REMOTE SENSING

Field Validation of a Remote Sensing Technique for Early Nitrogen Application Decisions in Wheat

Michael Flowers,* Randall Weisz, Ronnie Heiniger, Barry Tarleton, and Alan Meijer

ABSTRACT

Studies have shown that winter wheat (*Triticum aestivum* L.) tiller density at growth stage 25 (GS 25) can be used to determine when a GS-25 N application is needed. However, determining GS-25 tiller density is difficult and time consuming. Color infrared aerial photographs have been successfully used to predict GS-25 tiller density. The objective of this study was to validate a previously reported remote sensing technique to predict GS-25 tiller density based on near-infrared (NIR) digital counts and within-field tiller density references across a wide range of environments. The NIR remote sensing technique was evaluated through linear regression and quadrant plot analysis to determine the accuracy of GS-25 tiller density predictions and GS-25 N application decisions based on a critical GS-25 tiller density threshold. The impact of different wheat varieties, soil colors, and weed populations were also evaluated through covariate analysis using 10 site-years of data. At three site-years, a randomized complete block design with three varieties and either two or three seeding rates was used. At these site-years, variety had a significant influence on spectral measurements. Seven additional site-years had a single variety and seeding rate. The NIR remote sensing technique was found to account for 76% of the variation between predicted and measured GS-25 tiller density across 10 site-years of data. Accurate GS-25 N application decisions were made 85.5% of the time by the NIR remote sensing technique across a wide range of environments including six soil types, six wheat varieties, and two systems.

Soft red winter wheat is an important component of southeastern U.S. cropping systems. In this region, sandy soils and high rainfall during fall and winter cause leaching or denitrification of N fertilizer applied before wheat planting (Scharf et al., 1993; Scharf and Alley, 1993). Therefore, it is critical to apply N at the appropriate times for plant uptake. Baethgen and Alley (1989a) reported that maximum N uptake in soft red winter wheat occurs just before Zadoks's GS 30 (Zadoks et al., 1974). In densely tillered wheat, Baethgen and Alley (1989b) showed that N applied at GS 30 was the most efficient means of supplying N and optimizing grain yield. However, in poorly tillered wheat, Weisz et al. (2001) showed that earlier spring N applications at GS 25 increased wheat grain yield by stimulating tiller development. In the Southeast, tiller development can be stimulated by GS-25 N applications because winter wheat does not enter a dormant state in these southern latitudes. Consequently, GS-25 N applications are critical for remediating thin wheat stands in southeastern winter wheat production systems.

Several N management strategies have been developed for increasing tiller density in winter wheat stands in the Southeast. Scharf and Alley (1993) recommended applying N at GS 25 when the average tiller density was $<$1000 tillers m^{-2}. Weisz et al. (2001) examined optimum N rates across a wide range of GS-25 tiller densities and suggested a critical threshold of 540 tillers m^{-2}. They found that for wheat fields with GS-25 tiller densities below this threshold, optimum grain yields were obtained by applying N at GS 25. Fields with higher tiller densities were best managed by withholding N until GS 30. Therefore, for growers to maximize winter wheat grain yields, they must know the tiller density at GS 25 and be able to apply N quickly if N is required.

To assist growers in estimating GS-25 tiller density, Flowers et al. (2001) developed a remote sensing technique based on NIR digital counts from color infrared (CIR) aerial photographs. However, there are many factors that can influence the measured reflectance in the visible and NIR spectrums and could complicate the use of CIR aerial photographs to estimate GS-25 tiller density across environments. Crop conditions such as weed populations (Menges et al., 1985), plant diseases (Colwell, 1956), insect damage and water stress (Wildman, 1982), varietal differences (Stone et al., 1996; Hatfield, 1990), plant nutrition (Wildman, 1982), and differences in soil backgrounds (Huete et al., 1985; Hatfield, 1990; Bausch, 1993) have all been shown to affect measured reflectance. Atmospheric effects (Jackson et al., 1983), sun angle (Avery and Berlin, 1992), bidirectional reflectance, the lack of radiometric correction, digitization processes, camera settings, film exposure, and film processing may also affect the measured reflectance in CIR aerial photographs. Because of the large number of factors that could potentially influence the relationship between measured reflectance and crop measurements, Blackmer et al. (1996) concluded that ground observations or the inclusion of known reference conditions could benefit the use of remote sensing across environments. Consequently, the NIR remote sensing technique developed by Flowers et al. (2001) used within-field references in the form of a high and low (or bare soil)

M. Flowers, R. Weisz, and B. Tarleton, Dep. of Crop Sci., North Carolina State Univ., Box 7620, Raleigh, NC 27695-7620; and R. Heiniger and A. Meijer, Dep. of Crop Sci., North Carolina State Univ., Vernon James Res. and Ext. Cent., 207 Research Rd., Plymouth, NC 27962. Received 5 Jan. 2002. *Corresponding author (mflowers@cropserv1.cropsci.ncsu.edu).

Published in Agron. J. 95:167–176 (2003).

Abbreviations: B, blue (band); CIR, color infrared; DVI, difference vegetation index; G, green (band); GS, growth stage; NDVI, normalized difference vegetation index; NIR, near infrared; OSAVI, optimized soil-adjusted vegetation index; R, red (band); RVI, ratio vegetation index; SAVI, soil-adjusted vegetation index.

tiller density measurement to remove differences across environments and estimate GS-25 tiller density. This NIR remote sensing technique was easy to use and required minimal ground truthing. Using the critical tiller threshold (540 tillers m^{-2}) reported by Weisz et al. (2001), the NIR remote sensing technique correctly recommended N at GS 25 82% of the time. However, the NIR technique was established based on data from a limited number of wheat fields under ideal conditions (without weeds, across uniform soil types, and a single wheat variety).

Consequently, our first objective was to validate the NIR remote sensing technique (Flowers et al., 2001) over a wide range of field environments. In addition to testing the method in a large number of fields, we specifically wanted to determine if wheat varieties, tillage practices, soil types, and weed populations interfere with the NIR remote sensing technique's estimation of GS-25 tiller density. In developing the technique, Flowers et al. (2001) found that NIR digital counts were more robust estimators of GS-25 tiller density compared with a wide range of spectral indices derived from CIR aerial photographs. Consequently, our second objective was to confirm that NIR digital counts continued to be the best estimator of GS-25 tiller density across a larger and more varied data set. Ultimately, the adoption of a remote sensing technique in this production system will not be determined by its ability to accurately predict tiller density but rather by its effectiveness in determining if N applications are required at GS 25. In this light, our third objective was to test the accuracy of GS-25 N application recommendations made using this NIR remote sensing technique (Flowers et al., 2001) when combined with the critical GS-25 tiller density threshold for winter wheat reported by Weisz et al. (2001).

