0.82**	0.52**	NS	0.10*	NS	NS	NS	0.51**	NS	0.35**	NS	0.70**	NS	0.53**	NS
RSAVI	0.19**	NS	NS	NS	0.58**	NS	0.44*	NS	NS	0.31**	0.57**	NS	0.26**	NS	NS	NS	0.56**	NS
GSAVI	0.10*	NS	0.67**	0.77**	0.62**	NS	0.13*	NS	NS	NS	0.61**	NS	0.13*	NS	0.67**	NS	0.64**	NS
RGSAVI	0.18**	NS	NS	NS	0.59**	NS	0.44**	NS	0.24*	NS	0.55**	NS	0.24**	NS	NS	NS	0.56**	NS
OSAVI	0.32**	NS	0.73**	0.82**	0.52**	NS	0.10*	NS	NS	NS	0.51**	NS	0.35**	NS	0.70**	NS	0.53**	NS
ROSAVI	0.19**	NS	NS	NS	0.57**	NS	0.43**	NS	NS	NS	0.56**	NS	0.25**	NS	NS	NS	0.55**	NS
GOSAVI	0.10*	NS	0.67**	0.77**	0.62**	NS	0.13*	NS	NS	NS	0.61**	NS	0.13*	NS	0.67**	NS	0.63**	NS
RGOSAVI	0.18**	NS	NS	NS	0.57*	NS	0.43**	NS	0.23*	NS	0.53	NS	0.24**	NS	NS	NS	0.55**	NS

*, **, NS Significant at the 0.05, and 0.01 probability levels and not significant, respectively.

Table 7. ANOVA for VT corn biomass, plant N concentration, total N uptake, near-infrared (NIR), red (R), green (G), and grain yield as affected by year and fertilizer N applied at planting (N_{PL})

						Digital Number (DN)		
Source of Variation	df	Biomass	Plant N concentration	Total N uptake	Grain yield	NIR	Red	Green
				Non-Irrigated				
Year	1	NS	NS	NS	NS	**	*	**
N_{PL}	3	**	**	**	**	NS	**	**
Year × N_{PL}	3	NS	NS	NS	NS	NS	NS	NS
				Irrigated				
Year	1	NS	NS	NS	NS	*	NS	NS
N_{PL}	3	*	*	*	*	NS	**	**
Year × N_{PL}	3	NS	NS	NS	*	**	NS	NS

*, **, NS Significant at the 0.05, and 0.01probability levels and not significant, respectively.

Table 8. Response of VT corn biomass, plant N concentration, total N uptake, near-infrared (NIR), red (R) and green (G) bands, and grain yield to N fertilizer at planting (N_{PL}) under irrigated and non-irrigated conditions across 2000 and 2001.

					Digital Number (DN)		
N_{PL}	Biomass	N Conc.	N uptake	Grain Yield	NIR	Red	Green
kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	Mg ha^{-1}			
			Non-Irrigated				
0	3141a	16.4a	52.1a	4.7a	156a	131a	146a
112	4300b	17.5ab	75.7b	7.1b	156a	113b	133b
168	4307b	18.6b	80.2b	8.0b	153a	98c	123c
224	4389b	20.6c	90.3b	9.0c	153a	102c	123c
			Irrigated				
0	2906a	14.2a	41.9a	3.8a	159a	159a	164a
112	4115b	16.0ab	66.4b	7.6b	159a	131b	146b
168	4506b	18.6bc	84.6bc	8.2b	160a	127b	145b
224	4770b	19.7c	93.3c	9.6b	159a	118c	140c

†Within a column, means followed by the same letter are not significantly different at P= 0.05 level.

Table 9. Regression analysis of VT plant biomass, plant N concentration, and total N uptake versus near-infrared (NIR), red (R), green (G), and various spectral indices under non-irrigated conditions. The model significance and the coefficients of determination (r^2 or R^2) for the linear (L) and quadratic (Q) models are given.

	Biomass						Plant N Concentration						Total N uptake					
	All data		2000		2001		All data		2000		2001		All data		2000		2001	
Indices	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q
	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2
NIR	0.48**	NS	0.45**	NS	NS	NS	NS	0.23*	0.54**	0.55**	NS	NS	0.21*	NS	0.60**	NS	NS	NS
Red	0.65**	NS	0.70**	NS	0.34**	0.23*	NS	NS	0.73**	NS	NS	NS	0.39**	NS	0.85**	NS	NS	NS
Green	0.59**	NS	0.65**	NS	0.43*	NS	NS	0.31*	0.75**	NS	NS	NS	0.35**	0.45*	0.84**	NS	NS	NS
Norm NIR	0.58**	0.66*	0.59**	0.70*	NS	NS	NS	NS	0.68**	NS	NS	NS	0.56**	NS	0.78**	NS	NS	NS
Norm Red	0.61**	NS	0.67**	NS	NS	NS	NS	NS	0.70**	NS	NS	NS	0.56**	NS	0.83**	NS	NS	NS
Norm Green	0.38**	NS	0.38**	NS	NS	NS	NS	NS	0.55**	NS	NS	NS	0.39**	NS	0.58**	NS	NS	NS
Rel NIR	NS	NS	NS	NS	0.52**	NS	NS	NS	NS	NS	NS	NS	0.18*	NS	NS	NS	0.36*	NS
Rel Red	NS	NS	NS	NS	0.38*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.46*	NS
Rel Green	NS	NS	NS	NS	0.35*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.45*	NS
DVI	0.39**	NS	0.68**	NS	NS	0.55*	NS	NS	0.68**	NS	NS	NS	0.38**	NS	0.82**	NS	NS	NS
RDVI	0.22*	0.36*	NS	NS	0.50*	NS	NS	NS	NS	NS	NS	NS	0.26**	NS	NS	NS	0.52**	NS
GDVI	0.55**	NS	0.55**	NS	NS	NS	NS	NS	0.64**	NS	NS	NS	0.52**	NS	0.74**	NS	NS	NS
RGDVI	NS	NS	NS	NS	NS	NS	0.15*	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.39*	NS
RVI	0.52**	0.63*	0.53**	0.70*	NS	NS	NS	NS	0.64**	NS	NS	NS	0.54**	NS	0.73**	0.83**	NS	NS
RRVI	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.44*	NS
GRVI	0.49**	0.62**	0.48**	0.63**	NS	NS	NS	NS	0.63**	NS	NS	NS	0.51**	NS	0.69**	0.78*	NS	NS
RGRVI	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.34*	NS	NS	NS	NS	NS	0.36*	NS

NDVI	0.62**	NS	0.65**	NS	NS	NS	NS	NS	0.70**	NS	NS	NS	0.57**	NS	0.82**	NS	NS	NS
RNDVI	NS	NS	NS	NS	0.46*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.46*	NS
GNDVI	0.56**	0.63*	0.55**	NS	NS	NS	NS	NS	0.67**	NS	NS	NS	0.53**	NS	0.75**	NS	NS	NS
RGNDVI	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.35*	NS
SAVI	0.62**	NS	0.65**	NS	NS	NS	NS	NS	0.70**	NS	NS	NS	0.57**	NS	0.82**	NS	NS	NS
RSAVI	NS	NS	NS	NS	0.39*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.47*	NS
GSAVI	0.56**	0.63*	0.55**	NS	NS	NS	NS	NS	0.67**	NS	NS	NS	0.53**	NS	0.75**	NS	NS	NS
RGSAVI	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.35*	NS
OSAVI	0.62**	NS	0.65**	NS	NS	NS	NS	NS	0.70**	NS	NS	NS	0.57**	NS	0.82**	NS	NS	NS
ROSAVI	NS	NS	NS	NS	0.37*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.46*	NS
GOSAVI	0.56**	0.63*	0.55**	NS	NS	NS	NS	NS	0.67**	NS	NS	NS	0.53**	NS	0.75**	NS	NS	NS
RGOSAVI	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.35*	NS

*, **, NS Significant at the 0.05, and 0.01 probability levels and not significant, respectively.

