Remote Sensing of Canopy Dynamics and Biophysical Variables Estimation of Corn in Michigan

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ABSTRACT

Remotely sensed data can aid in estimating biophysical variables of corn (*Zea mays* L.). This study identifies spectral wavelengths, spectral vegetation indices (SVIs), and timing needed for estimating yield and leaf area index (LAI) for corn. Canopy reflectance (460–810 nm range) was measured periodically in 1999 and 2000 within a field study varying N and irrigation management for corn. Corn grain yield was strongly related to canopy reflectance for either individual wavelengths or for SVIs, reaching an optimum ($R^2 > 0.9$) at R5 dent stage in both years. Green reflectance based on simple ratio (green simple ratio index, GSRI) had the highest R^2, lowest RMSE, and most consistent slope and intercept between years. In contrast, LAI was best predicted by normalized difference vegetation index (NDVI) (RSME = 0.426) while green normalized difference vegetation index (GNDVI) performed poorly (RMSE = 0.604). Corn grain yield in this study was best predicted at stage R5 using the green simple ratio index.

Optical remote sensing provides a powerful tool for monitoring changes in the crop canopy over the growing season and can provide crop developmental information that is time-critical for site-specific crop management (Moran et al., 1997). It is well known, for example, that plant biochemicals such as chlorophyll can be estimated from spectral reflectance characteristics of plants (Hatfield and Pinter, 1993). Chlorophyll is readily detected because reflectance in the visible part of the spectrum increases with N deficiency (Blackmer et al., 1994). Blackmer et al. (1996) correlated relative corn grain yield to a reflective radiation from a photometric cell centered around 550 nm and concluded that this wavelength was also more sensitive than other wavelengths to N stress in corn. In general, remote sensing has been used for some time to characterize properties of vegetation, to estimate yield, to estimate total biomass, and to monitor plant health and plant stress (Jackson and Pinter, 1986). However, there is room for improvement in the performance of remote sensing for these estimates, particularly in their use in developing and implementing site-specific management systems.

Spectral vegetation indices, calculated as the ratio of various bands or combinations of spectral bands, have been related to a large number of vegetation properties, including yield (Tucker et al., 1980; Wiegand et al., 1990), chlorophyll content (Al-Abbas et al., 1974), and LAI (Qi et al., 2000a). The underlying principle of these empirical spectral indices is that they are affected by the fraction of photosynthetically active radiation absorbed by the vegetation. Commonly used SVIs include the simple ratio index (SRI), which is the ratio of near infrared (NIR) to the red (Jordan, 1969), and the NDVI, which is the ratio of (NIR − red) to (NIR + red) (Rouse et al., 1974). Many other SVIs have been proposed, some more complex in attempts to reduce the effects of other factors such as soil adjusted vegetation index (SAVI) to account for soil background effects (Huete, 1988). Jackson and Huete (1991) provide a discussion and interpretation of the utility of SVIs. More recently, there has been interest in SVIs calculated using the green band in lieu of the red band. Shibayama and Akiyama (1989) suggested using the NIR to green ratio or green simple ratio index (GSRI) for estimation of LAI. Gitelson and Merzlyak (1994) have found that the ratio (NIR to green) is closely related to leaf chlorophyll content. Gitelson et al. (1996) suggested using the NIR to green or GSRI for estimation of physiological status of vegetation. Recent study by Gitelson et al. (2003) have shown that chlorophyll content in corn canopy closely related to LAI and employed the ratio of NIR to green to accurately estimate green LAI in crops.

Remote sensing has also been used to estimate biophysical variables such as LAI, an important input into crop simulation models. Additionally, the temporal and spatial distributions of LAI are often needed in global circulation models to compute energy and water fluxes (Qi et al., 2000b). Qi et al. (2000a) listed two approaches to estimate LAI using remote sensing data, for example, vegetation index approach and a radiative transfer modeling approach. Using a SVI such as NDVI, LAI can be estimated using empirical relationships such as:

$$\mathrm{LAI} = aX^3 + bX^2 + cX + d \qquad [1]$$

where X is either a SVI or reflectance derived from remote sensing data and the coefficients a, b, c, and d are empirically derived. These types of equations can also be applied to remote sensing imagery to map spatial and temporal dynamics of vegetation (Qi et al., 2000a). While easy to use, the coefficients vary with vegetation type. In the radiative transfer modeling, LAI is an input parameter to the model and reflectance is the output. The major advantage of radiative transfer modeling over the regression approach is that it is independent of vegetation types. Carlson and Ripley (1997) used a simple transfer model to illustrate that NDVI, LAI, and frac-