MATERIALS AND METHODS

Site Description

Research was conducted at 10 sites in 2000 and 2001. In 2000, two on-farm studies were located near Belhaven, NC (B-1), and Wilson, NC (W-1). Another study was conducted in Salisbury, NC, on the Piedmont Research Station (P-1). In 2001, another Piedmont Research Station site (P-2) was used along with six sites in Kinston, NC. Two of these sites were located on the Cunningham Research Station (K-1 and K-2), and four were at the Lower Coastal Plain Tobacco Research Station (K-3, K-4, K-5, and K-6). Soils at the sites included a Ponzer muck (loamy, mixed, dysic, thermic Terric Medisaprists) at B-1; an Appling-Marlboro complex (clayey, kaolinitic, thermic Typic Kanhapudults) at W-1; a Hiwassee clay loam (fine, kaolinitic, thermic Typic Rhodudults) at P-1 and P-2; a Rains sandy loam (fine, loamy, siliceous, thermic Typic Paleaquults) at K-1 and K-3; a Lynchburg sandy loam (fine, loamy, siliceous, thermic, Aeric Paleaquults) at K-2; a Goldsboro loamy sand (fine, loamy, siliceous, thermic Aquic Paludults) at K-4 and K-6; and a combination of a Goldsboro loamy sand, Lynchburg sandy loam, and a Norfolk loamy sand (fine, loamy, siliceous, thermic Typic Paleudults) at K-5. Table 1 further describes the sites, including the wheat varieties, seeding rates, tillage system, plot size, and number of sample locations at each site.

At P-2 and K-1, randomized complete block designs with six replications were used. Treatments included three varieties and two seeding rates (Table 1). At these two sites, five sample locations per plot (equally spaced down the length of each plot) and 15 bare soil sample locations were used for analysis. The P-1 site also used a randomized complete block design with six replications. Treatments included three varieties and three seeding rates (Table 1). Four sample locations per plot (equally spaced down the length of each plot) and 12 bare soil sample locations were used for analysis. All other sites received a single seeding rate and variety (Table 1). One sample location per plot and up to nine bare soil sample locations were used for analysis at these sites.

At all sites, GS-25 tiller density was determined at the center of each sample location by averaging two 1-m sections of row within a 1.2-m radius circle. For all sites, weed population was visually estimated at each sample location at the time of GS-25 tiller density measurement. Because a wide range in weed populations did not exist at any site, the weed population data was simplified into two data categories (present or absent) for analysis. Sample locations were considered to have a weed population if weeds were visually estimated to occupy >50% of the surface area at the sample location. A visual estimation

Table 1. Year, soil type, wheat varieties, seeding rates, tillage system, plot size, and total number of sample locations at each of the 10 site-years

Site	Year	Soil type	Wheat variety	Seeding rate(s)	Tillage system	Plot size	Sample locations
				seeds m^{-2}		m	
P-1	2000	Hiwassee clay loam	Coker '9704'	High—640	No-till	10.6 by 3.1	228
			Pioneer '2580'	Medium—394			
			'Roane'	Low—80			
B-1	2000	Ponzer muck	Coker '9835'	414	Conventional	9.2 by 3.7	64
W-1	2000	Appling-Marlboro complex	FFR '555'	414	Conventional	15.4 by 15.4	106
P-2	2001	Hiwassee clay loam	Coker 9704	Medium– 474	No-till	22 by 6.8	195
			Pioneer 2580	Low– 145			
			Roane				
K-1	2001	Rains sandy loam	Coker 9704	Medium—467	Conventional	20 by 7.4	195
			Pioneer 2580	Low—225			
			Roane				
K-2	2001	Lynchburg sandy loam	Coker 9704	467	Conventional	9.2 by 4.6	65
K-3	2001	Rains sandy loam	Roane	467	Conventional	9.2 by 4.6	78
K-4	2001	Goldsboro loamy sand	Pioneer '26R91'	467	Conventional	9.2 by 4.6	78
K-5	2001	Goldsboro loamy sand,	Coker 9704	467	Conventional	9.2 by 4.6	39
		Lynchburg sandy loam,					
		Norfolk loamy sand					
K-6	2001	Goldsboro loamy sand	Roane	467	Conventional	9.2 by 4.6	78

of >50% was chosen for simplicity and not based on crop or weed characteristics.

All sites except K-5 contained a single soil type. Due to the size of the K-5 site (approximately 15 ha), there were significant portions of the site in a Lynchburg sandy loam, a Goldsboro loamy sand, and a Norfolk loamy sand. To differentiate soil boundaries, a digitized version of the soil boundaries published by Aull (1972) for the K-5 site was used.

Aerial Photography

Remote sensing was performed as described previously (Flowers et al., 2001). Latitude and longitude for all sample locations and of four aerial targets placed at field corners were determined using a differential global positioning system (DGPS) receiver with 1-m accuracy (Trimble AgGPS 132, Trimble Navigation, Sunnyvale, CA). Aerial photographs were taken from a belly-mounted platform using a 35-mm Canon 81 camera (Canon USA, Lake Success, NY) on the same day (26 Jan. 2001 for K-1, K-2, K-3, K-4, K-5, and K-6) or within 1 wk (26 Jan. 2000 for P-2 and 10 Feb. 2000 for P-1, W-1, and B-1) of tiller density measurements. Color infrared film (Kodak Ektachrome 153) along with a Kodak Wratten gelatin filter number 15 (Eastman Kodak Co., Rochester, NY) were used for the aerial photographs. A series of aerial photographs with differing exposures bracketed on F/8 and a shutter speed of 1/250 s were taken at each site. All CIR film was AR-5–processed to obtain false CIR slides. With the exception of K-5, aerial photographs were taken at altitudes as low as possible while ensuring that each site was contained in a single photograph. This resulted in a range of altitudes (approximately 854 m) across sites. All aerial photographs were taken on cloudless days between 1200 and 1400 h standard time.

Digitization of Images and Photographic Analysis

Photographic analysis and digitization of images were performed on the positive false color slides from the CIR film as described by Flowers et al. (2001). 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 the software package Adobe Photoshop v 4.0 (Adobe Syst., San Jose, CA). The brightness and contrast were not adjusted on the digitized image. The digitized image was not sharpened using the scanner software. The image was scanned with a resolution of 47 pixels mm^{-1}, with each pixel representing a range in area of 0.25 to 0.48 m^2 of ground area. The range in ground area was due to differences in altitude when the image was taken. With the exception of K-5, each field was contained within a single aerial photograph, and consequently, all comparisons were limited to within a given photograph. The digitized images were rectified in ERDAS Imagine (ERDAS, 1997) using the latitude and longitude of the four aerial targets at each site. Root mean square error (RMSE) was calculated for each rectified image and ranged between 0.1 and 1.5 m.

The K-5 site was 15 ha in size, and two sequential aerial photographs were required to capture the entire site. The sequential aerial photographs were taken on the same pass and at the same altitude. Each aerial photograph covered approximately 60% of the site, resulting in approximately 10% of the site being common to both aerial photographs. For data analysis, the NIR digital counts from the two sequential aerial photographs were combined. A 0.5- by 0.5-m grid was draped over the portion of the site contained within each aerial photograph. The pixel closest to the center of each grid cell was selected. This resulted in 33 193 field locations, each represented by two pixels (one pixel in each aerial photograph). The NIR digital counts for these pixels were determined (see below), and the NIR digital counts from the two photographs were regressed against each other (SAS Inst., 1998). The resultant linear model ($r^2 = 0.71$) was used to convert NIR digital counts for each pixel in one photograph to approximate those in the other. The two photographs were then combined into a single adjusted image.