Table 10. Regression analysis of VT plant biomass, plant N concentration, and total N uptake versus near-infrared (NIR), red (R), green (G), and the various spectral indices under irrigated conditions. The model significance and the coefficients of determination (r^2 or R^2) for the linear (L) and quadratic (Q) models are given.

	Biomass						Plant N concentration						Total N uptake					
	All data		2000		2001		All data		2000		2001		All data		2000		2001	
Indices	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q
	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2	r^2	R^2
NIR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.78*	NS	NS	NS	NS	NS	NS
Red	0.44**	NS	0.80**	NS	NS	NS	NS	NS	0.74**	0.86*	NS	NS	NS	NS	0.92**	NS	NS	NS
Green	0.36**	NS	0.62**	0.87**	NS	NS	NS	0.44**	0.86**	NS	NS	NS	NS	0.36*	0.94**	NS	NS	NS
Norm NIR	0.60**	NS	0.79**	NS	NS	NS	0.30*	NS	0.74**	0.88**	NS	NS	0.55**	NS	0.91**	NS	NS	NS
Norm Red	0.36**	NS	0.85**	NS	NS	NS	NS	NS	0.58*	NS	NS	NS	0.26*	NS	0.80**	NS	NS	NS
Norm Green	0.33*	NS	0.55*	0.82*	NS	NS	0.33*	NS	0.89**	NS	NS	0.86*	0.45**	NS	0.92**	NS	NS	0.78*
Rel NIR	NS	NS	0.72**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.50*	NS	NS	NS
Rel Red	0.52**	NS	0.66**	NS	0.93**	NS	0.45**	NS	0.46**	NS	NS	NS	0.57**	NS	0.63**	NS	0.71**	NS
Rel Green	NS	NS	NS	NS	0.93**	NS	0.25*	NS	NS	NS	NS	NS	0.22*	NS	NS	NS	0.68*	NS
DVI	0.43**	NS	0.85**	NS	NS	NS	NS	NS	0.58*	NS	NS	NS	0.33*	NS	0.80**	0.90*	NS	NS
RDVI	0.65**	NS	0.83*	NS	0.94**	NS	0.42**	NS	0.49*	NS	NS	NS	0.64**	NS	0.71**	NS	0.69**	NS
GDVI	0.69**	NS	0.80**	NS	0.69*	NS	0.40**	NS	0.73**	0.90*	NS	NS	0.68**	NS	0.90**	0.95*	NS	NS
RGDVI	0.38**	NS	0.72**	NS	0.81**	NS	0.46**	NS	0.45**	NS	0.57**	NS	0.49**	NS	0.64**	NS	0.77**	NS
RVI	0.47**	NS	0.80**	NS	NS	NS	NS	NS	0.72**	NS	NS	NS	0.40**	NS	0.90**	NS	NS	NS
RRVI	0.48**	NS	0.76**	NS	0.87**	NS	0.51**	NS	0.51*	NS	NS	NS	0.59**	NS	0.71**	NS	0.78**	NS
GRVI	0.59**	NS	0.71*	0.86*	0.59*	NS	0.38**	NS	0.83**	NS	NS	NS	0.63**	NS	0.95**	NS	NS	NS
RGRVI	NS	NS	0.56*	NS	0.74**	NS	0.39**	NS	NS	NS	0.61*	NS	0.31*	NS	0.54*	NS	0.75**	NS

NDVI	0.50**	NS	0.83**	NS	NS	NS	NS	NS	0.66**	NS	NS	NS	0.41**	NS	0.86**	NS	NS	NS
RNDVI	0.49**	NS	0.79**	NS	0.91**	NS	0.47**	NS	0.49**	NS	NS	NS	0.57**	NS	0.71*	NS	0.76**	NS
GNDVI	0.62**	NS	0.76**	NS	0.61*	NS	0.38**	NS	0.78**	0.91*	NS	NS	0.64**	NS	0.93**	NS	NS	NS
RGNDVI	NS	NS	0.63**	NS	0.74**	NS	0.40**	NS	0.41*	NS	0.60*	NS	0.34*	NS	0.58*	NS	0.75**	NS
SAVI	0.50**	NS	0.83**	NS	NS	NS	NS	NS	0.66**	NS	NS	NS	0.41**	NS	0.86**	NS	NS	NS
RSAVI	0.50**	NS	0.80**	NS	0.92**	NS	0.47**	NS	0.49*	NS	NS	NS	0.57**	NS	0.71**	NS	0.75**	NS
GSAVI	0.62**	NS	0.76**	NS	0.61*	NS	0.38**	NS	0.78**	0.91*	NS	NS	0.64**	NS	0.93**	NS	NS	NS
RGSAVI	0.23*	NS	0.65**	NS	0.74**	NS	0.41**	NS	0.42*	NS	0.60*	NS	0.36**	NS	0.59**	NS	0.75**	NS
OSAVI	0.50**	NS	0.83**	NS	NS	NS	NS	NS	0.66**	NS	NS	NS	0.41**	NS	0.86**	NS	NS	NS
ROSAVI	0.49**	NS	0.79**	NS	0.91**	NS	0.47**	NS	0.49*	NS	NS	NS	0.57**	NS	0.71**	NS	0.76**	NS
GOSAVI	0.62**	NS	0.76**	NS	0.61*	NS	0.38**	NS	0.78**	0.91*	NS	NS	0.64**	NS	0.93**	NS	NS	NS
RGOSAVI	NS	NS	0.63**	NS	0.74**	NS	0.40**	NS	0.41*	NS	0.60*	NS	0.34*	NS	0.58*	NS	0.75**	NS

*, **, NS Significant at the 0.05, and 0.01 probability levels and not significant, respectively.

Table 11. Regression analysis of VT plant biomass, plant N concentration, and total N uptake versus the relative spectral indices under both irrigated and non-irrigated conditions. The model significance and the coefficients of determination (r^2 or R^2) for the linear and quadratic models are given.