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Abbreviations: DOY, day of year; GNDVI, green normalized difference vegetation index; GSRI, green simple ratio index; KBS, W.K. Kellogg Biological Station; LAI, leaf area index; MTA, mean tip (inclination) angle; NDVI, normalized difference vegetation index; NIR, near infrared; NSI, nitrogen sufficiency index; SAVI, soil adjusted vegetation index; SRI, simple ratio index; SVI, spectral vegetation index.

tional cover (f_c) are interdependent. Qi et al. (2000b) used an empirical approach to estimate LAI and f_c from imagery acquired from Landsat TM, Spot Vegetation, and aircraft sensors. In addition, they also used the neural fuzzy inference system to estimate LAI from remotely sensed data.

The biophysical variables of yield, chlorophyll, and LAI are of great interest in developing and implementing site-specific management systems for corn production and can be estimated spatially and temporally using remote sensing. The objectives of this paper were to (i) identify spectral wavelengths and SVIs that are sensitive to corn N deficiency detection and yield estimation, (ii) identify the optimum growth stage for corn grain yield estimation from SVIs, and (iii) estimate biophysical variables of corn such as LAI from multi-spectral data acquired over corn during two growing seasons.

MATERIALS AND METHODS

This remote sensing study is a subcomponent of a field experiment designed to evaluate site-specific approaches to N fertilizer management for corn conducted in Michigan in 1999 and 2000. Irrigation and N management treatments along with spatial variability of soils in the experimental area induced a broad range of variability in corn growth, development, and yield providing an opportunity for quantifying the relationship between canopy spectral reflectance and SVIs and corn performance. A brief description of the field experiment is provided here to establish the context within which the remote sensing component was performed. The focus here is on the methods and procedures used to measure corn performance and to obtain radiometric measurements.

Site Description

The study was conducted at the W.K. Kellogg Biological Station (KBS) located in southwestern Michigan (85°24′ W long, 42°24′ N lat). The experimental area is gently sloping with soils developed in coarse textured glacial outwash and includes a mixture of two soil series, both Typic Hapludalfs, including the fine-loamy, mixed mesic Kalamazoo series and the coarse-loamy, mixed mesic Oshtemo series (Mokma and Doolittle, 1993). Mean annual temperature at KBS is 9.4°C with annual precipitation averaging 920 mm spread evenly throughout the year and potential evaporation exceeding precipitation for three growing season months per year (Crum et al., 1990). In most years, these soils respond to irrigation and are vulnerable to leaching.

Experimental Design

The field experiment evaluated four N treatments for corn production with and without irrigation. The experimental design was a split-plot with irrigation as the main plot and N treatments were subplots with four replications (total of 48 plots). The irrigation treatments evaluated were (i) none (control), and (ii) irrigation scheduled according to the Michigan irrigation scheduling program (Shayya et al., 1990). The four N fertilizer treatments evaluated included (i) none (control), (ii) N applied at planting (202 and 145 kg ha^{-1} for irrigated and nonirrigated corn, respectively), (iii) N application based on PSNT obtained at V6 leaf stage of corn development, and (iv) sensor based N application in which N was applied in 70 kg ha^{-1} increments when N sufficiency based on relative leaf chlorophyll measurements fell below a critical level. All fertilizer N was applied as 28% solution using a precise liquid fertilizer applicator equipped with a capacity to apply N throughout the N uptake phase of corn growth and development. Fertilizer N application rates for corn following corn were based on MSU fertilizer recommendations (Vitosh et al., 1995) while PSNT fertilizer N rates were reduced based on the PSNT values of N in the surface (0–30 cm). Nitrogen applied at planting was 145 kg ha^{-1} for a yield goal of 7.8 Mg ha^{-1} for nonirrigated corn and 202 kg ha^{-1} for a yield goal of 12.5 Mg ha^{-1} for irrigated corn. Nitrogen was applied in 70 kg ha^{-1} increments from V6 to V14 for sensor-based N treatments based on weekly leaf chlorophyll readings using the N applied at planting as the reference crop. A Minolta SPAD-502 (Spectrum Technologies, Plainfield, IL) chlorophyll meter was used to measure red (690 nm) and NIR (940 nm) leaf transmittance on 30 plants per plot from V6 to V14 stages of growth. The upper most, fully expanded leaf with a leaf collar exposed was measured from V6 to tassel stage after which the ear leaf was measured. Nitrogen fertilizer application was triggered in the stress-based N treatment when reflectance of corn reached 96% of the reflectance of well-fertilized corn (the nitrogen sufficiency index, or NSI) as this level has been shown to maintain corn yield (Schepers et al., 1996).