Spectral Indices

Digital counts representing the spectral reflectance for each sample location were derived using ERDAS Imagine as described by Flowers et al. (2001). Color infrared 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 value represents RGB digital counts within the range from 0 to 255. The spectral properties of CIR film result in wide overlapping wavelength bands. In our case, Band 1 (NIR) of the image covered the wavelengths between 490 and 900 nm, Band 2 (R) between 490 and 700 nm, and Band 3 (G) between 490 and 620 nm. While these bands overlap, differences in spectral sensitivity exist between them. Maximum sensitivity occurs at 730 nm in the NIR band, 650 nm in the R band, and 550 nm in the G band. These differences in spectral sensitivity may offer increased information through the use of a spectral index.

In that light, several spectral indices in addition to digital counts for the NIR band were examined. A normalized difference vegetation index (NDVI; Yang and Anderson, 1999) was determined using the digital counts from the NIR and R bands such that:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R}) \quad [1]$$

A normalized NIR value (Jain, 1989) was derived from all bands such that:

$$\text{Normalized NIR} = \mathrm{NIR}/(\mathrm{NIR} + \mathrm{R} + \mathrm{G}) \quad [2]$$

A ratio vegetation index (RVI) (Jordan, 1969) and a difference vegetation index (DVI) (Tucker, 1979) were calculated as:

$$\mathrm{RVI} = \mathrm{NIR}/\mathrm{R} \quad [3]$$

$$\mathrm{DVI} = \mathrm{NIR} - \mathrm{R} \quad [4]$$

A soil-adjusted vegetation index (SAVI) (Huete, 1988) and an optimized soil-adjusted vegetation index (OSAVI) (Rondeaux et al., 1996) were calculated as:

$$\mathrm{SAVI} = [(\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R} + 0.5)] \times 1.5 \quad [5]$$

$$\mathrm{OSAVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R} + 0.16) \quad [6]$$

Finally, the digital counts for the NIR and R bands were summed (Wanjura and Hatfield, 1987).

Data Analysis

For P-1, P-2, and K-1, analysis of covariance (general linear models, SAS Inst., 1998) was used to determine if wheat varieties influenced the relationship between GS-25 tiller density and NIR digital counts, NDVI, normalized NIR, RVI, DVI, NIR + R, SAVI, and OSAVI. Variety was considered as a class variable, with GS-25 tiller density as the covariate (linear and quadratic terms). Analysis of covariance was also used at P-2, W-1, and K-5 to determine if weed population and soil type influenced the relationship between GS-25 tiller density and NIR digital counts, NDVI, normalized NIR, RVI, DVI,

Table 2. Seeding rate, growth stage 25 (GS-25) least square mean tiller density, and standard deviation for 10 site-years. A *t* test was used for least square mean separations for site-years with multiple seeding rates.

Site	Seeding rate	Mean tiller density	Standard deviation†
	seeds m^{-2}	tillers m^{-2}	
P-1	640	813 a‡	
	394	754 b	
	180	610 c	
B-1	414	488	63
W-1	414	540	76
P-2	474	374 a	
	145	237 b	
K-1	467	612 a	
	225	501 b	
K-2	467	361	121
K-3	467	765	105
K-4	467	345	57
K-5	467	598	91
K-6	467	756	109

† Standard deviations are given for site-years with single seeding rate.
‡ Means followed by the same letter are not significantly different at the 0.05 level (within site-year).

NIR + R, SAVI, and OSAVI. Weed population and soil type were considered as class variables and GS-25 tiller density as the covariate. Pearson correlations (SAS Inst., 1998) were used to compare NIR digital counts, NDVI, normalized NIR, RVI, DVI, SAVI, OSAVI, and the summed NIR + R with GS-25 tiller density.

Flowers et al. (2001) modified a procedure originally described by Blackmer et al. (1996) and developed a technique for estimating GS-25 tiller density across environments using NIR digital counts and minimal ground truthing. Initially, relative NIR digital counts ($NIR_{Relative}$) and relative tiller density ($TD_{Relative}$) are determined for each site such that:

$$NIR_{Relative} = (NIR - NIR_{min})/(NIR_{max} - NIR_{min}) \quad [7]$$

$$TD_{Relative} = (TD - TD_{min})/(TD_{max} - TD_{min}) \quad [8]$$

where NIR and TD are the NIR digital count and tiller density at a given sample location, NIR_{min} and TD_{min} are the NIR digital count and tiller density at the sample location with the lowest tiller density (or bare soil), and NIR_{max} and TD_{max} are the NIR digital count and tiller density at the sample location with the highest tiller density. Linear regression of $NIR_{Relative}$ vs. $TD_{Relative}$ ($r^2 = 0.77$) from four site-years (Flowers et al., 2001) resulted in:

$$NIR_{Relative} = 1.04 \times TD_{Relative} + 0.07 \quad [9]$$

Rearranging Eq. [7–9] results in the following equation for predicting tiller density ($TD_{Predicted}$) from remotely sensed data at any given site:

$$TD_{Predicted} = [(TD_{max} - TD_{min}) \times (NIR_{Relative} - 0.07)/1.04] + TD_{min} \quad [10]$$

To validate this NIR remote sensing technique for determining $TD_{Predicted}$, the data from each of the 10 site-years studied in this research were first converted to $NIR_{Relative}$ and $TD_{Relative}$ (Eq. [7] and Eq. [8]) and then regressed as in Eq. [9]. The

Table 3. Covariate analysis of near infrared (NIR), normalized NIR, normalized difference vegetation index (NDVI), ratio vegetation index (RVI), difference vegetation index (DVI), the summed NIR and red bands (NIR + R), the soil-adjusted vegetation index (SAVI), and the optimized soil-adjusted vegetation index (OSAVI). Tiller density (TD) was treated as a covariable with linear and quadratic terms. Variety, weed, and soil interactions were considered to be class variable at five locations (P-1, P-2, K-1, W-1, and K-5).