	Biomass		Plant N concentration		Total N uptake	
Indices	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic
	r^2	R^2	r^2	R^2	r^2	R^2
Rel NIR	NS	0.14*	NS	NS	NS	0.14*
Rel Red	NS	NS	0.15**	0.26**	0.14*	NS
Rel Green	NS	NS	NS	0.19*	NS	NS
RDVI	0.38**	NS	0.29**	NS	0.43**	NS
RGDVI	0.12*	NS	0.31**	NS	024**	NS
RRVI	NS	NS	0.23*	NS	0.17**	NS
RGRVI	NS	NS	0.14*	0.26*	NS	NS
RNDVI	0.17*	NS	0.29**	NS	0.29**	NS
RGNDVI	NS	NS	0.19**	0.28*	NS	NS
RSAVI	0.20**	NS	0.30**	NS	0.31**	NS
RGSAVI	NS	NS	0.21**	0.29*	0.10*	NS
ROSAVI	0.18*	NS	0.29**	NS	0.29**	NS
RGOSAVI	NS	NS	0.19**	0.28**	NS	NS

*, **, NS Significant at the 0.05, and 0.01 probability levels and not significant, respectively.

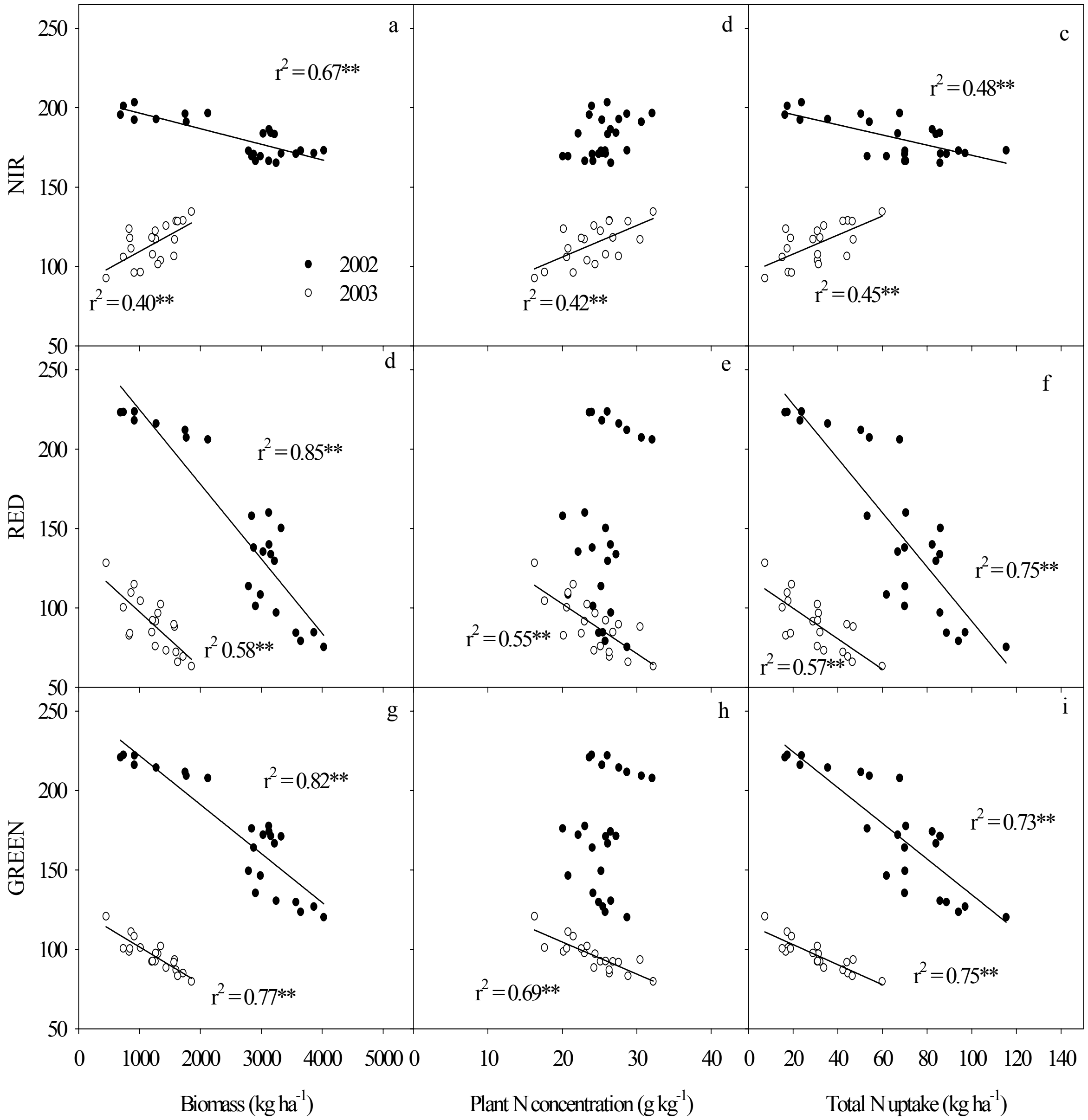


Fig. 1. Relationships of V7 biomass, plant N concentration, and total N uptake with near-infrared (NIR), red (R), and green (G) spectral bands in 2002 and 2003. Significant regression lines are shown with their coefficients of determination.