Soil was fall chisel plowed and fitted with a field cultivator before planting. Pioneer 3730 corn variety was planted on 26 Apr. 1999 and 29 Apr. 2000 at seeding rates of 64 250 and 86 500 seeds ha^{-1} for nonirrigated and irrigated corn, respectively.

Water was applied using drip irrigation with application beginning on day of year (DOY) 197 in 1999, approximately at the time of silking. Applications of 12.7 mm (0.5 inch) of water were applied when prescribed by the irrigation scheduling program. High seasonal precipitation in 2000 precluded the need for irrigation. A weather station at KBS provided input for irrigation scheduling calculations and a rain gauge was maintained at the site to ensure a site-specific rainfall record.

A multispectral ground-based radiometer (CropScan, MSR87, CropScan, Rochester, MN) was used to measure the green, red, and NIR spectral reflectance bands. The CropScan radiometer contains a set of eight narrow band filters with band width of 457 to 463, 506 to 515, 556 to 564, 606 to 616, 654 to 665, 702 to 714, 756 to 766, and 797 to 829 nm. The filters centered at 460, 510, 560, 610, 660, 710, 760, and 810 nm, respectively. The CropScan radiometer has a 28-degree field of view for reflected radiation. The sensor was mounted on a 2.62-m pole positioned above the canopy at nadir viewing and a cherry picker was used when the crop reached silking stage of growth. Measurements were taken under clear sky conditions. The sensor was oriented parallel (north to south direction) to the corn rows resulting in a circular ground area of about 1.34 m^2. Weekly multispectral measurements were taken using the CropScan radiometer from the V6 growth stage to maturity. Two measurements per plot were taken in 1999 between 1030 and 1330 h for the following days of the year: 162, 167, 175, 177, 181, 188, 195, 217, 224, and 238. Three measurements per plot were taken in 2000 on days of the year 161, 168, 172, 179, 188, 202, 208, 217, 222, 229, 238, 245, and 250.

Leaf area was measured from V6 (2000 season only) to silking for each plot using the LAI-2000 plant canopy analyzer (Li-Cor leaf area meter, Li-Cor, Lincoln, NE). The LAI-2000 computes an estimate of LAI and mean tip (inclination) angle (MTA) for a vegetative canopy from measurements of light interception made at five angles simultaneously. Light readings made below a canopy are divided by readings made above the canopy to compute transmittance at the five angles. A control unit records these readings and calculates LAI and MTA from transmittance. Twenty readings per plot were taken every week from V6 stage of growth to silking to evaluate LAI for 2000 growing season. The value of LAI is in m^2 foliage per m^2 of soil.

Statistical Analysis

Regression analysis was performed on grain yield for each plot for all N treatments at different wavelengths and against selected vegetation indices such as NDVI, SAVI, SRI, GNDVI, and GSRI using the SAS PROC REG procedure (SAS Inst., 2000). Coefficients for Eq. [1] were empirically obtained for combined N treatments to model LAI for NDVI, GNDVI, and SAVI. Coefficients of determination and RMSE are reported to compare the results at different wavelengths and the performance of SVIs.

RESULTS AND DISCUSSION

The 1999 growing season was warm and dry with a mean seasonal (May–September) temperature of 26°C and seasonal rainfall of 363 mm, while the 2000 growing season was cooler than 1999 and very wet with a mean seasonal temperature of 23°C and seasonal rainfall of 698 mm (Fig. 1). The lack of rainfall in 1999 produced an early season drought and supplemental irrigation was required for reasonable corn grain yields. Even though the installation of irrigation delayed water application in 1999 until early July approximately at silking, irrigation increased grain yields to maximum levels observed for this location. The rainfall in 2000 was sufficient in both frequency and quantity to preclude the need for irrigation. However, the range in grain yield in 2000 was similar to 1999 due to the lower yields attained in the control N treatments.