Site	Source of variation	NIR	Normalized NIR	NDVI	RVI	DVI	NIR + R	SAVI	OSAVI
P-1	Rep	*	*	*	*	*	*	*	*
	Variety	*	*	*	*	*	†	*	*
	TD (linear)	*	*	*	*	*	*	*	*
	Variety × TD (linear)	NS‡	NS	NS	NS	NS	NS	NS	NS
	TD (quadratic)	*§	*§	*§	NS	*§	NS	*§	*§
	Variety × TD (quadratic)	NS	NS	NS	NS	NS	NS	NS	NS
P-2	Rep	*	*	*	*	*	*	*	*
	Variety	*	*	*	*	NS	NS	NS	NS
	Weeds	NS	NS	NS	NS	NS	NS	NS	NS
	TD (linear)	*	NS	NS	NS	NS	NS	NS	NS
	Variety × Weeds	NS	NS	NS	NS	NS	NS	NS	NS
	Variety × TD (linear)	*	*	*	*	*	NS	*	*
	Weeds × TD (linear)	NS	NS	NS	NS	NS	NS	NS	NS
	Variety × Weeds × TD (linear)	NS	NS	NS	NS	NS	NS	NS	NS
	TD (quadratic)	NS	NS	NS	NS	NS	NS	NS	NS
	Variety × TD (quadratic)	NS	*§	*§	*§	*§	NS	*§	*§
	Weeds × TD (quadratic)	NS	NS	NS	NS	NS	NS	NS	NS
	Variety × Weeds × TD (quadratic)	NS	NS	NS	NS	NS	NS	NS	NS
K-1	Rep	*	*	*	*	*	*	*	*
	Variety	*	*	*	*	*	*	*	*
	TD (linear)	*	*	NS	*	NS	*	NS	NS
	Variety × TD (linear)	NS	NS	*	NS	*	*	*	*
	TD (quadratic)	NS	NS	NS	NS	NS	*§	NS	NS
	Variety × TD (quadratic)	NS	NS	*§	NS	*§	NS	*§	*§
W-1	Weeds	*	*	*	*	*	*	*	*
	TD (linear)	*	*	*	*	*	*	*	*
	Weeds × TD (linear)	*	*	*	*	*	*	*	*
K-5	Soil type	*	NT¶	NT	NT	NT	NT	NT	NT
	TD	*	NT	NT	NT	NT	NT	NT	NT
	Soil type × TD (linear)	*	NT	NT	NT	NT	NT	NT	NT

* Significant at the 0.05 level.
† Significant at the 0.1 level.
‡ NS, no significance.
§ Indicates that even though the quadratic model was statistically significant, there was not an improvement in model fit over the linear model.
¶ NT, not tested.

resulting slope and intercept of the linear regression from each site-year was then compared to that found previously and described in Eq. [9].

In the limited data set used to develop Eq. [10], Flowers et al. (2001) found that it correctly predicted the tiller density to be either above or below the critical tiller density threshold (540 tillers m^{-2}) recommended for making N application decisions (Weisz et al., 2001) 82% of the time. Equation [10] was used to calculate $TD_{Predicted}$ for each sample location in the 10 site-years studied here. A quadrant plot (Flowers et al., 2001) was used to determine the accuracy of these predictions in making GS-25 N recommendations. A plot of $TD_{Predicted}$ vs. TD was divided into quadrants at $TD_{Predicted}$ and TD equal to 540 tillers m^{-2} and the percentage of data in each quadrant computed. Data in the upper right and lower left quadrants represented instances when N management decisions based on Eq. [10] would have been correct. Data in the upper left and lower right quadrants represented the percentage of incorrect N management decisions based on Eq. [10].

RESULTS AND DISCUSSION

Seeding Rate

Significant differences in tiller density were found between all seeding rates at P-1, P-2, and K-1 (Table 2). For P-1 and P-2, the mean GS-25 tiller density values for all seeding rates were greater than or less than the threshold, respectively. At K-1, the mean GS-25 tiller density was higher or lower than the threshold for the medium and low seeding rates, respectively. All other sites had mean GS-25 tiller densities that ranged from 345 to 765 tillers m^{-2} (Table 2). The B-1, K-2, and K-4 sites had lower mean GS-25 tiller densities than the threshold. The mean GS-25 tiller density at W-1 was equal to the threshold, and K-3, K-5, and K-6 had higher mean GS-25 tiller densities than the threshold.

Choice of Model

The three sites where seeding rate was varied to achieve a wide range of tiller densities (P-1, P-2, and K-1) were examined to determine which model (linear or quadratic) would best fit the relationship between spectral indices and GS-25 tiller density. Quadratic models were found to be statistically significant for several sites and spectral measurements (Table 3). Coefficients of simple determination (r^2) for linear models at sites where quadratic models were statistically significant ranged from 0.68 to 0.75 while coefficients of multiple determination (R^2) for quadratic models at these sites had values ranging from 0.71 to 0.77, with the largest increase in R^2 by using a quadratic model being only 0.03. Consequently, there appeared to be little benefit in using a quadratic model over a linear model to describe the relationship between GS-25 tiller density and spectral measurements, and linear models were chosen for further analysis.

Variety Effect

Stone et al. (1996) found different wheat varieties and morphology affected spectral reflectance. At P-1, P-2, and K-1, the influence of wheat variety on the relationship between tiller density and NIR digital counts, normalized NIR, NDVI, RVI, DVI, NIR + R, SAVI, and OSAVI was tested (Table 3). Wheat variety significantly affected the relationship between all spectral measurements and tiller density. This agrees with Stone et al. (1996) and indicates that within-field tiller density references for each wheat variety should be obtained. In our case, there were color differences between Pioneer '2580', which had a blue-green color, and Coker '9704' and 'Roane', which had a greener color. Another difference between these varieties is their growth habit. Pioneer 2580 tends to have upright leaves while both Roane and Coker 9704 tend to have more prostrate

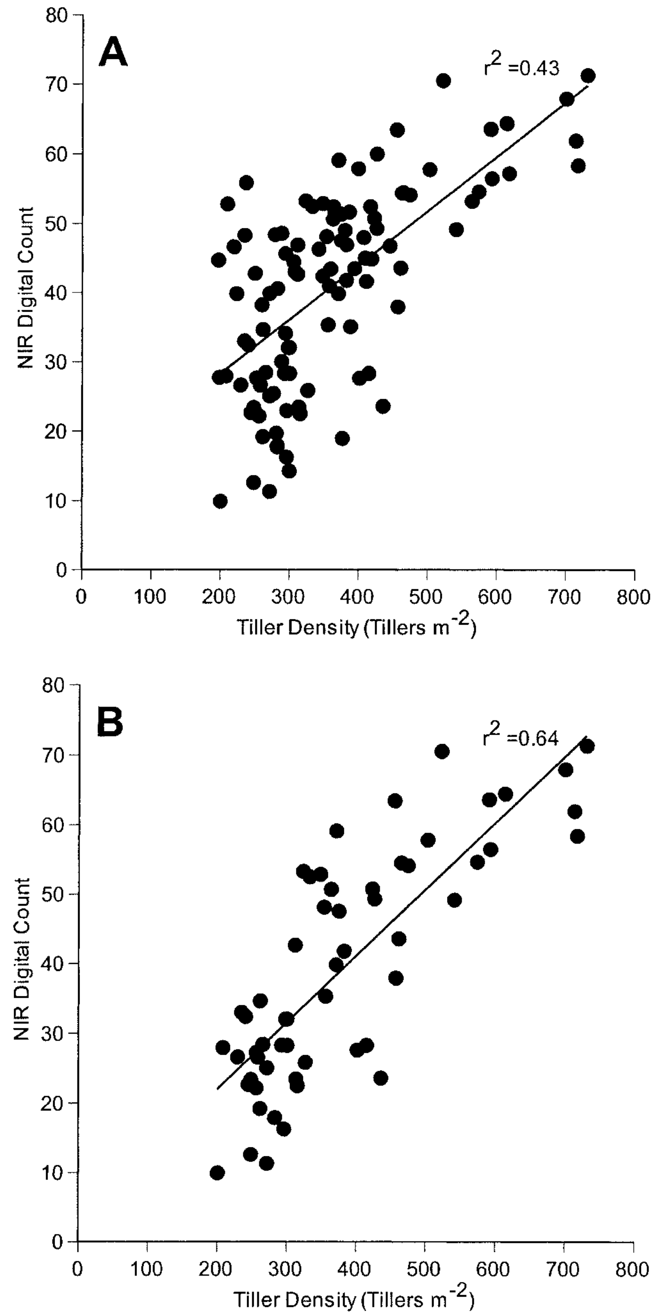

Fig. 1. Near-infrared (NIR) digital counts vs. tiller density for W-1, (A) all sample locations and (B) with the weedy sample locations removed.

leaves. These differences may have affected the relationship between spectral measurements and tiller density by altering the amount of reflected radiation. Due to these varietal influences on reflected radiation, a separate relationship between GS-25 tiller density and spectral measurements for each variety was used in all further analysis of data.