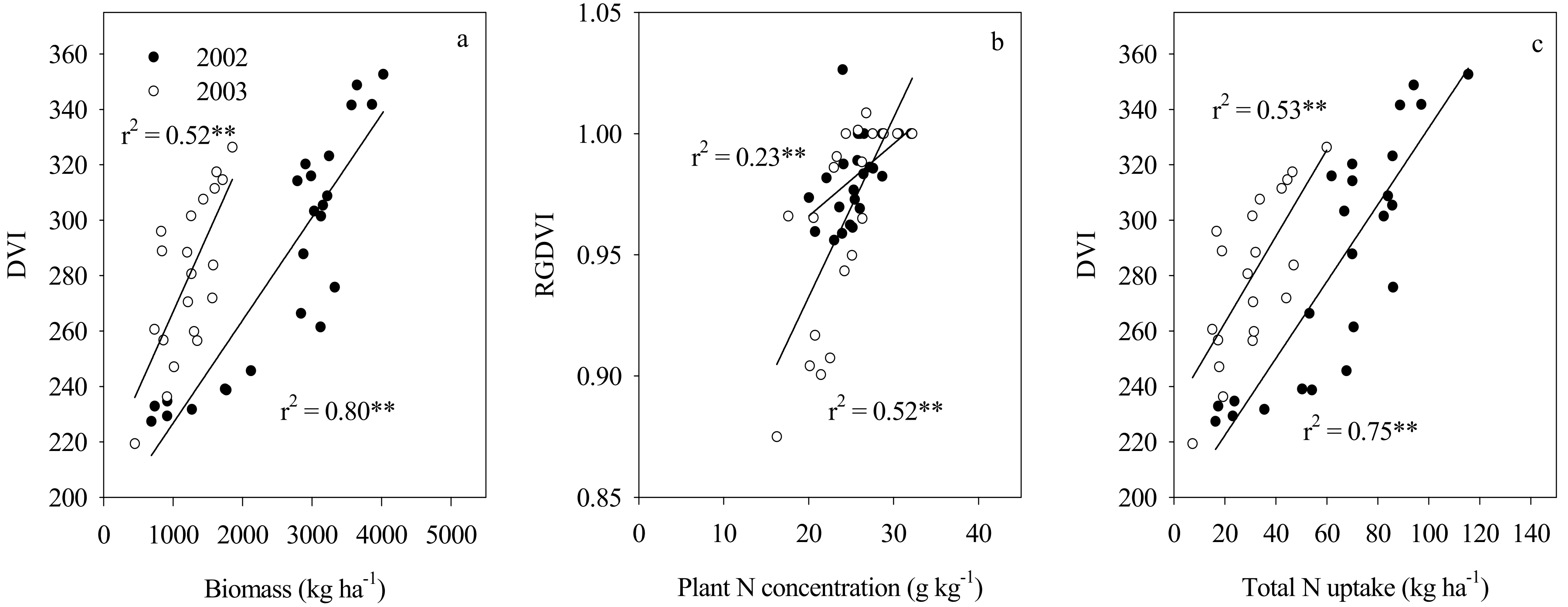


Fig. 2. Relationships of (a) corn biomass with the difference vegetation index (DVI), (b) plant N concentration with the relative green difference vegetation index (RGDVI), and (c) total N uptake with the DVI at V7 in 2002 and 2003. Significant regression lines are shown with their coefficients of determination.

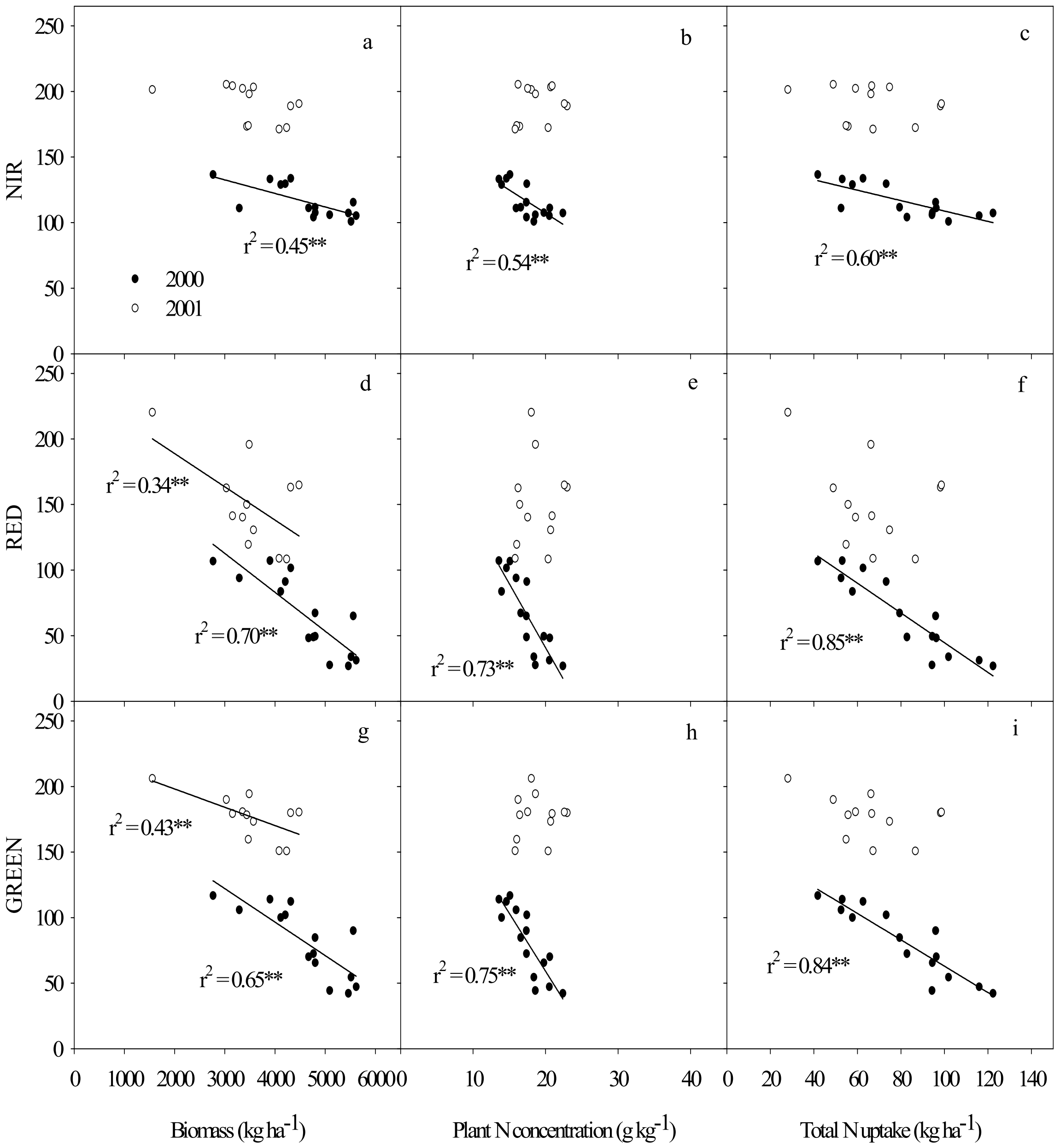


Fig. 3. Relationships of VT biomass, plant N concentration, and total N uptake with near-infrared (NIR), red (R), and green (G) spectral bands for the non-irrigated study in 2000 and 2001. Significant regression lines are shown with their coefficients of determination.

