Precision Agric (2010) 11:291–305
DOI 10.1007/s11119-009-9137-x

Within-field nitrogen response in corn related to aerial photograph color

J. D. Williams · N. R. Kitchen · P. C. Scharf · W. E. Stevens

Abstract Precise management of nitrogen (N) using canopy color in aerial imagery of corn (*Zea mays* L.) has been proposed as a strategy on which to base the rate of N fertilizer. The objective of this study was to evaluate the relationship between canopy color and yield response to N at the field scale. Six N response trials were conducted in 2000 and 2001 in fields with alluvial, claypan and deep loess soil types. Aerial images were taken with a 35-mm slide film from $\geq$1100 m at the mid- and late-vegetative corn growth stages and processed to extract green and red digital values. Color values of the control N (0 kg N ha^{-1}) and sufficient N (280 kg N ha^{-1} applied at planting) treatments were used to calculate the relative ratio of unfertilized to fertilized and relative difference color values. Other N fertilizer treatments included side-dressed applications in increments of 56 kg N ha^{-1}. The economic optimal N rate was weakly related ($R^2 \leq 0.34$) or not related to the color indices at both growth stages. For many sites, delta yield (the increase in yield between control N and sufficient N treatments) was related to the color indices ($R^2 \leq 0.67$) at the late vegetative growth stage; the best relationship was with green relative difference. The results indicate the potential for color indices from aerial photographs to be used for predicting delta yield from which a site-specific N rate could be determined.

Disclaimer: Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture or the University of Missouri.

J. D. Williams (✉)
Agribusiness, Plant and Animal Department, Brigham Young University, Idaho, Rexburg, ID, USA
e-mail: williamsj@byui.edu

N. R. Kitchen
USDA-ARS, Cropping Systems and Water Quality Research Unit, Columbia, MO 65211, USA

P. C. Scharf
Plant Science Division, University of Missouri, Columbia, MO 54211, USA

W. E. Stevens
Plant Science Division, University of Missouri, Portageville, MO 63873, USA

Keywords Aerial photography · Remote sensing · Nitrogen · Variable-rate · Corn (*Zea mays* L.)

Introduction

Recent increases in energy costs have not only resulted in higher fuel costs for farmers, but also higher nitrogen (N) fertilizer prices. In addition, environmental concerns stemming from N levels in groundwater, lakes and rivers over past decades continue to stimulate interest in improved agricultural management of N (USEPA 2002; Puckett et al. 2008). Historically, producers have applied more N fertilizer on corn than is used by the crop in a given season. Surveys have shown that a majority of producers over-estimate their historic yield when determining N recommendations (Schepers and Mosier 1991) because of the historically low cost of applying ample N fertilizer to ensure that it will not be limiting, regardless of environmental and climatic conditions. This approach to N management does not account well for seasonal factors, such as water availability, temperature and sunlight, and their impact on the efficiency of N use (Schepers et al. 1986; Franzen et al. 1996). For some states in the USA, N management recommendations were, for many years, based on field-average yield of previous years (Rice and Havlin 1994). More recently, yield has been shown to be a poor predictor of crop N requirements in humid environments (Lory and Scharf 2003; Sawyer et al. 2006; Scharf et al. 2006a, b). Even where yield is somewhat related to N needs, the use of field averages results in under application of fertilizer in high-yielding areas and over application in low-yielding areas of the same field (Bundy and Andraski 1995; Kitchen and Goulding 2001). In practice, ‘insurance’ N amounts have been used so that high-yielding areas are not compromised, and to ensure sufficient N is available for years when ideal growing conditions produce ‘above average’ yields (Schepers and Mosier 1991; Arregui and Quemada 2008).

Site-specific management of N fertilizer could help to reduce the negative environmental impact of excess N fertilizer application and increase producers’ profit margins (Scharf and Lory 2002; Hong et al. 2007). Advantages of site-specific N fertilizer management are that fertilizer is applied variably to match site-specific crop N need. Site-specific N management practices have been explored using intensive grid soil sampling (Williams et al. 2005) and plant chlorophyll content measurement (Scharf et al. 2006a). As these approaches are point measurements they are time consuming, and it is costly to create maps of within-field variation.

Another approach for assessing site-specific N need within the growing season is by assessing crop color, either by ground-based reflectance sensing (Stone et al. 1996; Teal et al. 2006.) or by aerial imagery (Scharf and Lory 2002; Sripada et al. 2006). Reflectance sensing or photography has great potential because canopy color expresses the types and amounts of pigments, especially chlorophyll (Blackmer et al. 1994). Leaf chlorophyll content and other pigments are typically positively correlated to N concentration (Wolfe et al. 1988). When crops are deficient in N, the chlorophyll content is sub-optimal and visible band reflectance increases. Other reflectance information related to plant biomass may also be used when assessing crop N health and for making management decisions. The difference in light absorption between soil and plants of near infrared light provides a contrast that has been the basis for numerous biomass or vegetative indices (e.g. normalized difference vegetative index or NDVI) (Pinter et al. 2003). Calculations that combine visible light reflectance (a measure of the plant’s photosynthetic health) with NIR reflectance (a measure of the plant's structure and capacity to assimilate carbon) have been used successfully in evaluating crop N health and for making N fertilizer additions (Mullen et al. 2003; Sripada et al. 2006).

Aerial photographs of plants have been shown to indicate soil variability because the plants are sensitive to changes in conditions in the root zone (Long et al. 1989). Aerial photography has the advantage of being relatively inexpensive and capable of determining variation in N need over an entire field instantaneously. In corn, the change in visible band reflectance has been measured by aerial photographs and related to plant N status (Blackmer and Schepers 1996; Sripada et al. 2006). Aerial photography has been used to identify N-stressed areas of corn fields by comparing canopy color from areas where sufficient N fertilizer has been applied with other areas within the field (Blackmer et al. 1996; Schepers et al. 1996). Thus, relative within-field color differences indicate the crop's ability to have acquired N from the soil.