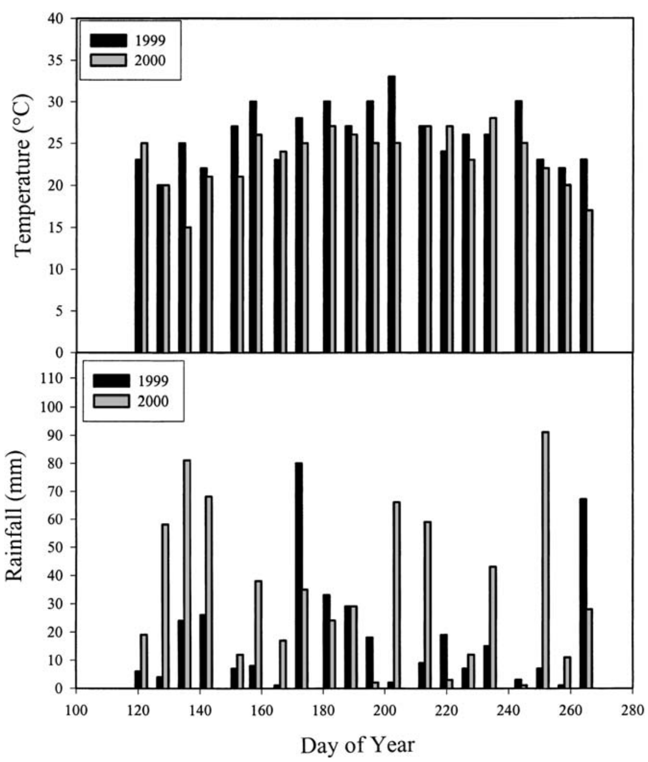

Fig. 1. Seasonal (May–September) weekly average temperature (°C) and rainfall (mm) for the 1999 and 2000 growing seasons.

Data for NSI for 1999 and 2000 are presented in Fig. 2 to document how N sufficiency in corn varied throughout the growing season and corn response to intervention N management. Early in the 1999 growing season (from DOY 160 to 180), NSI declined where soil N was not adequate (Fig. 2). The NSI recovered in the PSNT and sensor-based N treatments once N fertilizer was applied but the recovery was prolonged (DOY 180–200), probably due to dry soil conditions. Although irrigation was begun on DOY 197, NSI recovery in the irrigated PSNT and sensor N treatments took longer than in the nonirrigated N treatments. As expected, NSI in the N control treatments continued to decline throughout the growing season, with the irrigated N control consistently lagging behind the nonirrigated N control treatment until sometime after DOY 217. On DOY 217, all treatments receiving N fertilizer had similar NSI, but within a short time period the nonirrigated corn rapidly senesced due to the season long drought causing NSI to drop rapidly relative to the irrigated corn. In 2000, the early season pattern for the PSNT and sensor-based N treatments was similar to 1999 and the control N treatment declined throughout the season (Fig. 2). Overall, there was N deficiency of some sort in the corn most of the growing season, creating the range of N deficiency and yield variability needed for assessing the relationship between important properties of corn and canopy reflectance and SVIs.

Blackmer et al. (1996) suggested the use of relative reflectance as a way to eliminate non-N-based illumination differences between different N treatments. The