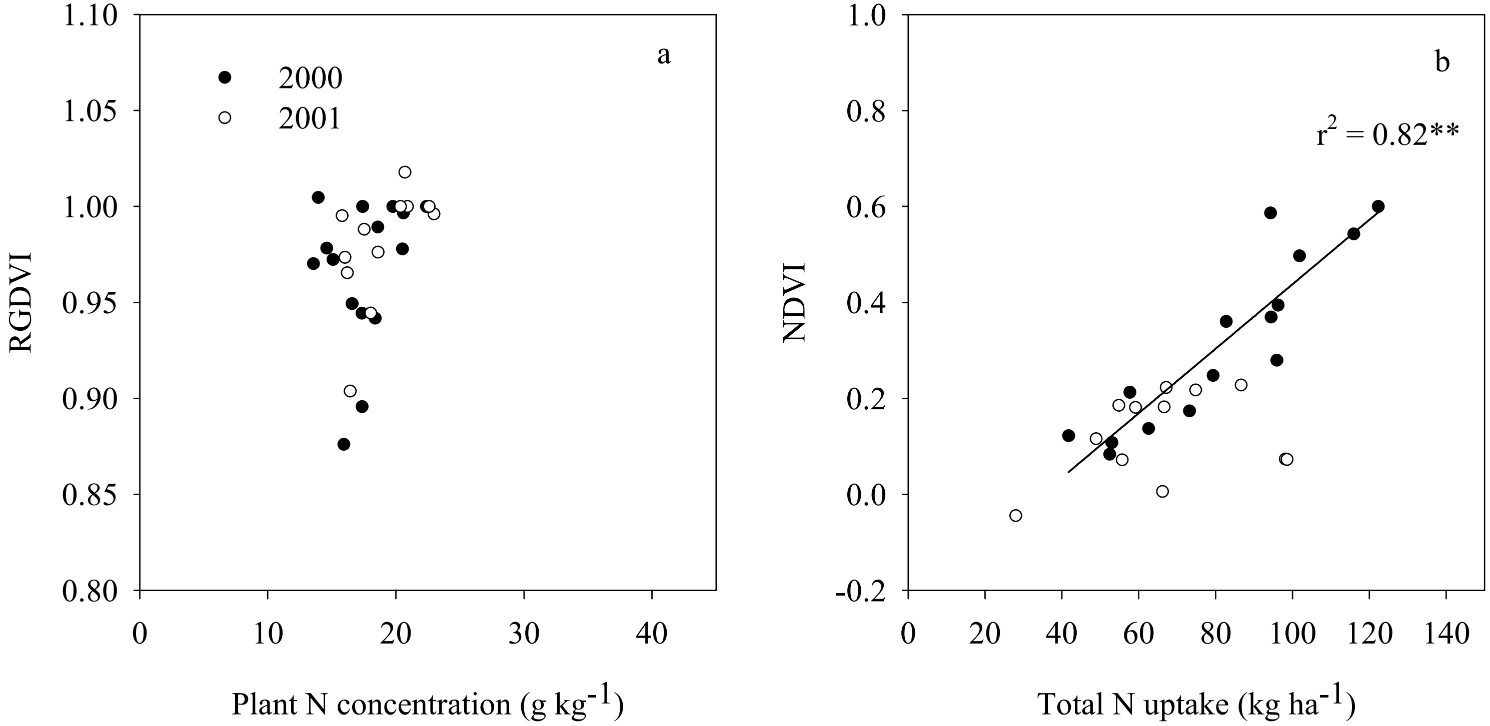


Fig. 4. Relationships of (a) VT corn plant N concentration with relative green difference vegetation index (RGDVI), and (b) total N uptake with normalized difference vegetation index (NDVI) at VT for the non-irrigated study in 2000 and 2001. Significant regression lines are shown with their coefficients of determination.

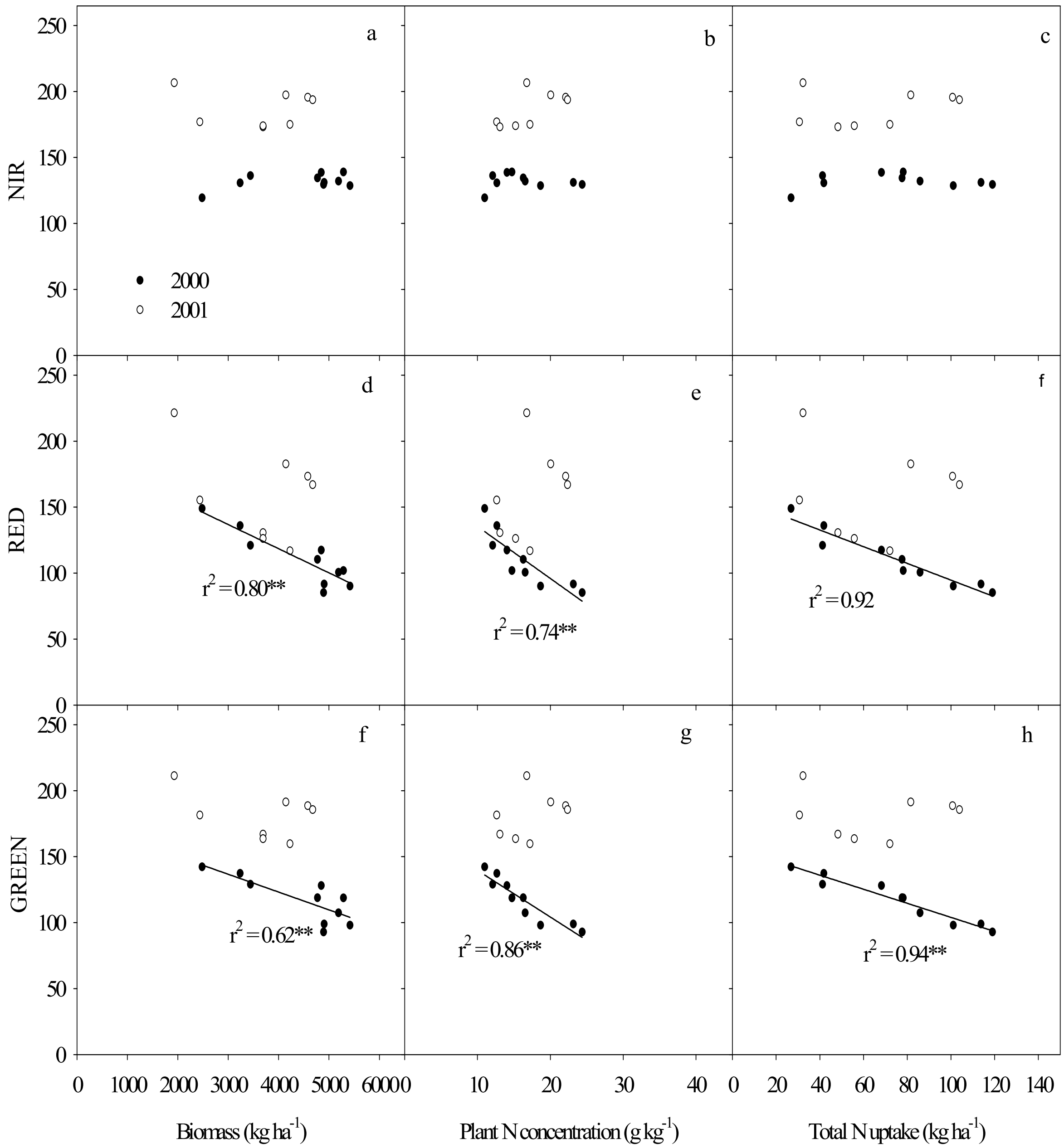


Fig. 5. Relationships of VT biomass, plant N concentration, and total N uptake with near-infrared (NIR), red (R), and green (G) spectral bands for the irrigated study in 2000 and 2001. Significant regression lines are shown with their coefficients of determination.