While differences in the spectral reflectance between wheat varieties exist, these differences may not affect remote sensing applications. Fields are typically sown with a single variety, and as a general practice, aerial photographs typically include a single field. Therefore, remote sensing would be used on a field-by-field basis and thus avoid any effect wheat variety may have on spectral reflectance.

Weed Effect

Italian ryegrass (*Lolium multiforum* Lam.) was present in W-1 at GS 25 (49 of 106 sample locations). The GS-25 weed density significantly affected all spectral measurements at W-1 (Table 3). The degradation of the relationship between GS-25 tiller density and NIR digital counts due to the presence of Italian ryegrass at W-1 is shown in Fig. 1. The improvement in linear correlation between all spectral measurements and tiller density by the removal of weedy sample locations (n = 49) at the W-1 site is shown in Table 4. Spectral indices were not any more robust than NIR digital counts when weeds were present at this location (Table 4).

Common chickweed [*Stellaria media* (L.) Villars] and henbit (*Lamium amplexicaule* L.) were prevalent at P-2 at GS 25 (84 of 195 sample locations), but the weed effect was not significant (Table 3). However, weeds at this site were clustered, and consequently a weed effect may have been masked by the strong replication effect (Table 3). Consistent with W-1, improvements were seen in all spectral indices when weedy sample locations (n = 84) were removed from the P-2 data set (Table 4). For further analysis, weedy locations were removed from these two site-years.

Of all the problems faced by the remote sensing, weed population may be the easiest to resolve. Good weed control is an essential component of current agricultural practices. Due to the expense of remote sensing, fields with good weed control may be candidates for remote sensing while weedy fields will not be candidates. Therefore, in practice, weedy fields may be avoided.

Soil Type Effect

Bausch (1993) reported that soil background color significantly altered NDVI values throughout the vegetative growth period of corn (*Zea mays* L.). A similar result was found at K-5 where soil type significantly influenced the relationship between GS-25 tiller density and NIR digital counts (Table 3). When NIR digital counts were regressed against GS-25 tiller density, there was no significant difference in the intercept and slope between data from the Norfolk and Goldsboro loamy sand areas (Table 5). Therefore, the Norfolk and Goldsboro loamy sand sample locations were combined to produce a single linear relationship between NIR digital counts and GS-25 tiller density (Fig. 2 and Table 5). The NIR digital counts for the same tiller densities were lower for the Lynchburg sandy loam compared with the Goldsboro or Norfolk loamy sand. This resulted in one relationship between GS-25 tiller density and NIR digital counts for the Lynchburg sandy loam and a second relationship for the Norfolk and Goldsboro loamy sand.

Soil type differences present a problem for remote sensing because they commonly occur within a field. Huete et al. (1985) reported that soil background influences could affect the spectral properties of a vegetated

Table 4. Correlation coefficients (*r*) for tiller density and near infrared (NIR), normalized NIR, normalized difference vegetation index (NDVI), ratio vegetation index (RVI), difference vegetation index (DVI), the summed NIR and red bands (NIR + R), the soil-adjusted vegetation index (SAVI), and the optimized soil-adjusted vegetation index (OSAVI) at each of the 10 site-years.

Site	Variety	NIR	Normalized NIR	NDVI	RVI	DVI	NIR + R	SAVI	OSAVI
P-1	Coker '9704'	0.85*	0.86*	0.86*	0.85*	0.85*	0.63*	0.86*	0.86*
	Pioneer '2580'	0.78*	0.79*	0.73*	0.63*	0.71*	0.28*	0.73*	0.73*
	'Roane'	0.87*	0.87*	0.88*	0.86*	0.87*	0.66*	0.88*	0.88*
B-1	Coker '9835'	0.79*	0.81*	0.82*	0.79*	0.64*	0.78*	0.82*	0.82*
W-1 w/ weeds	FFR '555'	0.66*	0.65*	0.64*	0.68*	0.71*	0.59*	0.64*	0.64*
W-1 w/o weeds	FFR 555	0.80*	0.80*	0.79*	0.82*	0.83*	0.76*	0.79*	0.79*
P-2 w/ weeds	Coker 9704	0.69*	0.73*	0.73*	0.72*	0.68*	0.46*	0.73*	0.73*
	Pioneer 2580	0.49*	0.61*	0.62*	0.61*	0.56*	0.33*	0.62*	0.62*
	Roane	0.61*	0.77*	0.76*	0.76*	0.74*	0.23†	0.76*	0.76*
P-2 w/o weeds	Coker 9704	0.81*	0.79*	0.78*	0.78*	0.73*	0.72*	0.78*	0.78*
	Pioneer 2580	0.79*	0.76*	0.75*	0.74*	0.67*	0.73*	0.75*	0.75*
	Roane	0.69*	0.77*	0.77*	0.76*	0.75*	0.38*	0.77*	0.77*
K-1	Coker 9704	0.84*	0.82*	0.80*	0.78*	0.81*	−0.33*	0.80*	0.80*
	Pioneer 2580	0.84*	0.81*	0.80*	0.78*	0.80*	−0.29*	0.80*	0.80*
	Roane	0.81*	0.80*	0.79*	0.76*	0.80*	−0.19	0.79*	0.79*
K-2	Coker 9704	0.92*	0.90*	0.91*	0.89*	0.91*	0.65*	0.91*	0.91*
K-3	Roane	0.91*	0.89*	0.84*	0.81*	0.81*	0.60*	0.84*	0.84
K-4	Pioneer '26R91'	0.71*	0.79*	0.80*	0.79*	0.78*	0.53*	0.80*	0.80*
K-5 Goldsboro	Coker 9704	0.85*	NT‡	NT	NT	NT	NT	NT	NT
K-5 Lynchburg	Coker 9704	0.98*	NT	NT	NT	NT	NT	NT	NT
K-5 Norfolk	Coker 9704	0.99*	NT	NT	NT	NT	NT	NT	NT
K-6	Roane	0.80*	0.82*	0.84*	0.70*	0.88*	0.05	0.84*	0.84*

* Significant at the 0.05 level.
† Significant at the 0.1 level.
‡ NT, not tested.