The N requirements for corn can vary spatially within fields (e.g. Scharf et al. 2005; Williams et al. 2005). In Missouri, eight fields studied in three major soil areas showed that within-field economic optimal N rate (EONR) varied on average by 120 kg ha^{-1} (Scharf et al. 2005). These authors concluded that if EONR could be determined and N applied at about the V8 growth stage, the farmer's profit would increase by about \$37 ha^{-1} when compared to historic field-average or yield-based fertilizer recommendations.

Previous research using in-season aerial photography to develop site-specific N rate recommendations have been promising (Scharf and Lory 2002; Sripada et al. 2006). Scharf and Lory (2002) used aerial photographs of plot experiments over a wide-range of soil types to derive a strategy for determining EONR for corn. They showed that the ratio of green (or blue) reflectance from unfertilized corn to reflectance from fertilized corn was the best predictor of EONR ($R^2 > 0.70$). However, correlation coefficients were small ($R^2 < 0.30$) unless spectral noise from soil and mixed soil and plant pixels were removed from the photographic images.

The objective of this research was to assess, at the field scale, brightness values from inexpensive aerial photographs of corn during vegetative growth stages to predict response to within-season N fertilizer application.

Materials and methods

Nitrogen response experiments were conducted on farm fields in three major soil areas (claypan, deep loess and the Mississippi delta) in 2000 and 2001. These areas represent three unique row crop regions of Missouri (central, west central and southeast; Table 1). Different fields were used each year (total of six fields); the fields were chosen so that the row direction crossed different soil types and landscape units. All fields had been planted with soybean (*Glycine max*) the year prior to the study. Corn was planted by the cooperating producers, and they chose the planting date, hybrid, planting population and tillage practices (Table 1).

A randomized complete block design containing seven N rate treatments and four replicates was used (there were only three replicates for 2000 in the deep loess field). Treatments included an N control (0 kg N ha^{-1}), sufficient N (280 kg N ha^{-1} applied at planting) and five early side-dressed (V6; Ritchie et al. 1993) fertilizer applications from 56 to 280 kg N ha^{-1} in 56 kg N ha^{-1} increments. Treatment plots were 4.5 m wide (six rows of corn with a row spacing of 76 cm) and varied in length from 400 to 800 m,

Table 1 Soil and cropping information of experimental corn fields

Field	Year	Texture[a]	Soil great group	Hybrid	Tillage[b]	Previous crop[c]
Claypan	2000	SiL	Albaqualfs	Dekalb 626B	T	SB
	2001	SiL	Albaqualfs	Bo-jac 5557	T	SB
Deep loess	2000	SiL	Argiudolls	Pioneer 33A14	NT	SB
	2001	SiL	Argiudolls	Pioneer 33P72	NT	SB
Mississippi delta	2000	SiCL	Fluvaquents	Asgrow RX770	T	DCSB
	2001	Loam	Endoaquolls	Dekalb 697	T	DCSB

[a] *SiL* silt loam, *SiCL* silt clay loam

[b] *T* tilled, *NT* no-tilled

c *SB* soybean, *DCSB* double-cropped soybean following wheat

depending on the field size. Fertilizer was applied to the soil surface as ammonium nitrate (NH_4NO_3) by a Gandy Orbit Air model (Gandy Co., Owatonna, MN) fertilizer applicator.

At harvest, yield measurements were recorded on 1-s intervals from the center four rows of each six-row treatment using a grain combine equipped with an AgLeader yield monitor and real-time kinematic GPS. Yield data points considered questionable or unreliable because of errors or other operational problems were removed as described by Sudduth and Drummond (2007). Plant population data were taken using a proto-type electro-mechanical stalk-counter mounted on the combine's corn platform (Sudduth et al. 2000). Yield data were corrected to take account of the variation in plant population following procedures described in Scharf and Lory (2002).

Photographs were taken from a fixed-wing aircraft at mid- (about V6) and late- (V9-12) vegetative growth stages (only V12 for 2000 Mississippi delta). The actual time of photography varied slightly because of weather conditions and pilot availability (Table 2). The length of some fields required two photographs of the entire research area at the desired spatial resolution. Because of variation in the field and differences in brightness observed between these two photographs, they were separated for processing and analysis, and were designated as side A and B within a field. Photographs were taken using a 35-mm camera equipped with an ultraviolet filter using Elite Chrome Extra Color 100 slide film (Eastman Kodak Co., Rochester, NY). Camera settings were set at infinite focus, 1/500 s shutter speed and 7.0 aperture for all photographs. After standard E-6 processing, the slides were scanned using a CS-2700 (Polaroid Corp., Cambridge, MA) slide scanner at an output resolution of 1200 dpi. Image pixels assessed to be associated primarily with reflectance from the soil were identified by a *k*-means unsupervised classification in ENVI 3.4 software (Research Systems Inc., Boulder, CO) and removed. Unsupervised classification was used because of the difficulty of designating training cells that are necessary in supervised classification. Image data were imported into Arcview GIS 3.2 (ESRI, Redlands, CA) for georeferenced matching to yield for each EONR cell (discussed later). Statistical analysis of the red and green digital counts from the image data were analyzed further with SAS 8.2 (SAS Inst., Cary, NC). Values from the N control (0 kg N ha^{-1}) and sufficient N (280 kg N ha^{-1} applied at planting) treatments only were used from the images. From these, the following relative indices were calculated: relative ratio of color values was calculated by dividing the fertilized by the unfertilized treatment values for red ($RelR_R$) and green ($RelR_G$), similar to that described by Scharf and Lory (2002), and relative difference of color values was calculated by subtracting the fertilized values from unfertilized values for red ($RelD_R$) and green ($RelD_G$).

Table 2 Aerial photograph dates, times and conditions for experimental corn fields

Field	Growth stage	Date	Time (h)	Altitude (m)	Weather conditions
Claypan	V6	7 June 2000	1200	1200	Clear
	V10	22 June 2000	1700	1100	Clear
	V6	18 June 2001	1545	1825	Hazy
	V9	25 June 2001	1500	1200	Hazy
Deep loess	V6	7 June 2000	1200	1675	Clear
	V10	22 June 2000	1600	1675	Clear
	V6	8 June 2001	1440	1200	Hazy
	V11	25 June 2001	1430	1125	Overcast
Mississippi delta	V12	22 June 2000	1100	1525	Hazy
	V6	29 May 2001	1205	1125	Hazy
	V11	18 June 2001	1215	1185	Hazy

Yield and image data were analyzed at a spatial scale smaller than the plots to address the spatial variation in EONR. Details of how this was done have been documented previously (Scharf et al. 2005). In brief, each block of N-rate strips was divided into cells 20 m long (in the direction of the corn rows). This gave between 30 and 100 sets of N response cells per field from which EONR could be determined. The 20-m length was chosen as the minimum length that would provide a robust yield estimate (Birrell et al. 1996). Images were processed on these same cells, but centered on the middle 4.5-m long by 3-m wide portion of each cell.