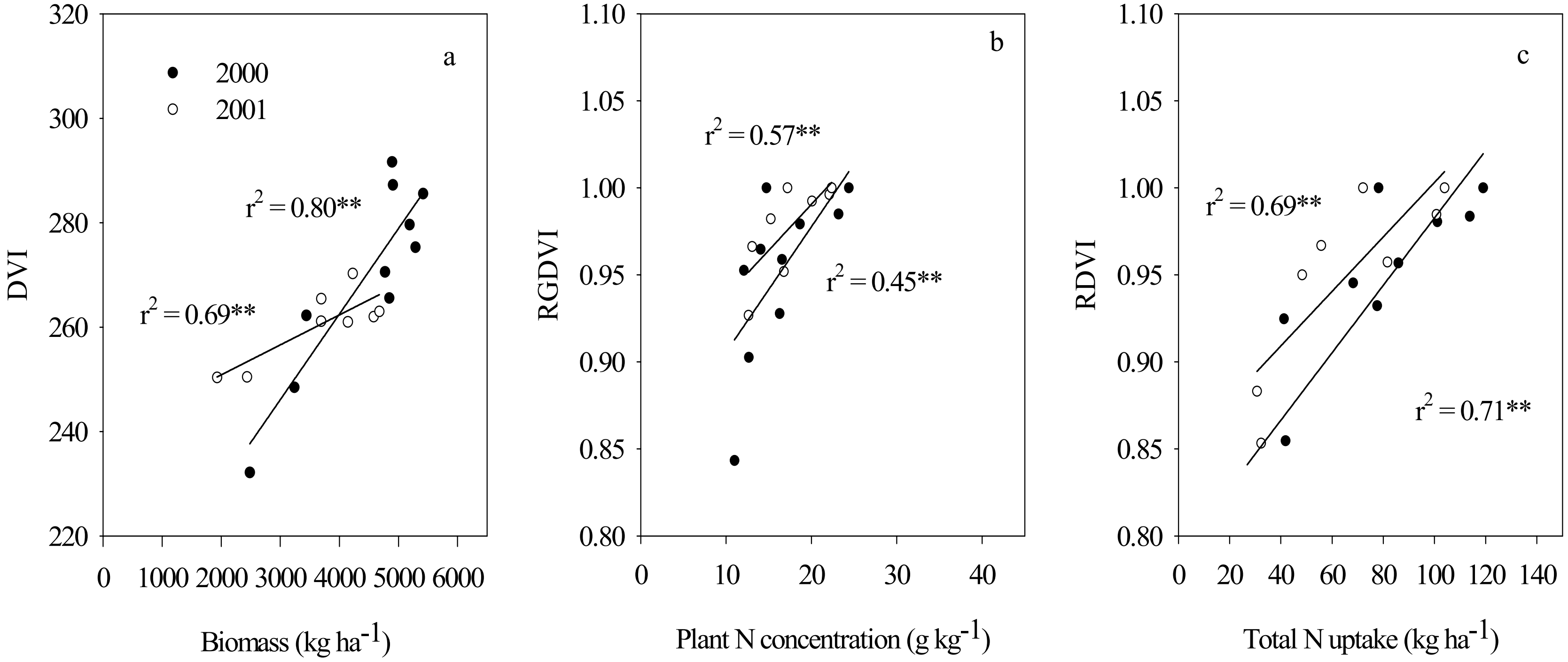


Fig. 6. Relationships of (a) corn biomass with green difference vegetation index (GDVI), (b) plant N concentration with relative green difference vegetation index (RGDVI), and (c) total N uptake with relative difference vegetation index (RDVI) at VT for the irrigated study in 2000 and 2001. Significant regression lines are shown with their coefficients of determination.

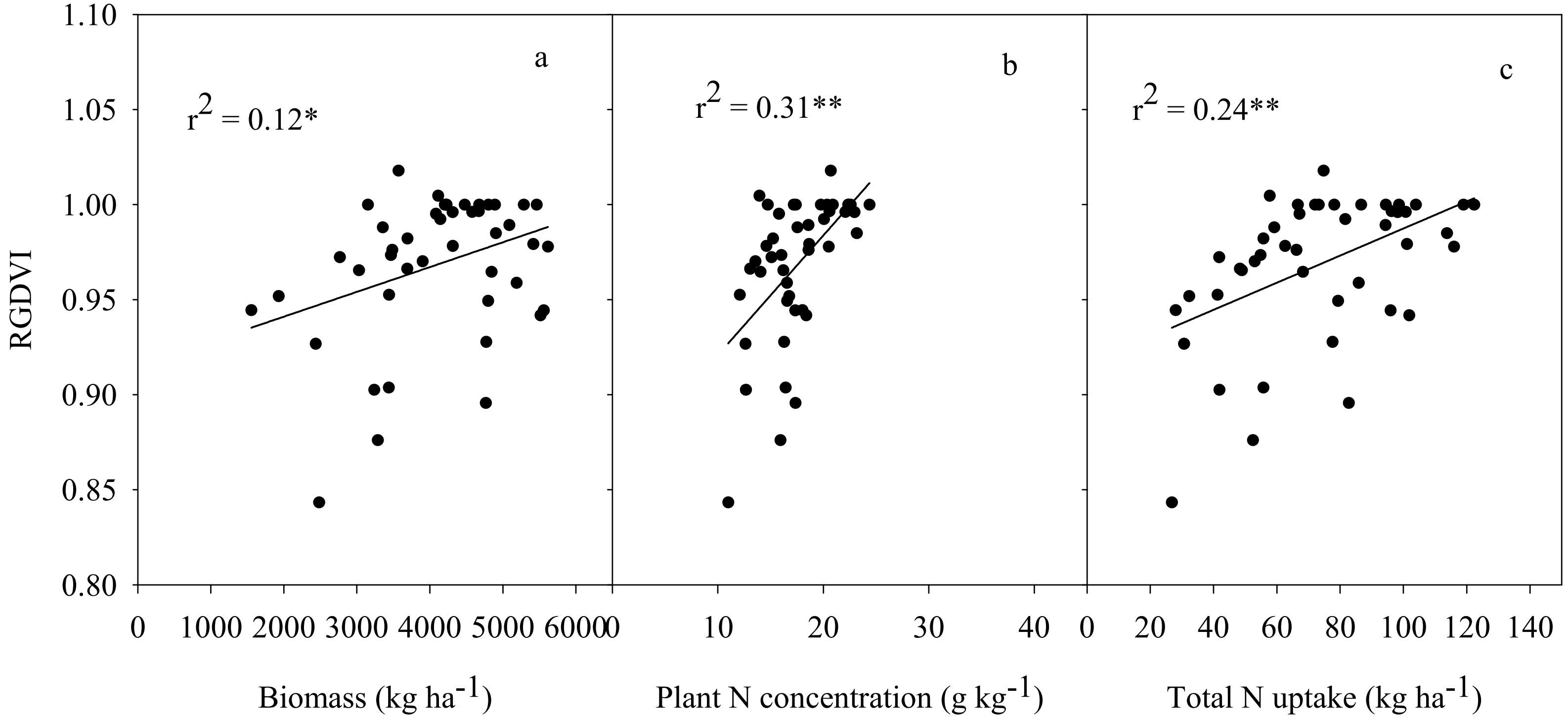


Fig. 7. Relationships of VT corn biomass, plant N concentration, and total N uptake with the relative green difference vegetation index (RGDVI) across irrigated and non-irrigated experiments in 2000 and 2001.

APPENDICES

Appendix A. Table of the optimum N rate, mean grain yield, chlorophyll meter reading, total biomass, plant N concentration, total N uptake and the corresponding near-infrared (NIR), red (R), and green (G) spectral values observed for different N rates at planting (N_{PL}) at different experimental sites during 2000 - 2003.