Table 5. Intercept, slope, 95% confidence interval, and coefficient of determination (r^2) values for the linear regression of near-infrared (NIR) digital counts and tiller density at each of 10 site-years based on false color infrared aerial photography.

	NIR digital counts					
Site	Variety	Intercept†	95% confidence interval	Slope†	95% confidence interval	r^2
P-1	Coker '9704'	2.27 a	−1.3–+5.8	0.03 a	0.03–0.04	0.72*
	Pioneer '2580'	5.35 a	1.9–8.8	0.03 a	0.02–0.03	0.61*
	'Roane'	4.93 a	1.46–8.34	0.03 a	0.03–0.04	0.75*
B-1	FFR '535'	−3.53 a	−9.79–+2.74	0.07 b	0.05–0.08	0.62*
W-1 w/o weeds	FFR '555'	2.63 a	−5.23–+10.50	0.10 bc	0.08–0.11	0.63*
P-2 w/o weeds	Coker 9704	86.08 b	76.5–95.7	0.10 bc	0.07–0.14	0.64*
	Pioneer 2580	84.38 b	73.1–95.7	0.16 c	0.10–0.21	0.60*
	Roane	96.17 b	88.0–104.3	0.07 bc	0.05–0.09	0.47*
K-1	Coker 9704	181.07 c	178.0–184.1	0.03 a	0.03–0.04	0.70*
	Pioneer 2580	180.69 c	177.9–183.4	0.03 a	0.03–0.04	0.69*
	Roane	181.23 c	177.6–184.9	0.04 a	0.03–0.04	0.65*
K-2	Coker 9704	115.3 d	110.1–120.4	0.10 c	0.09–0.11	0.85*
K-3	Roane	135.6 e	130.3–140.8	0.07 b	0.06–0.07	0.82*
K-4	Pioneer '26R91'	126.9 de	120.4–133.4	0.09 bc	0.07–0.11	0.50*
K-5 Goldsboro	Coker 9704	114.3 f	104.4–124.2	0.06 b	0.04–0.08	0.71*
K-5 Lynchburg	Coker 9704	85.2 b	77.4–93.0	0.09 bc	0.07–0.11	0.94*
K-5 Norfolk	Coker 9704	116.9 f	110.2–123.5	0.06 b	0.05–0.08	0.98*
K-5 Gold/Nor	Coker 9704	115.7 f	108.8–122.6	0.06 b	0.04–0.07	0.74*
K-6	Roane	64.1 b	56.3–71.9	0.06 b	0.05–0.07	0.64*

* Significant at the 0.05 level.
† Letters indicate statistical difference across site-years based on 95% confidence intervals.

crop canopy. In our study, Fig. 2 and Table 3 show that soil type differences may or may not affect the spectral reflectance. Therefore, remote sensing applications must account for or remove spectral reflectance differences due to soil type. Bausch (1993) reported that SAVI and OSAVI might remove spectral reflectance differences between soil types. This effect was not tested in this study due to the complex nature of combining two aerial photographs. However, spectral indices such as these may offer a solution to the problem of soil type differences within a field.

Choice of Spectral Measure

Consistent significant linear correlations were found between tiller density and NIR digital counts, normalized NIR, NDVI, RVI, DVI, SAVI, and OSVI in all 10 site-years (Table 4). As reported by Flowers et al. (2001), there appeared to be no advantage in using a spectral index derived using wide-band spectral data from CIR aerial photographs over NIR digital counts to estimate tiller density. Consequently, only NIR digital counts were used for further analysis.

Validation of Remote-Sensed Nitrogen Application Decisions

The intercept, slope, and r^2 of NIR digital counts regressed against GS-25 tiller density for all 10 site-years are reported in Table 5. A single equation might be used to predict tiller density across environments if the slope and intercept values were similar for each site. However, consistent with previous findings (Flowers et al., 2001), the slope and intercept values are statistically different across the 10 site-years (Table 5). To remove these differences across environments, Eq. [7] and Eq. [8] were used to convert NIR digital counts and tiller densities to relative values that were regressed against each other. The resultant slope and intercept for 9 of the 10 site-years (Table 6) were not significantly different from those previously reported (Eq. [9]). These nine site-years represented a wide range of environmental conditions, geographical areas, and wheat varieties. Soil types at these sites included a dark mineral organic soil at B-1, lightly colored sandy loams at W-1 and K-1 through K-6, and a red clay soil at P-1 and P-2. Both conventional tillage and no-till with high-residue systems were included. The effectiveness of this technique to remove environmental differences across this range of soils, tillage systems, and varieties indicate that the procedure is robust.

The P-2 site was the only site that had slope and intercept values that were significantly different from Eq. [9]. The difference between this site and the other

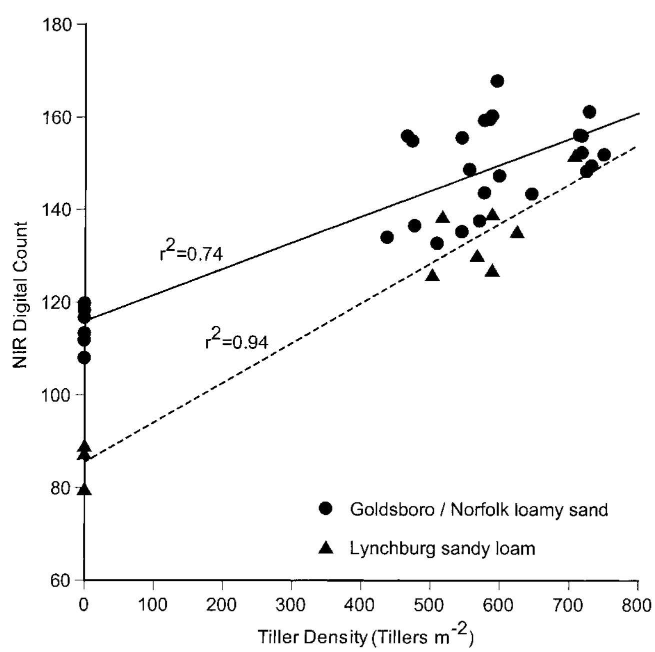

Fig. 2. Near-infrared (NIR) digital counts vs. tiller density by soil type for K-5.

Table 6. Intercept, slope, 95% confidence interval, and coefficient of determination (r^2) values for the linear regression of relative near-infrared (NIR) digital counts and relative tiller density at 10 site-years and for Eq. [9] (Flowers et al., 2001).