Statistical analyses were performed with SAS (SAS Inst., Cary, NC). The PROC NLIN with quadratic-plateau regression modeling was used to obtain EONR (Fig. 1). The quadratic-plateau function uses the first derivative of the model and a price ratio of \$32 Mg^{-1} for corn and N fertilizer cost of \$0.55 kg N^{-1} (representative values in 2000 and 2001; those for 2009 are \$64 Mg^{-1} for corn and \$1.19 kg N^{-1} fertilizer [price ratios among years are similar]). Delta yield was calculated using the EONR model results by subtracting yield with no N applied from the optimal yield (Fig. 1). Previous work showed delta yield to be more related to EONR than to realistic expectations of yield (Lory and Scharf 2003). The EONR and delta yield were related to the four relative color indices described above using SAS PROC REG.

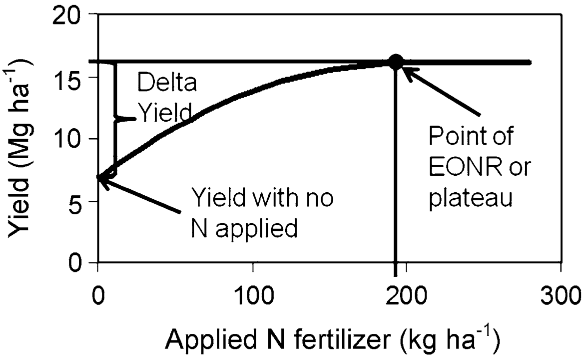

Fig. 1 An example of a quadratic-plateau model for determining economic optimal nitrogen rate and delta yield

Ground verification of corn response to N rate was done using a Minolta SPAD 502 chlorophyll meter (Minolta Camera Co., Osaka, Japan). To record chlorophyll, three or four transects were randomly placed across each block of N strips (plots), and twenty chlorophyll meter readings were taken from each N rate treatment for each transect for the V9-12 growth stage. Readings were taken midway between the base and tip of the leaf, and midway between the mid-rib and the margin from the most recently collared leaf. These were usually measured within 2 days of the aerial photographs, but on a few occasions inclement weather prevented this for a few additional days. Chlorophyll readings and yield were related to N rate with the quadratic-plateau regression function (Scharf et al. 2005).

Results and discussion

Corn responded to N fertilizer application in this investigation, and a quadratic-plateau function best described the response to N for these six fields as had been reported by Scharf et al. (2005). Corn response to N was verified with the chlorophyll readings (V9-V12 growth stage only) and grain yield (Fig. 2). Chlorophyll measurements and yield responded to increasing N fertilizer amounts similarly, with maximum chlorophyll readings and maximum yield occurring at approximately the same N rate.

In general, EONR is weakly related to the aerial photograph color indices (Table 3). For two fields (V6, claypan 2000; V9-12, Mississippi delta 2000) EONR is weakly related, but no relative color index (red or green; ratio or difference) stands out as being any better. Combined across all locations for the V6 growth stage, EONR versus the color indices has a weak negative relationship (the opposite of what was hypothesized). At the V9-12 growth stage, the combined site model between EONR and the color indices show a weak positive relationship (Table 3; Fig. 3).

Yield increase with N fertilizer application (delta yield) is also weakly related to the color indices using V6-stage photographs of the corn, but a majority of these relationships are negative (Table 3). Again, this is the opposite of what was expected. Red indices tend to be related better to delta yield than green for individual fields, but coefficients of determination are small for all indices at this growth stage ($R^2 \leq 0.34$).

Delta yield and photograph color indices are significantly related and have larger coefficients of determination for V9-12 corn (Table 3; Fig. 4). Relations are significant for at least one color index at all but one site (Claypan 2001). The field showing the best relationship between delta yield and the color indices is also the field with the best relationship between EONR and color indices (Mississippi delta, 2000). In general, when comparing the four different indices, $\mathrm{RelD_G}$ is approximately equal to or better than any of the other indices for predicting delta yield. Also, color *difference* indices often predict delta yield better than the color *ratio* indices.

In part, we attribute this outcome between the ratio and difference indices to the fact that color difference is affected less in photographs with varying brightness. Variation in brightness was observed among photographs including those where two photographs were required to cover the field (Table 2). Variation in brightness resulted in dissimilar relationships among and within sites between yield response parameters and relative color indices. For example, the V9-12 photographs of the 2001 Mississippi delta field showed that delta yield was related to $\mathrm{RelR_G}$ for Side A only, but related to $\mathrm{RelD_G}$ for sides A and B (Table 3). Image brightness can be influenced by fixed camera settings, overcast conditions and time of day of photograph acquisition. Images taken late in the day and or with overcast conditions tended to be slightly underexposed with the camera fixed at the same