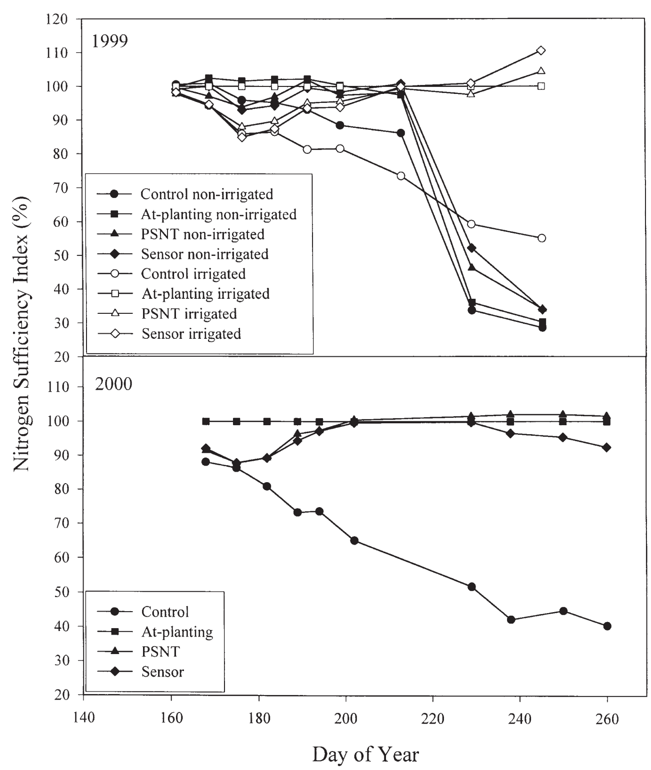

Fig. 2. Variation in nitrogen sufficiency index (NSI) over time for irrigated and nonirrigated N treatments in 1999 and N treatments averaged over irrigation in 2000.

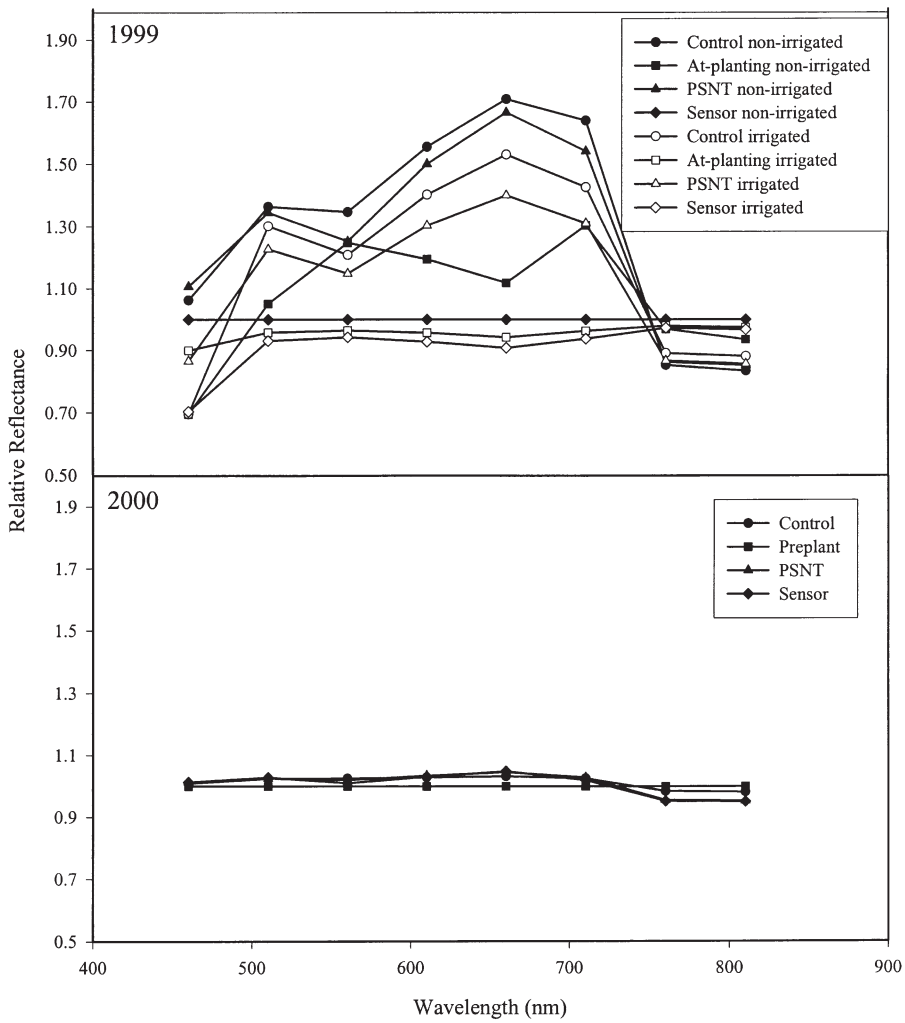

Fig. 3. Variation in the relative reflectance of corn canopy as a function of wavelength near silking on 5 Aug. 1999 for both irrigated and nonirrigated N treatments and near silking on 4 Aug. 2000 for N treatments averaged over irrigation. PSNT, presidress nitrogen treatment.