	Relative NIR digital counts				
Site	Intercept†	95% confidence interval	Slope†	95% confidence interval	r^2
P-1‡	0.06 a	0.01–0.11	1.01 a	0.91–1.10	0.67*
B-1	−0.07 a	−0.20–+0.06	1.10 a	0.89–1.31	0.62*
W-1 w/o weeds	0.20 a	0.12–0.27	0.83 a	0.66–0.99	0.63*
P-2 w/o weeds‡	0.24 b	0.15–0.33	0.64 b	0.52–0.76	0.55*
K-1‡	0.07 a	0.0–0.14	0.89 a	0.80–0.98	0.66*
K-2	0.05 a	−0.04–+0.13	1.08 a	0.96–1.19	0.85*
K-3	0.13 a	0.05–0.21	1.02 a	0.91–1.13	0.82*
K-4	0.20 a	0.07–0.33	0.84 a	0.65–1.03	0.51*
K-5§	0.02 a	−0.09–+0.12	0.89 a	0.74–1.03	0.80*
K-6	0.18 a	0.06–0.31	0.95 a	0.79–1.11	0.64*
Flowers et al. (2001)	0.07 a	0.01–0.13	1.04 a	0.94–1.14	0.77*

* Significant at the 0.05 level.
† Letters indicate statistical difference from the model based on 95% confidence intervals.
‡ Relative tillers and relative NIR were computed by variety.
§ Relative tillers and relative NIR were computed by soil type.

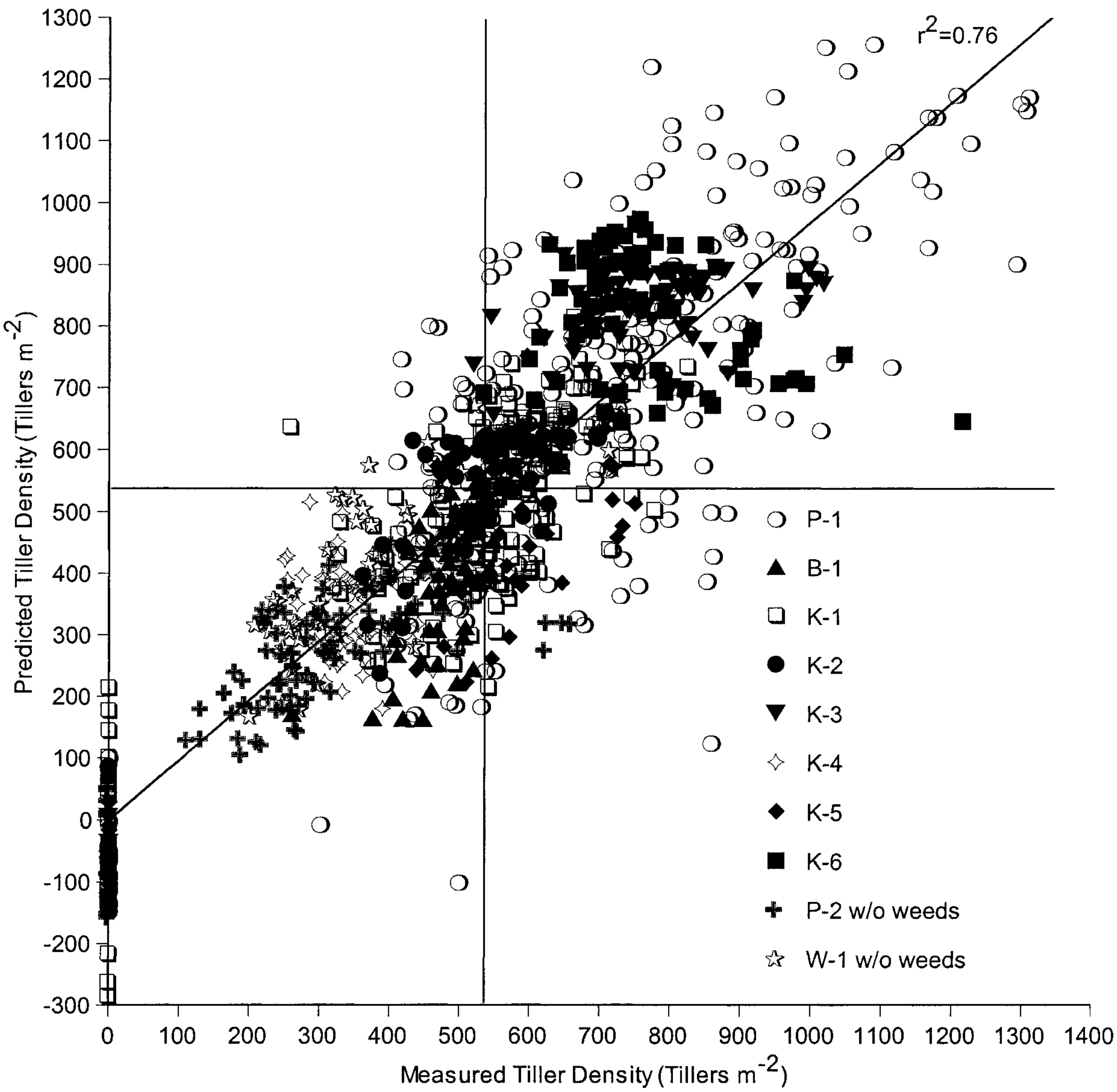

Fig. 3. Predicted tiller density vs. measured tiller density (n = 978) with the critical threshold value of 540 tillers m^{-2} shown. Predicted tiller density for P-1, P-2, and K-1 was calculated by wheat variety. Predicted tiller density for K-5 was calculated by soil type.

Table 7. Number and percentages of incorrectly and correctly recommended growth stage 25 (GS-25) N applications based on the threshold of 540 tillers m^{-2} (Weisz et al., 2001) at each of the 10 site-years.

	Incorrect recommendations			
Site	N needed but not applied	N applied but not needed	Correctly recommended	Total
P-1†	12 (5.3%)	23 (10.0%)	193 (84.7%)	228
B-1	2 (3.1%)	5 (7.8%)	57 (89.1%)	64
W-1 w/o weeds	4 (7.0%)	2 (3.5%)	51 (89.5%)	57
P-2 w/o weeds†	0 (0.0%)	5 (5.2%)	91 (94.8%)	96
K-1†	9 (4.6%)	38 (19.5%)	148 (75.9%)	195
K-2	16 (24.6%)	6 (9.2%)	43 (66.2%)	65
K-3	2 (2.6%)	0 (0.0%)	76 (97.4%)	78
K-4	0 (0.0%)	0 (0.0%)	78 (100.0%)	78
K-5‡	2 (5.1%)	14 (35.9%)	23 (59.0%)	39
K-6	1 (1.3%)	0 (0.0%)	77 (98.7%)	78
All sites	48 (5.0%)	93 (9.5%)	837 (85.5%)	978

† Predicted tiller densities were computed by variety.
‡ Predicted tiller densities were computed by soil type.

sites was that P-2 had a substantial GS-25 weed population (weeds were present in approximately 75% of the site). Even though plots with >50% weed coverage (n = 84) were removed from the data set, there may have been some degradation of the relationship between relative NIR ($NIR_{Relative}$) and relative tiller density ($TD_{Relative}$) due to the lower weed populations in the remaining sample locations. Additionally, the mean tiller density for all seeding rates at P-2 was extremely low (approximately 200 tillers m^{-2} below the threshold). At these low tiller densities, it may be difficult to reliably detect changes in tiller density with remote sensing.

Making Nitrogen Application Decisions

Equation [10] was used to determine predicted tiller density ($TD_{Predicted}$) for data from all 10 site-years (Fig. 3). The relationship was linear with a slope of 0.96 and an intercept of −3.82 (not significantly different than a slope of 1.0 and an intercept of 0.0). The NIR remote sensing technique (Eq. [10]) accounted for 76% of the variation (r^2) between predicted vs. measured GS-25 tiller density across the 10 site-years.