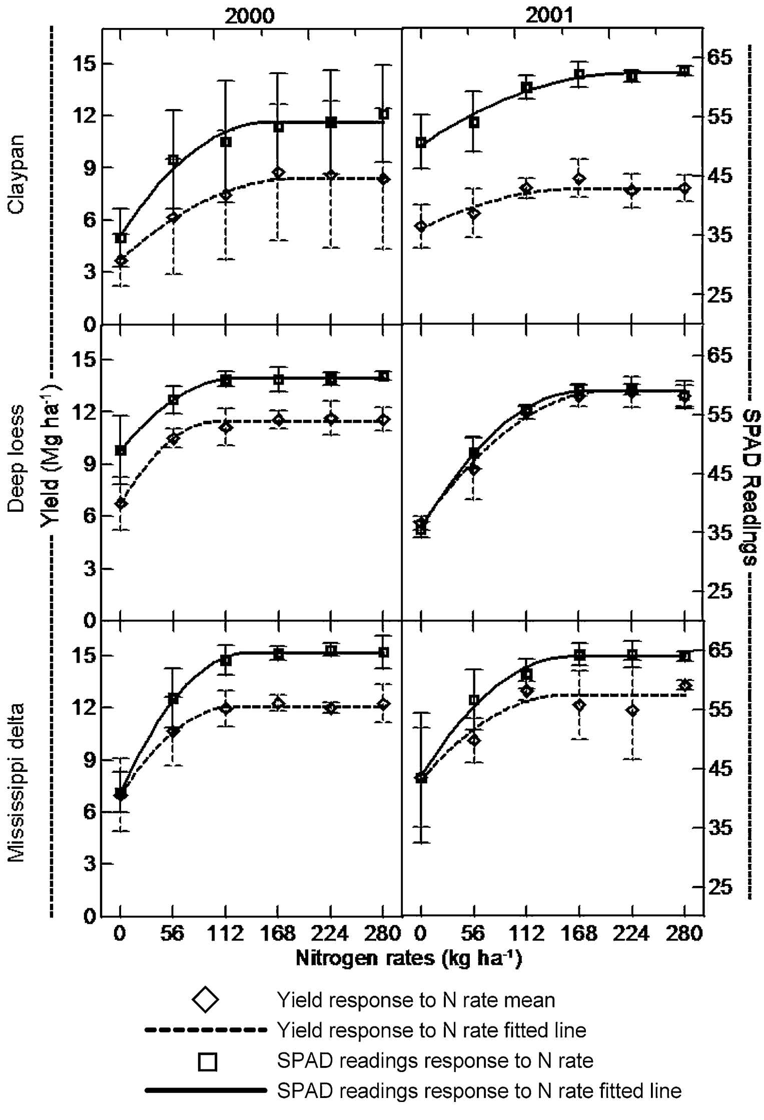

Fig. 2 Yield and SPAD readings (V9-12 growth stage) as a function of N rate. Bars indicate standard deviation of measurements

exposure time and aperture settings. Underexposed photographs give smaller digital count values, resulting in larger relative color ratios. As an example, a photograph under lower brightness conditions could give digital color counts of 100 for the control treatment and 50 for the sufficient N treatment. The same scene at higher brightness levels could have digital color counts of 150 and 100 for no N and sufficient N, respectively. Although the relative color ratio would be 2.0 for the low brightness photograph and 1.5 for the high brightness one, the relative difference would be the same (i.e. 50) for both photographs. Previous research has noted that factors such as bidirectional reflectance, the lack of radiometric correction, digitization procedures, camera settings, film exposure and

Table 3 Coefficients of determination for linear regression models for predicting economic optimal N rate (EONR) and delta yield (yield increase with V6 N fertilizer application) from color values extracted from aerial photographs at two vegetative growth stages

Growth stage	Field	Year	Side	EONR				Delta yield			
				RelR$_R$	RelD$_R$	RelR$_G$	RelD$_G$	RelR$_R$	RelD$_R$	RelR$_G$	RelD$_G$
V6	Claypan	2000		0.09	*0.13*		0.09				
		2001	A					**0.34**†	*0.21*†	*0.24*†	0.17†
			B								
	Deep loess	2000							**0.11**		0.06
		2001	A								
			B					0.13†		0.13†	
	Mississippi delta	2001	A								
			B					0.28†	0.30†		
	All sites combined			*0.03*†	**0.06**†	**0.05**†	**0.08**†	**0.16**†	**0.28**†	**0.20**†	**0.31**†
V9-12	Claypan	2000						**0.36**	**0.43**	**0.54**	**0.60**
		2001	A								
			B								
	Deep loess	2000						**0.38**	**0.43**	**0.35**	**0.45**
		2001	A					*0.19*	0.16	*0.17*	0.16
		2001	B					0.14	*0.27*	**0.37**	**0.49**
	Mississippi delta	2000		**0.30**	**0.32**	**0.32**	**0.33**	**0.62**	**0.64**	**0.66**	**0.67**
		2001	A						*0.36*	**0.61**	**0.67**
		2001	B								0.29
	All sites combined			**0.07**		**0.11**	**0.08**	**0.16**‡	0.01‡	**0.35**‡	**0.37**‡

Indices were calculated using red and green digital counts from photographs of corn adequately fertilized with N at planting and corn with no N fertilizer as follows: relative ratio of unfertilized to fertilized for red (RelR$_R$) and green (RelR$_G$), and relative difference with fertilized subtracted from unfertilized for red (RelD$_R$) and green (RelD$_G$)

Fields requiring two photographs to capture the field were divided into sides A and B. Coefficients of determination are shown only when regression slope coefficients were significant ($\alpha \leq 0.05$) using an ANOVA *F*-test

ANOVA *F*-test significant probability levels at 0.05 are normal font, at 0.01 are italic and at 0.001 are bold

† Indicates a negative relationship

‡ Coefficients of determination for all sites combined at the V9-12 growth stage excluding Claypan 2001: RelR$_R$, $R^2 = 0.24$; RelD$_R$, $R^2 = 0.48$; RelR$_G$, $R^2 = 0.44$; RelR$_G$, $R^2 = 0.58$

processing can affect reflectance information extracted from aerial photographs (Flowers et al. 2003). Some of these factors, such as radiometric correction (over and under-exposure of photographs), can be corrected by using reflectance panels with known reflectance values (Shanahan et al. 2001). Digital counts from photographs with reflectance panels allow them to be standardized and compared with counts from different photographs. Reflectance panels were not used in this study because of concerns with their practicality in using aerial photography to manage N at a large scale.