relative reflectance is defined as the ratio of reflected radiation from different N treatments to reflected radiation from a reference canopy treatment (Blackmer et al., 1996). In 1999, relative reflectance was greatly enhanced in the nonirrigated corn and to a lesser extent in the irrigated N control treatment, particularly in the 610, 660, and 710 nm wavelengths for DOY 217 in Fig. 3. Contrast this response to the relative lack of response in the NSI on DOY 217 in 1999 (Fig. 2). In 2000, also on DOY 217, there was only a very slight effect of N treatment on relative reflectance (Fig. 3). The difference in relative reflectance between treatments in 1999 and 2000 and the lack of differences in NSI suggest that relative reflectance may be sensitive to water stress levels in corn more than N stress.

The relationship between canopy reflectance, expressed as percent reflectance, and corn grain yield varied throughout the growing season in both 1999 and 2000 (Table 1). The strength of the relationship varied by wavelength and progressively increased as the growing season progressed. In 1999, the highest R^2 occurred on DOY 224 and in the 560, 610, and 710 nm wavelengths. By DOY 238 the relationship collapsed at all wavelengths. In 2000, the relationship was strong by DOY 217 for all wavelengths and peaked on DOY 238, collapsing by DOY 250. It would appear that wavelengths 560 and 710 nm observed near the R5 dent stage but before maturity would provide a good prediction of corn grain yield over crop years.

A comparison of red and green reflectance-based SVIs for corn yield prediction shows that, for both 1999 and 2000, corn yield prediction progressively improved during the growing season, was optimal by the R5 dent stage, and collapsed by maturity (Table 2). Poor relationships early in the season are attributed to the fact that SVIs early in the season do not represent the canopy photosynthetic size (maximum leaf area index). When LAI reaches its maxima or plateau value for the season, the sink for photosynthetic assimilates is dominated by the plant parts that constitute yield (Wiegand et al., 1990). However, grain yields are generally better correlated with SVIs integrated over the growing season than single date SVIs (Wiegand et al., 1990; Wiegand and Richardson, 1990). In 1999, a year of significant water stress, the GNDVI and GSRI performed better than NDVI and SRI as evidenced by higher R^2 and lower

Table 1. The relationship between corn grain yield (Mg ha^{-1}) and various wavelengths throughout the 1999 and 2000 growing seasons as measured by coefficients of determination (R^2) and RMSE (48 samples).†

	Wavelength														
	510		560		610		660		710		760		810		
DOY	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	Stage of growth
							1999								
162	0.10	0.25	0.00	0.54	0.19	0.56	0.33	0.49	0.08	0.78	0.58	2.01	0.54	2.40	V6 leaf
167	0.16	0.87	0.05	3.12	0.01	1.58	0.32	0.83	0.23	1.19	0.18	1.34	0.24	1.30	V7 leaf
175	0.23	0.55	0.29	0.56	0.24	0.85	0.24	0.99	0.24	0.95	0.00	1.85	0.01	2.20	V8 leaf
177	0.32	0.46	0.39	0.95	0.38	0.87	0.34	0.80	0.37	1.38	0.02	3.32	0.0	3.35	V10
181	0.42	0.39	0.38	0.74	0.47	0.70	0.45	0.69	0.43	0.98	0.12	1.90	0.20	1.97	V10-V14
188	0.55	0.41	0.35	0.69	0.48	0.83	0.52	0.83	0.43	1.07	0.04	1.72	0.07	1.80	tasseling
195	0.55	0.41	0.35	0.68	0.48	0.82	0.52	0.82	0.43	1.06	0.09	1.70	0.07	1.77	silking
217	0.51	0.47	0.79	0.46	0.67	0.74	0.56	0.95	0.75	1.03	0.49	1.96	0.63	2.00	R2-R3
224	0.68	0.30	0.90	0.31	0.82	0.52	0.68	0.75	0.88	0.65	0.68	1.91	0.78	1.90	R5-dent
238	0.01	0.52	0.09	0.79	0.10	0.69	0.16	0.53	0.15	0.67	0.12	1.95	0.12	2.31	maturity
							2000								
161	0.00	0.20	0.01	0.57	0.00	0.48	0.00	0.38	0.01	0.73	0.02	2.16	0.03	2.57	V6 leaf
168	0.00	1.98	0.05	1.44	0.00	6.94	0.01	5.37	0.00	8.72	0.00	2.06	0.02	1.84	V7–V8
172	0.02	1.42	0.06	1.43	0.01	6.95	0.01	5.37	0.00	8.72	0.00	2.06	0.00	1.91	V10
179	0.08	1.80	0.07	2.45	0.08	3.09	0.08	3.15	0.08	3.38	0.05	3.63	0.05	3.81	V12–V14
188	0.08	1.80	0.19	1.87	0.19	2.37	0.20	2.48	0.19	2.68	0.05	3.22	0.05	3.30	tasseling
202	0.15	1.43	0.55	0.41	0.41	0.56	0.38	0.62	0.35	0.74	0.09	2.00	0.10	2.25	tasseling
208	0.42	0.21	0.48	0.71	0.48	0.60	0.47	0.44	0.47	1.03	0.29	1.69	0.35	2.16	silking
217	0.72	0.198	0.92	0.40	0.91	0.31	0.82	0.29	0.92	0.52	0.22	2.16	0.48	2.49	silking
222	0.81	0.16	0.94	0.34	0.91	0.31	0.88	0.25	0.94	0.46	0.68	1.46	0.81	1.61	R2–R3
229	0.81	0.17	0.94	0.35	0.90	0.37	0.85	0.33	0.94	0.52	0.47	1.76	0.66	1.98	R4
238	0.89	0.12	0.96	0.29	0.94	0.30	0.92	0.26	0.95	0.43	0.78	1.38	0.85	1.55	R5
245	0.62	0.20	0.72	0.56	0.70	0.52	0.67	0.42	0.72	0.82	0.49	1.76	0.57	2.09	R5
250	0.03	0.45	0.03	0.93	0.03	1.03	0.4	0.94	0.04	1.42	0.06	1.86	0.06	2.33	maturity