A quadrant plot (Fig. 3) was used to determine the accuracy of the NIR remote sensing technique (Eq. [10]) for predicting if a GS-25 N application was needed based on the tiller density threshold (540 tillers m^{-2}). Table 7 shows quadrant information for each individual site-year. Equation [10] predicted the correct GS-25 N application decision 85.5% of the time across all 10 site-years. Equation [10] incorrectly predicted 5% of the time that a GS-25 N application was not needed and incorrectly predicted 9.5% of the time that a GS-25 N application was needed. Based on the study by Weisz et al. (2001) and the incorrect predictions from Eq. [10], it would be likely that 5% of the time growers would see a reduction in grain yield by not applying N when required. Growers would increase the susceptibility of their wheat crop to freeze 9.5% of the time by applying N applications when not required.

CONCLUSION

The NIR remote sensing technique (Eq. [10]) for predicting GS-25 tiller density was validated over a wide range of environments including differences in wheat varieties, soil types, and the presence or absence of weeds. Weeds degraded the relationship between NIR digital counts and GS-25 tiller density (Fig. 1 and Table 4), indicating that accurate remote sensing of tiller density will be problematic in field areas with weed populations.

Soil type and wheat variety (Table 3) influenced the relationship between tiller density and all spectral measurements. The influence of soil type and wheat variety are significant factors in utilizing remote sensing as they directly influence the amount of actual data that must be collected in the field. To use Eq. [10], the variables TD_{max}, TD_{min}, NIR_{max}, and NIR_{min} must be known for a given field (or photograph). If the soil type or wheat variety changes across the field, values of all four parameters must be determined for each soil type or wheat variety.

Our second objective was to confirm that spectral indices did not improve the ability to determine GS-25 tiller densities compared with NIR digital counts. Near-infrared digital counts, normalized NIR, NDVI, RVI, DVI, SAVI, and OSAVI were strongly and consistently correlated with GS-25 tiller density (when no weeds were present) across all 10 site-years, six varieties, six soil types, and two tillage systems (Table 4). There was no advantage of using a spectral index derived using wide-band spectral data from CIR aerial photographs compared with NIR digital counts alone. Additionally, we also determined that linear models of spectral indices or NIR digital counts and GS-25 tiller density were not improved by considering quadratic terms (Table 3).

Our final objective was to validate the remote sensing technique (Eq. [10]) for making GS-25 N application decisions. Our research shows that Eq. [10] was highly effective in estimating GS-25 tiller density (n = 978, r^2 = 0.76; Fig. 3) across all 10 site-years. Using this NIR remote sensing technique and a critical tiller density threshold for applying N at GS 25 (Weisz et al., 2001), correct application decisions were made 85.5% of the time.

ACKNOWLEDGMENTS

We thank Dr. Carl Crozier, John Burleson, and Brian Roberts for their field support. We would also like to acknowledge the staff at the Piedmont and Cunningham Research Stations and Circle Grove and Hocutt Farms.

REFERENCES

Aull, L.E. (ed.) 1972. Soils of the lower coastal plain tobacco research station, Kinston, North Carolina, and their technical and usability classification. North Carolina Agric. Exp. Stn., North Carolina Dep. of Agric., Raleigh, and USDA, Raleigh.

Avery, T.E., and G.L. Berlin. 1992. Fundamentals of remote sensing and airphoto interpretation. Prentice Hall, Upper Saddle River, NJ.

Baethgen, W.E., and M.M. Alley. 1989a. Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat: I. Crop nitrogen uptake. Agron. J. 81:116–120.

Baethgen, W.E., and M.M. Alley. 1989b. Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat: II. Critical levels and optimum rates of nitrogen fertilizer. Agron. J. 81:120–125.

Bausch, W.C. 1993. Soil background effects on reflectance-based crop coefficients for corn. Remote Sens. Environ. 46:213–222.

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and G.E. Meyer. 1996. Analysis of aerial photography for nitrogen stress within corn fields. Agron. J. 88:729–733.

Colwell, R.N. 1956. Determining the prevalence of certain cereal crop diseases by means of aerial photography. Hildgardia 26:223–286.

ERDAS. 1997. ERDAS Imagine V 8.3 tour guides. ERDAS, Atlanta, GA.

Flowers, M., R. Weisz, and R. Heiniger. 2001. Remote sensing of winter wheat tiller density for early nitrogen application decisions. Agron. J. 93:783–789.

Hatfield, J.L. 1990. Remote detection of crop stress: Application to plant pathology. Phytopathology 80:37–39.

Huete, A.R., R.D. Jackson, and D.F. Post. 1985. Spectral response of a plant canopy with different soil backgrounds. Remote Sens. Environ. 17:37–53.

Huete, A.R. 1988. A soil-adjusted vegetation index (SAVI). Remote Sens. Environ. 25:295–309.

Jackson, R.D., P.N. Slater, and P.J. Pinter, Jr. 1983. Discrimination of growth and water stress in wheat by various vegetation indices through clear and turbid atmospheres. Remote Sens. Environ. 13:187–208.

Jain, A.K. 1989. Fundamentals of digital image processing. Prentice Hall, Englewood Cliffs, NJ.

Jordan, C.F. 1969. Derivation of leaf area index from quality of light on the forest floor. Ecology 50:663–666.

Menges, R.M., P.R. Nixon, and A.J. Richardson. 1985. Light reflectance and remote sensing of weeds in agronomic and horticultural crops. Weed Sci. 33:569–581.

Rondeaux, G., M. Steven, and F. Baret. 1996. Optimization of soil-adjusted vegetation indices. Remote Sens. Environ. 55:95–107.

SAS Institute. 1998. SAS version 7. SAS Inst., Cary, NC.

Scharf, P.C., and M.M. Alley. 1993. Spring nitrogen on winter wheat: II. A flexible multicomponent rate recommendation system. Agron. J. 85:1186–1192.

Scharf, P.C., M.M. Alley, and Y.Z. Lei. 1993. Spring nitrogen on winter wheat: I. Farmer-field validation of tissue test-based rate recommendations. Agron. J. 85:1181–1186.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE 39:1623–1631.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127–150.

Wanjura, D.F., and J.L. Hatfield. 1987. Sensitivity of spectral vegetative indices to crop biomass. Trans. ASAE 30:810–816.

Weisz, R., C.R. Crozier, and R.W. Heiniger. 2001. Optimizing nitrogen application timing in no-till soft red winter wheat. Agron. J. 93:435–442.

Wildman, W.E. 1982. Detection and management of soil, irrigation, and drainage problems. p. 387–401. *In* C.J. Johannsen and J.L. Sanders (ed.) Remote sensing for resource management. Soil Conserv. Soc. of Am., Ankeny, IA.

Yang, C., and G.L. Anderson. 1999. Airborne videography to identify spatial plant growth variability for grain sorghum. Precis. Agric. 1:67–79.

Zadoks, J.C., T.T. Chang, and C.F. Zonzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415–421.