Combined across all fields delta yield is positively related to color indices, but the coefficients of determination are noticeably less than many of those for individual years (Table 3). However, with the Claypan 2001 field excluded from the combined analysis, the

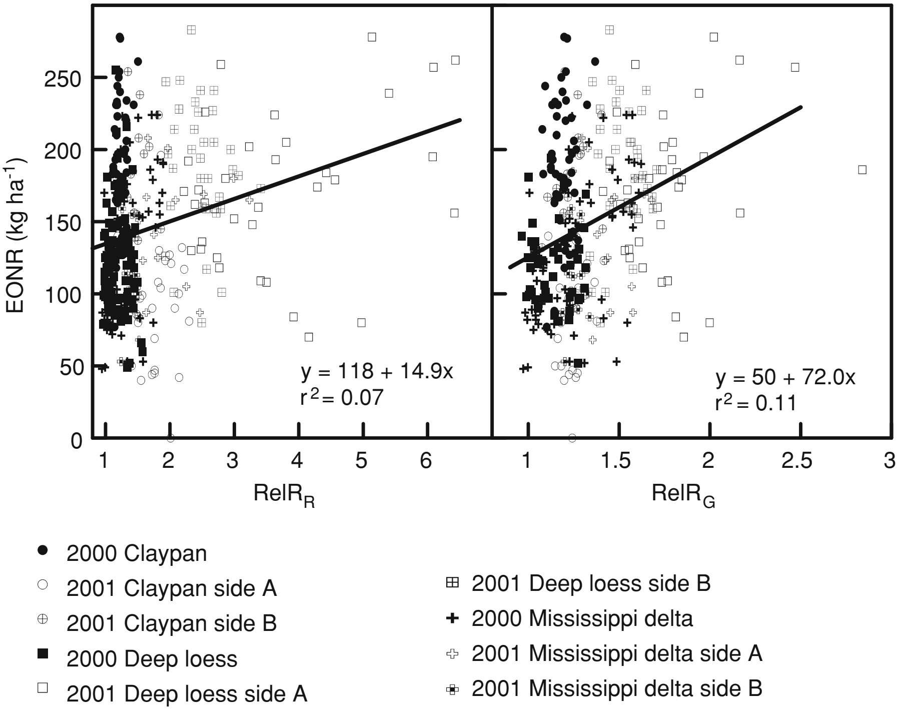

Fig. 3 Economic optimal N rate (EONR) from V6 N fertilizer application related to color value extracted from aerial photographs at the V9-12 vegetative growth stage combined across all fields. Red and green values from a photograph of corn adequately fertilized with N (at planting) and corn with no fertilizer N used to calculate relative ratio of unfertilized to fertilized for red ($\mathrm{RelR_R}$) and green ($\mathrm{RelR_G}$). Lines are drawn where F-test is significant at $\alpha \leq 0.05$

coefficients of determination are greatly improved (see Table 3 footnote; Fig. 5). As an example, with this site removed, the coefficient of determination relating $\mathrm{RelD_G}$ to delta yield increased from 0.37 to 0.58. Several factors were noted for the Claypan 2001 site that warranted its exclusion. On side A of the field, weeds (*Panicum dichotomiflorum* M. [Fall Panicum], *Abutilon theophrasti* M. [Velvetleaf] and *Xanthium strumarium* L. [Common Cocklebur]) were not well controlled by herbicides. As a result, they grew profusely in the high N-strips which caused unique color differences between the fertilized and unfertilized strips. A response for the Claypan 2001 site was observed, but it was unrelated to corn N response. On side B of this field, with an eroded side-slope landscape, corn emergence was reduced and the final stand was erratic as a result of early summer heavy rains and erosion.

Delta yield versus economic optimal nitrogen rate

Several points help to explain why color indices were better predictors of delta yield than they were for EONR. One relates to understanding the potential effect a single plot's yield has on the non-linear quadratic-plateau EONR modeling procedure. Model fitting of EONR is influenced especially by yield measurements near the point of transition between the quadratic function and the plateau (i.e. the point of EONR; Fig. 1). Minor changes in yield values at this transition can significantly change the EONR determination. In studies where N rate treatments are replicated, this sensitivity in model fitting is less of an issue.

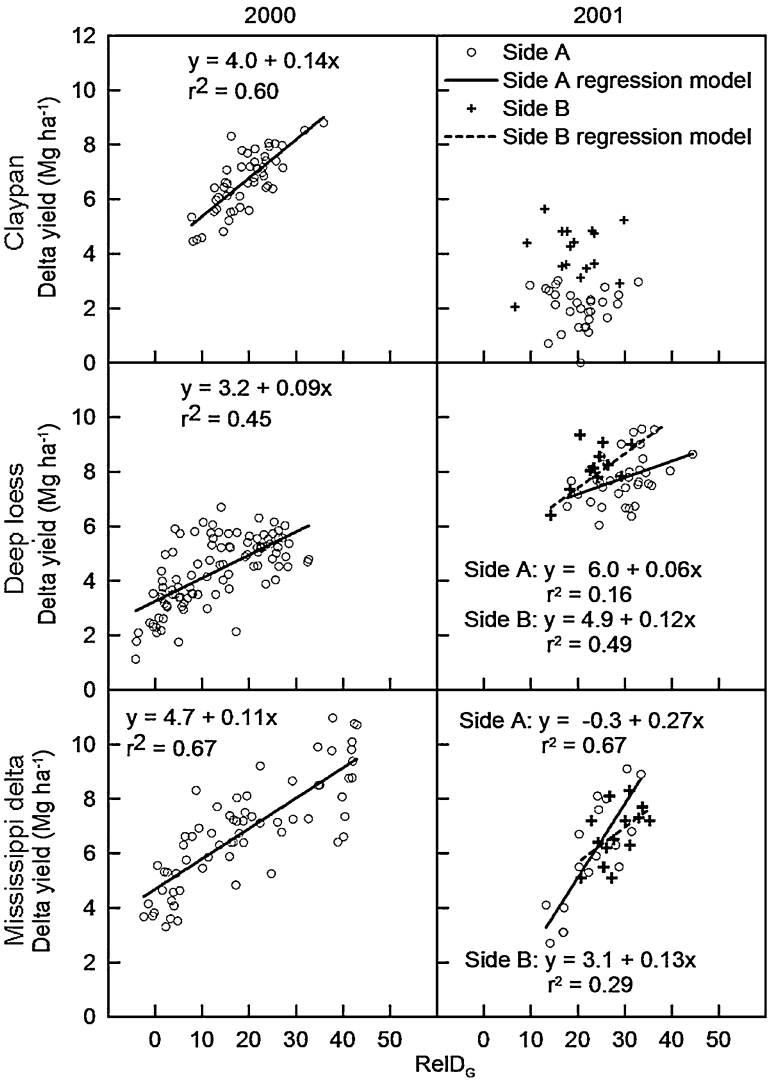

Fig. 4 Delta corn yield (yield increase with V6 N fertilizer application) related to color value extracted from aerial photographs at two vegetative growth stages. Green values from a photograph of corn adequately fertilized with N at planting and from corn with no fertilizer N used to calculate relative difference, with fertilized subtracted from unfertilized for green (RelD$_G$). Lines are drawn where *F*-test is significant at $\alpha \leq 0.05$