† DOY, day of year.

Table 2. The relationship between corn grain yield (Mg ha^{-1}) and various spectral vegetation indices throughout the 1999 and 2000 growing seasons as measured by coefficients of determination (R^2) and RMSE (48 samples).†

	Wavelength								
	NDVI		SRI		GNDVI		GSRI		
DOY	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	Stage of growth
				1999					
161	0.10	2593	0.11	2589	0.07	2694	0.07	2709	V6 leaf
167	0.1	2601	0.1	2610	0.09	2613	0.09	2617	V7 leaf
175	0.49	1947	0.38	1956	0.34	2225	0.38	2236	V8 leaf
177	0.48	1934	0.48	1978	0.32	2258	0.48	2292	V10
181	0.48	1966	0.49	1858	0.48	1973	0.50	1944	V10–V14
188	0.36	2195	0.40	2129	0.44	2046	0.45	2026	tasseling
195	0.61	1719	0.74	1382	0.87	1002	0.90	853	silking
217	0.71	1487	0.82	1167	0.92	788	0.95	607	R2–R3
224	0.20	2456	0.18	2473	0.19	2468	0.16	2511	R5-dent
238	0.20	2456	0.18	2473	0.19	2468	0.16	2511	maturity
				2000					
161	0.005	3258	0.002	3262	0.11	3074	0.11	3080	V6 leaf
168	0.12	3056	0.13	3055	0.12	3056	0.11	3088	V7–V8
172	0.27	2842	0.23	2878	0.29	2755	0.27	2783	V10
179	0.23	2861	0.23	2865	0.18	2960	0.18	2962	V12–V14
188	0.31	2601	0.27	2790	0.43	2357	0.37	2590	tasseling
202	0.41	2486	0.43	2466	0.47	2451	0.49	2389	tasseling
208	0.48	2345	0.48	2365	0.49	3232	0.49	2337	silking
217	0.90	1002	0.86	1218	0.96	667	0.96	683	silking
222	0.94	811	0.98	719	0.97	578	0.98	503	R2–R3
229	0.91	992	0.96	760	0.96	561	0.97	554	R4
238	0.93	875	0.96	690	0.97	572	0.97	532	R5
245	0.70	1797	0.68	1840	0.74	1674	0.72	1743	R5
250	0.05	3182	0.04	3196	0.04	3203	0.03	3214	maturity

† DOY, day of year; GNDVI, green normalized difference vegetation index; NDVI, normalized difference vegetation index; SRI, simple ratio index.