												Digital Number (DN)		
Site[†]	Year	Location[‡]	Irrigation[§]	n	N_{PL}	Optimum N rate[¶]	Grain yield	CI[#]	Biomass	Plant N concentration	Total N uptake	NIR	Red	Green
					kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}		kg ha^{-1}	g kg^{-1}	kg ha^{-1}			
1	2000	PBRS	IR	3	0	200	5.48	41.7	4771	16.3	77.6	134.4	110.3	118.9
				3	56	-	8.18	43.8	5189	16.5	85.9	132.0	100.6	107.4
				3	112	88	9.55	45.9	5416	18.7	101.1	128.6	90.1	98.1
				3	168	119	9.98	46.3	4904	23.2	113.8	131.1	91.6	98.9
				3	224	0	10.58	49.0	4892	24.4	119.0	129.5	85.1	92.9
2	2000	DEN	NI	3	0	145	2.88	36.9	2767	15.1	41.8	136.6	106.8	116.8
				3	56	106	5.97	43.4	3901	13.6	53.0	133.2	107.3	114.0
				3	112	73	5.85	43.7	4314	14.6	62.6	133.8	101.6	112.3
				3	168	43	3.62	39.0	4116	13.9	57.7	128.9	83.7	100.0
				3	224	0	6.17	46.7	4206	17.4	73.2	129.6	91.2	102.0
3	2000	HSOR	NI	3	0	170	7.76	48.4	4767	17.4	82.8	104.1	49.0	72.5
				3	56	159	9.86	49.8	5515	18.4	101.9	100.9	33.9	54.5
				3	112	119	9.99	50.7	5617	20.5	116.0	105.2	31.2	47.3
				3	168	0	11.69	50.3	5088	18.6	94.3	106.0	27.6	44.4
				3	224	0	11.88	54.3	5463	22.4	122.4	107.3	26.8	42.2
4	2000	HSSR	NI	3	0	209	3.27	38.2	3288	15.9	52.5	111.1	93.9	105.9
				3	56	140	5.58	44.0	4798	16.6	79.4	111.7	67.3	84.7
				3	112	129	5.14	44.2	5559	17.3	96.0	115.5	65.0	90.0
				3	168	0	5.04	44.5	4671	20.6	96.3	111.1	48.3	70.1
				3	224	0	7.07	45.0	4803	19.8	94.5	107.5	49.5	65.5
5	2000	TRS	IR	3	0	203	2.31	31.0	2485	11.0	26.8	119.4	148.8	142.3

				3	56	200	1.97	33.3	3238	12.7	41.8	130.7	136.0	137.3
				3	112	193	5.24	41.5	3441	12.1	41.3	136.3	121.0	129.1
				3	168	180	4.85	42.5	4846	14.0	68.2	138.6	117.4	128.1
				3	224	107	6.56	45.5	5286	14.7	78.2	139.0	101.8	118.7
6	2001	PBRS	IR	3	0	192	4.19	41.9	1930	16.8	32.3	206.7	221.3	211.3
				3	112		8.43	54.1	4143	20.1	81.6	197.3	182.7	191.3
				3	168	145	10.77	57.1	4580	22.1	100.8	195.7	173.3	188.7
				3	224	116	11.57	57.2	4676	22.4	103.9	193.7	167.0	185.7
7	2001	PBRS	NI	3	0	217	3.17	35.8	1557	18.0	28.0	201.5	220.3	206.1
				3	112	184	5.85	47.3	3486	18.6	66.2	198.1	195.8	194.3
				3	168	84	9.18	56.9	4312	23.0	98.2	189.0	163.1	179.9
				3	224	0	9.49	55.6	4480	22.6	98.6	190.6	164.8	180.5
8	2001	HSOR	NI	3	0	224	5.00	43.2	3030	16.2	48.9	205.3	162.7	190.0
				3	112	168	7.56	50.7	3354	17.5	59.2	202.3	140.3	180.7
				3	168	0	9.33	48.7	3571	20.7	74.8	203.3	130.7	173.3
				3	224	0	10.54	48.4	3153	20.9	66.6	204.3	141.3	179.3
9	2001	TRS	IR	3	0	224	3.18	36.5	2438	12.6	30.7	177.0	155.4	181.5
				3	112	171	7.10	45.0	3690	13.1	48.3	173.1	130.6	167.0
				3	168	0	7.11	47.6	3692	15.2	55.8	174.0	126.2	163.6
				3	224	0	9.22	45.6	4227	17.2	72.1	175.1	116.9	159.8
10	2001	TRS	NI	3	0	168	5.80	33.0	3438	16.4	55.7	173.3	150.1	178.3
				3	112	112	7.82	43.6	3468	16.0	54.8	174.0	119.5	159.7
				3	168	112	8.98	44.6	4082	15.8	67.2	171.3	108.9	151.0
				3	224	0	9.03	48.8	4230	20.4	86.7	172.4	108.4	150.8
11	2002	PBRS	IR	4	0	218	3.25	32.9	736	23.9	17.4	201.2	223.3	222.5
				5	56	154	3.48	38.9	915	26.0	23.7	203.3	223.7	222.1
				5	112	119	7.19	45.1	1748	28.7	50.3	196.2	212.1	211.7
				4	224	94	9.50	48.6	2121	32.1	67.7	196.6	206.0	207.9
12	2002	PBRS	NI	3	0	115	2.32	34.9	687	23.6	16.3	195.5	223.2	221.0
				4	56	119	3.96	39.1	914	25.3	23.1	192.4	218.1	216.2
				5	112	0	4.86	43.6	1271	27.6	35.5	192.8	216.1	214.5

				3	224	0	5.09	46.1	1767	30.6	54.2	191.1	207.4	209.3
13	2002	TRS	IR	4	0	79	7.36	48.8	2984	20.8	61.8	169.4	108.4	146.5
				4	56	127	8.06	50.3	2789	25.2	70.0	172.9	113.7	149.4
				4	112	0	9.49	52.1	2905	24.1	69.9	166.5	101.2	135.5
				3	224	0	10.50	53.1	3244	26.5	85.7	165.3	97.1	130.7
14	2002	TRS	NI	4	0	117	8.07	47.2	3028	22.1	66.8	183.7	135.5	172.1
				3	56	0	10.20	49.2	3157	27.2	85.7	184.2	133.8	171.4
				4	112	0	9.49	48.3	3127	26.5	82.3	186.3	139.9	174.3
				4	224	0	10.69	51.0	3217	26.1	84.0	183.3	129.6	166.7
15	2002	TRS	IR	3	0	103	6.71	45.3	3566	24.9	88.7	170.9	84.4	129.8
				3	56	0	9.60	50.1	3862	25.4	97.0	171.4	84.6	126.9
				3	112	0	10.88	51.0	3645	25.7	94.1	173.0	79.2	123.6
				3	224	0	10.44	53.6	4025	28.7	115.4	173.1	75.4	120.3
16	2002	TRS	NI	3	0	115	3.08	41.5	3121	23.0	70.5	166.5	160.0	177.7
				3	56	0	3.98	44.9	2841	20.0	53.2	169.4	158.0	176.1
				3	112	0	5.26	45.6	2874	24.0	69.9	170.8	138.0	164.0
				3	224	0	4.02	47.7	3325	25.8	85.9	171.2	150.4	171.1
17	2003	PBRS	IR	4	0	155	2.68	30.0	450	16.3	7.3	92.7	128.4	120.9
				3	56	149	4.46	38.2	1012	17.6	17.7	96.5	104.4	101.1
				4	112	170	7.54	42.6	1347	23.3	30.9	103.9	102.4	102.1
				4	224	0	9.56	42.6	1301	24.4	31.3	101.5	96.7	97.3
18	2003	PBRS	NI	4	0	0	11.10	30.8	946	15.5	14.6	114.2	111.0	109.8
				4	56	0	10.10	36.5	1316	18.6	24.3	120.5	106.5	104.5
				4	112	0	8.05	41.9	1600	22.3	35.8	119.0	90.3	91.6
				4	224	0	9.52	45.2	2046	24.9	52.4	120.8	91.1	92.0
19	2003	TRS	IR	3	0	125	3.76	36.3	829	20.1	16.7	123.7	82.7	98.6
				4	56	64	6.67	44.0	1434	24.2	33.7	125.8	73.2	88.5
				4	112	56	8.50	47.5	1713	26.3	44.5	129.0	69.4	85.0
				4	224	75	10.39	49.3	1853	32.2	59.9	134.6	63.3	79.8
20	2003	TRS	NI	3	0	83	4.47	39.8	840	22.5	18.8	117.9	84.1	100.6
				3	56	76	5.11	42.6	1259	25.1	30.8	122.4	75.9	92.4