Another characteristic of this study that could affect EONR determinations was the level of the increment in N rates, which was 56 kg N ha^{-1}. As a result, the resolution for modeling N response to determine EONR was not as precise as when N rate increments are less. For example, corn EONR calculations in Scharf and Lory (2002) were obtained from 28 kg N ha^{-1} increments. The disadvantages for determining EONR in this study were that treatments were not replicated and the increments between N rates were large. As

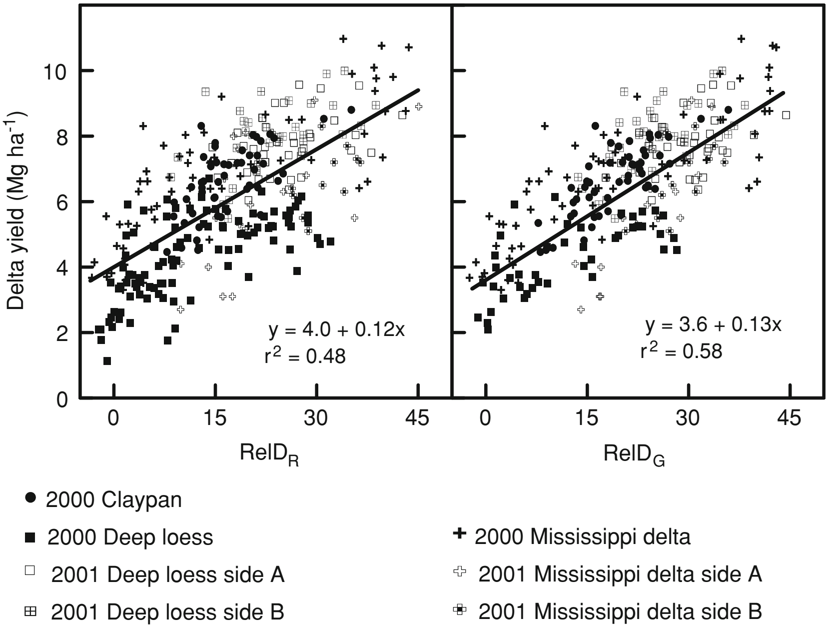

Fig. 5 Combined across all fields except for Claypan 2001, delta corn yield (yield increase with V6 N fertilizer application) related to color value extracted from aerial photographs at the V9-12 vegetative growth stage. Indices were calculated using red and green digital counts from photographs of adequately N-fertilized corn (at planting) and from corn with no fertilizer N were used to calculate relative difference, with fertilized subtracted from unfertilized for red (RelD$_R$) and green (RelD$_G$). Lines are drawn where *F*-test is significant at $\alpha \leq 0.05$

mentioned above, this research design was chosen to focus on characterizing EONR within and between production-scale fields for a given year, which has been given little attention previously. In spite of the disadvantages of the design, we are confident that this field-scale research produced reasonable and reliable estimates of EONR for these fields. Further analysis and discussion on the validity of EONR estimates for this research can be found in Scharf et al. (2005).

The advantage of delta yield is that a yield measurement from any individual plot, although it might be anomalous in relation to other N rate plots in that set of response plots, has less effect on the components (yield with no fertilizer N applied and optimal yield) needed for calculating delta yield than on EONR. For example, many of the response plots had optimal yields of <200 kg N ha^{-1}. Since the design included N rate treatments of 224 and 280 kg ha^{-1}, these larger rates of N helped to establish a more accurate measure of the 'plateau' or optimal yield. Although the study contained a 0 kg N ha^{-1} treatment, the variable 'yield with no fertilizer N applied' was calculated as the *y* intercept of the quadratic model. The advantage of this method was that several rates of N treatment typically shape the quadratic model and therefore contribute to predicting yield with no fertilizer N applied. With several yield measurements helping to define these two components of the quadratic-plateau model, an unusual response from an individual plot [caused by an anomaly in either soil or crop management or by uncontrolled experimental error (e.g. yield measurement)] would have less effect on calculating delta yield.

Interest in predicting delta yield during vegetative growth stages stems from previous work by Lory and Scharf (2003) who showed that EONR was related to delta yield ($R^2 = 0.65$) from 32 sites in Missouri. Combining the relationships identified in that research with the findings here, color differences between fertilized and unfertilized corn could be used to predict delta yield and a site-specific EONR estimated for side-dressed applications. When we took this approach to estimate EONR and compared it to the EONR derived from our actual yield measurements, the results were significant at $p < 0.05$, but were not very predictable ($R^2 = 0.15$). The EONR values calculated based on photograph-derived delta yield ($\mathrm{RelD_G}$ in Fig. 5) and then applied to the regression model of Lory and Scharf (2003) were generally larger.

In Fig. 5, the positive intercept of the regression lines relating delta yield as a function of $\mathrm{RelD_G}$ or $\mathrm{RelD_R}$ deserves further examination. Agronomically, the positive intercept means corn responds to side-dressed N fertilizer even when no differences were seen in the aerial photographs at V9-12 between corn receiving N at planting and unfertilized corn. This means, on average, a base amount of N fertilizer should be applied at side-dressing, even when no differences in photograph color are observed. A reasonable recommendation for this base application of N might come from taking the intercept value from the $\mathrm{RelD_G}$ graph of Fig. 5 (i.e. 3.6) and applying it to the commonly used rule of recommending 21 kg N $\mathrm{Mg^{-1}}$ (Lory and Scharf 2003), which gives a recommendation of 76 kg N $\mathrm{ha^{-1}}$.

Challenges of field-scale photographs and interpretation

This study was based on the presumption that the larger the color difference between well-fertilized and un-fertilized corn, the more side-dressed N fertilizer should be applied. Earlier work by Scharf and Lory (2002) showed good positive correlations between EONR and aerial photograph color $\mathrm{RelR_R}$ and $\mathrm{RelR_G}$ at an early growth stage (V6-7). The same was not found with this study. Comparing the results and methodology of these two investigations provide some possible reasons for these different outcomes.

This research was at the scale of large field areas (7–12 ha and up to 1200 m in length). The areas included more inherent spatial variation and much less management control of other yield-controlling factors than for the small-plot research of Scharf and Lory (2002). An example of reduced management control is illustrated with the weed and stand issues mentioned above for the 2001 Claypan field. The scales at which the research was done also affected the resolution of the photographs. The altitude of photographs for this research ranged from 1100 to 1800 m (Table 2), whereas photographs from the research of Scharf and Lory (2002) were at about 150 m. Film size was the same for both investigations. After digitizing photographs in the research reported here, each image pixel represented $\sim$0.25 $\mathrm{m^2}$. As such, pixels generally represented a mixture of corn plants, shadows, weeds and bare soil. As described in the procedures, pixels classified primarily as soil were removed. However, this step discounted only those pixels that were confidently known to be derived mainly from soil reflectance, and this was a small percentage of the total number of pixels (<5%). At the resolution of photographs in this investigation, color reflectance for many pixels came from an aggregate of corn and non-corn surface. Even at the V9-12 stage when the corn canopy was near closure, lighter-colored inter-rows were visible in some of the images. By contrast, pixels of images in work by Scharf and Lory (2002) were considerably smaller, which allowed them to remove many pixels ($\sim$50%) that appeared to be reflectance coming from something other than corn plants before analysis with EONR. As a result, relative ratio values from Scharf and Lory (2002) were considerably less than from this research. Bausch and Duke (1996) also noted that soil pixels were a major obstacle in analyzing imagery taken during early growth stages before complete canopy closure.

Another contrast between the two studies is how yield measurements were obtained. Here, yield for calculating EONR relied on a combine equipped with a yield monitoring system, which was probably less precise than might typically be achieved with plot research. Although the yield monitoring system used was well calibrated and the yield data carefully ‘cleaned’ before analysis, notable error is common with these yield measurements (up to 5–20%; Arslan and Colvin 2002).

Conclusions

The relationship of delta yield with green and red color difference indices at the V9-12 growth stage showed a consistent relationship to the indices. We suggest site-specific EONR recommendations could be determined from this relationship of color to delta yield, but some logistical concerns exist for corn producers to make aerial photography a viable approach for N fertilizer application. Many farmers would have to modify the timing of their current fertilizer N application from before planting or early side-dress (V3) to later side-dress (V9-12). Farmers may have concerns with a later side-dress N application because of the potential for yield loss by delaying fertilizer application and the narrow window for applying N at a later growth stage (Bausch and Duke 1996; Scharf and Lory 2002). In-season N applications based on aerial photographs would be most easily adapted for irrigated fields set up with fertigation equipment. In the USA alone there are over 4 million ha of corn cropped under pressure irrigation systems (USDA ERS 2005) that would be suitable for this technology.

For the early vegetative growth stage, image resolution was a major factor in this investigation. At the image resolution used in this study, it was virtually impossible to remove pixels that had a mixture of soil, plant and shadows at the V6 growth stage (because of canopy closure this was not considered a concern for the V9-12 corn growth stages). For aerial photography to be used to predict crop response at the earlier vegetative growth stages, high resolution digital cameras and or lower elevation flights would be needed to improve image resolution and allow for removal of non-corn reflectance.

References

Arregui, L. M., & Quemada, M. (2008). Strategies to improve nitrogen use efficiency in winter cereal crops under rainfed conditions. *Agronomy Journal, 100*, 277–284.

Arslan, S., & Colvin, T. S. (2002). An evaluation of the response of yield monitors and combines to varying yields. *Precision Agriculture, 3*, 107–122.

Bausch, W. C., & Duke, H. R. (1996). Remote sensing of plant nitrogen status in corn. *Transactions of ASAE, 39*, 1869–1875.

Birrell, S. J., Sudduth, K. A., & Borgelt, S. C. (1996). Comparison of sensors and techniques for crop yield mapping. *Computers and Electronics in Agriculture, 14*, 215–233.

Blackmer, T. M., & Schepers, J. S. (1996). Aerial photography to detect nitrogen stress in corn. *Journal of Plant Physiology, 148*, 440–444.

Blackmer, T. M., Schepers, J. S., & Varvel, G. E. (1994). Light reflectance compared with other nitrogen stress measurements in corn leaves. *Agronomy Journal, 86*, 934–938.

Blackmer, T. M., Schepers, J. S., Varvel, G. E., & Meyer, G. E. (1996). Analysis of aerial photography for nitrogen stress within corn fields. *Agronomy Journal, 88*, 729–733.

Bundy, L. G., & Andraski, T. W. (1995). Soil yield potential effects on performance of soil nitrate tests. *Journal of Production Agriculture, 8*, 561–568.

Flowers, M., Weisz, R., Heiniger, R., Tarleton, B., & Meijer, A. (2003). Field validation of a remote sensing technique for early nitrogen application decisions in wheat. *Agronomy Journal, 95*, 167–176.

Franzen, D. W., Cihacek, L. J., & Hofman, V. L. (1996). Variability of soil nitrate and phosphate under different landscapes. In P. C. Roberts, R. H. Rust, & W. E. Larson (Eds.), *Proceedings of third international conference on precision agriculture* (pp. 521–529). Madison, WI: American Society of Agronomy.

Hong, N., Scharf, P. C., Davis, J. G., Kitchen, N. R., & Sudduth, K. A. (2007). Economically optimal nitrogen rate reduces soil residual nitrate. *Journal of Environmental Quality, 36*, 354–362.