				3	112	59	9.06	47.3	1598	26.3	42.3	128.7	72.2	87.1
				4	224	0	10.17	49.3	1625	28.8	46.5	128.5	66.1	83.3
21	2003	TRS	IR	4	0	118	3.00	35.8	861	20.8	17.3	111.4	109.6	111.1
				4	56	75	4.80	41.6	1265	23.0	28.9	117.3	91.6	97.7
				4	112	133	7.51	45.5	1201	26.8	32.0	118.2	84.8	92.4
				4	224	0	8.11	46.9	1576	30.4	46.9	117.0	88.2	93.5
22	2003	TRS	NI	3	0	72	2.37	35.6	732	20.6	15.1	105.9	100.3	100.6
				2	56	65	4.98	41.6	913	21.5	19.3	96.1	114.8	108.2
				3	112	112	6.77	45.6	1213	25.8	31.0	107.7	92.2	92.6
				3	224	0	8.20	47.7	1564	27.5	44.1	106.6	89.7	91.9

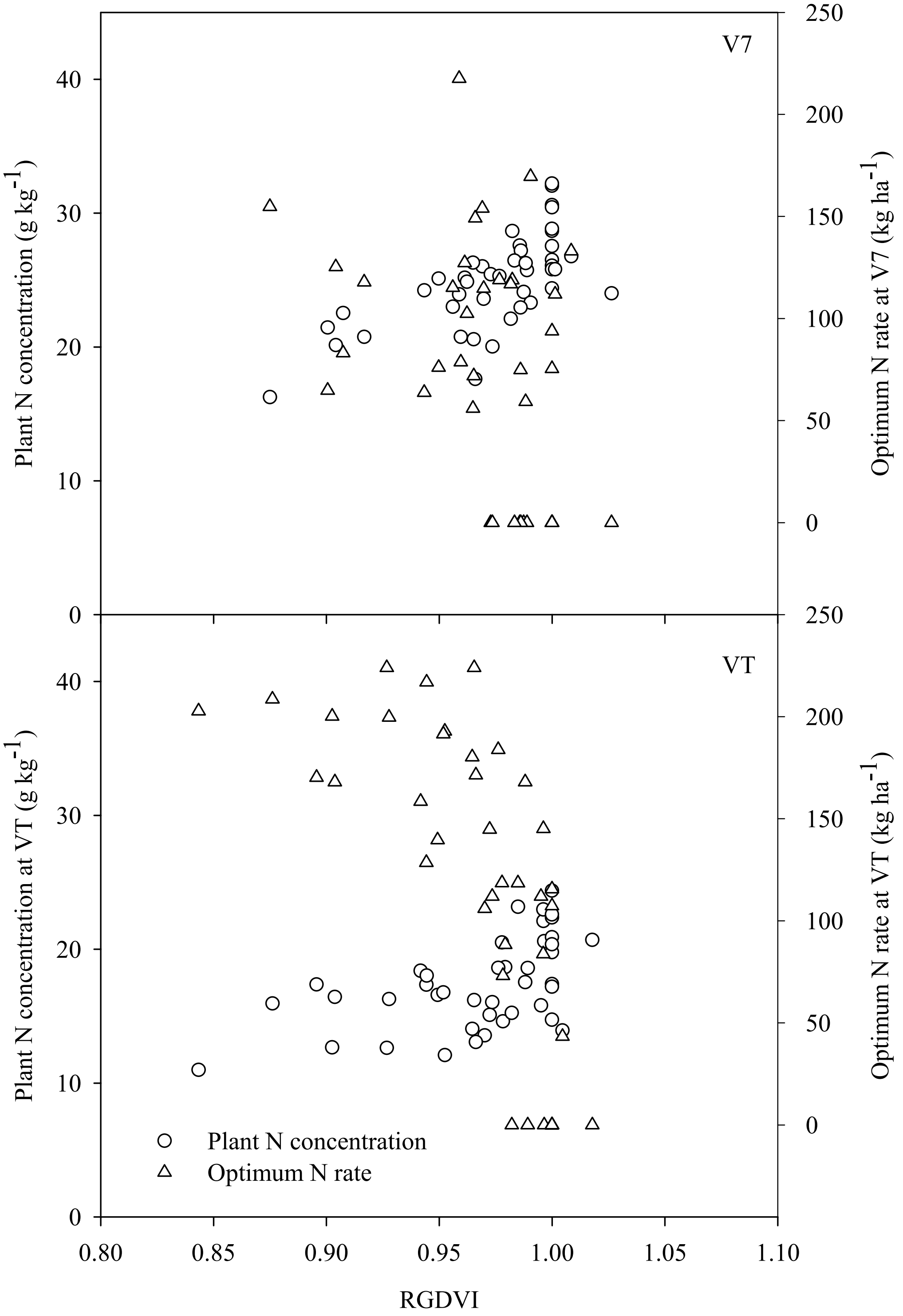
[†] Sites1-16 were used for VT Biomass analysis, sites 1-10 were used for the VT N uptake analysis, sites 1 - 10 were used for VT analysis, and sites 11 - 22 were used for V7 analysis.

[‡] PBRS, Peanut Belt Research Station. HSOR, Haslin Farms-Organic Ridge. HSSR, Haslin Farms-Sandy Ridge. TRS, Tidewater Research Station, DEN, Denton.

[§]IR: Irrigated; NI: Non-irrigated.

[¶] N_{V7}, optimum N rate at V7; N_{VT}, optimum N rate at VT

[#] CI, Chlorophyll Index measured with SPAD – 502 chlorophyll meter.



Appendix B. Relationship of relative green difference vegetation index (RGDVI) with corn plant N concentration and optimum N rate at V7 and VT during the 2000 to 2002 growing seasons.