Kitchen, N. R., & Goulding, K. W. T. (2001). On-farm technologies and practices to improve nitrogen use efficiency. In R. F. Follet & J. L. Hatfield (Eds.), *Nitrogen in the environment: Sources, problems, and management* (pp. 335–369). Amsterdam, The Netherlands: Elsevier Science B.V.

Long, D. S., Neilsen, G. A., & Carlson, G. R. (1989). Use of aerial photography for improving layout of field research plots. *Applied Agricultural Research, 4*, 96–100.

Lory, J. A., & Scharf, P. C. (2003). Yield goal versus delta yield for predicting fertilizer nitrogen need in corn. *Agronomy Journal, 95*, 994–999.

Mullen, R. W., Freeman, K. W., Raun, W. R., Johnson, G. V., Stone, M. L., & Solie, J. B. (2003). Identifying an in-season response index and the potential to increase wheat yield with nitrogen. *Agronomy Journal, 95*, 347–351.

Pinter, P. J., Hatfield, J. L., Schepers, J. S., Barnes, E. M., Moran, M. S., Daughtry, C. S. T., et al. (2003). Remote sensing for crop management. *American Society for Photogrammetry and Remote Sensing, 69*, 647–664.

Puckett, L. J., Zamora, C., Essaid, H., Wilson, J. T., Johnson, H. M., Brayton, M. J., et al. (2008). Transport and fate of nitrate at the ground-water/surface-water interface. *Journal of Environmental Quality, 37*, 1034–1050.

Rice, C. W., & Havlin, J. L. (1994). Integrating mineralizable nitrogen indices into fertilizer nitrogen recommendations. In J. L. Havlin & J. S. Jacobsen (Eds.), *Soil testing: Prospects for improving nutrient recommendations* (pp. 1–13). Madison, WI: Soil Science Society of America.

Ritchie, S. W., Hanway, J. J., & Benson, G. O. (1993). *How a corn plant develops*. Special Report, 48. Ames: Iowa State University.

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G., & Joern, B. (2006). *Concepts and rationale for regional nitrogen rate guidelines for corn*. Iowa State University Extension Publication, PM 2015.

Scharf, P. C., Brouder, S. M., & Hoeft, R. G. (2006a). Chlorophyll meter readings can predict nitrogen need and yield response of corn in the north-central USA. *Agronomy Journal, 98*, 655–665.

Scharf, P. C., Kitchen, N. R., Sudduth, K. A., & Davis, J. G. (2006b). Spatially variable corn yield is a weak predictor of optimal nitrogen rate. *Soil Science Society of America Journal, 70*, 2154–2160.

Scharf, P. C., Kitchen, N. R., Sudduth, K. A., Davis, J. G., Hubbard, V. C., & Lory, J. A. (2005). Field-scale variability in economically-optimal N fertilizer rate for corn. *Agronomy Journal, 97*, 452–461.

Scharf, P. C., & Lory, J. A. (2002). Calibrating corn color from aerial photographs to predict sidedress N need. *Agronomy Journal, 94*, 397–404.

Schepers, J. S., Blackmer, T. M., Wilhelm, W. W., & Resende, M. (1996). Transmittance and reflectance measurements of corn leaves from plants with different nitrogen and water supply. *Journal of Plant Physiology, 148*, 523–529.

Schepers, J. S., Frank, K. D., & Bourg, C. (1986). Effect of yield goal and residual soil nitrogen concentration on N fertilizer recommendations for irrigated maize in Nebraska. *Journal of Fertilizer Issues, 3*, 133–139.

Schepers, J. S., & Mosier, A. R. (1991). Accounting for nitrogen in nonequilibrium soil-crop systems. In R. F. Follett, D. R. Keeney, & R. M. Cruse (Eds.), *Managing nitrogen for groundwater quality and farm profitability* (pp. 125–128). Madison, WI: Soil Science Society of America.

Shanahan, J. F., Schepers, J. S., Francis, D. D., Varvel, G. E., Wilhelm, W. W., Tringe, J. M., et al. (2001). Use of remote sensing imagery to estimate corn grain yield. *Agronomy Journal, 93*, 583–589.

Sripada, R. P., Heiniger, R. W., White, J. G., & Meijer, A. D. (2006). Aerial color infrared photography for determining early in-season nitrogen requirements in corn. *Agronomy Journal, 98*, 968–977.

Stone, M. L., Solie, J. B., Raun, W. R., Whitney, R. W., Taylor, S. L., & Ringer, J. D. (1996). Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. *Transactions of the ASAE, American Society of Agricultural Engineers, 39*, 1623–1631.

Sudduth, K. A., Birrel, S. J., & Krumpelman, M. J. (2000). Field evaluation of corn population sensor. In P. C. Roberts, R. H. Rust, & W. E. Larson (Eds.), *Proceedings of the fifth international conference on precision agriculture* (paper 252). Madison, WI: American Society of Agronomy. CD format only.

Sudduth, K. A., & Drummond, S. T. (2007). Yield editor: Software for removing errors from crop yield maps. *Agronomy Journal, 99*, 1471–1482.

Teal, R. K., Tubana, B., Girma, K., Freeman, K. W., Arnall, D. B., Walsh, O., et al. (2006). In-season prediction of corn grain yield potential using normalized difference vegetation index. *Agronomy Journal, 98*, 1488–1494.

USEPA. (Aug 2002). *National water quality inventory: 2000 report*. EPA-841-R-02-001, Washington, DC.

USDA ERS. (2005). *Farm business and household survey data: Summaries from ARMS. 2005 Survey*. http://www.ers.usda.gov/data/ARMS/app/Crop.aspx.

Williams, J. D., Crozier, C. R., Crouse, D. A., White, J. G., Bang, J., & Duffera, M. (2005). Spatial relationships between soil amino sugar nitrogen, soil properties, and landscape attributes. In J. V. Stafford (Ed.), *Proceedings of the fifth European conference on precision agriculture* (pp. 303–309). Wageningen: Wageningen Academic Scientific Publishers.

Wolfe, D. W., Henderson, D. W., Hsaio, T. C., & Alvino, A. (1988). Interactive water and nitrogen effects on senescence of maize: II. Photosynthetic decline and longevity of individual leaves. *Agronomy Journal, 80*, 865–870.