RMSE (Table 2 and Fig. 4). In 2000, all four of the SVIs had very high predictive value (high R^2) for corn grain yield, but the GNDVI and the GSRI had lower RMSE values (Table 2 and Fig. 4). Overall, the GSRI had the highest R^2, lowest RMSE, and most consistent slope and intercept between years than the other SVIs (Fig. 4) at the R5 dent stage of corn development. Visual inspection of the plots in Fig. 4 clearly shows the better fit of the data points to the regression line in the GSRI plots for both years and hence the lowest RMSE. As expected, leaf chlorophyll content was highly correlated to corn grain yield at the R5 dent stage and highly correlated with the SVIs (Fig. 5). The RMSE of the regression between chlorophyll and corn grain yield was higher than

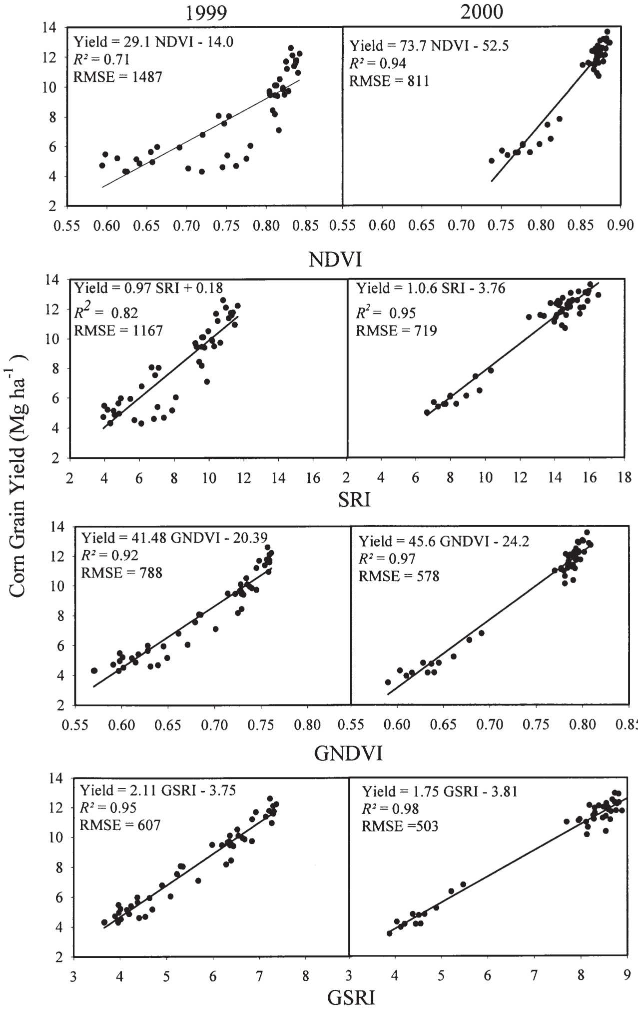

Fig. 4. The relationship between corn grain yield and spectral vegetation indices on 12 Aug. 1999 and 9 Aug. 2000. GNDVI, green normalized difference vegetation index; NDVI, normalized difference vegetation index; SRI, simple ratio index.

GNDVI and GSRI but lower than NDVI and SRI. Given the performance and the relative ease of obtaining data using SVIs, particularly the GNDVI and GSRI, remote sensing would be preferred over the use of hand held chlorophyll meters. These results suggest that overall, SVIs that use green reflectance values such as GNDVI and GSRI are better suited for corn grain yield prediction than vegetation indices that use red reflectance values, a conclusion supported by recent literature (Gitelson et al., 1996). Furthermore, these results suggest that corn grain yield is best predicted at reproductive stages of growth from milk to dent time.

Table 3. Empirical coefficients, coefficient of determination (R^2), and RMSE for the fit of Eq. [1] for NDVI, GNDVI, and SAVI for the modeling of LAI for 2000 growing season (32 samples).†

Coefficients	a	b	c	d	R^2	RMSE
Vegetation index						
NDVI	−0.077	0.296	−0.0218	0.316	0.839	0.358
GNDVI	0.0012	−0.067	0.372	0.246	0.907	0.273
SAVI	−0.072	0.343	−0.281	0.599	0.844	0.353

† GNDVI, green normalized difference vegetation index; LAI, leaf area index; NDVI, normalized difference vegetation index; SAVI, soil adjusted vegetation index.

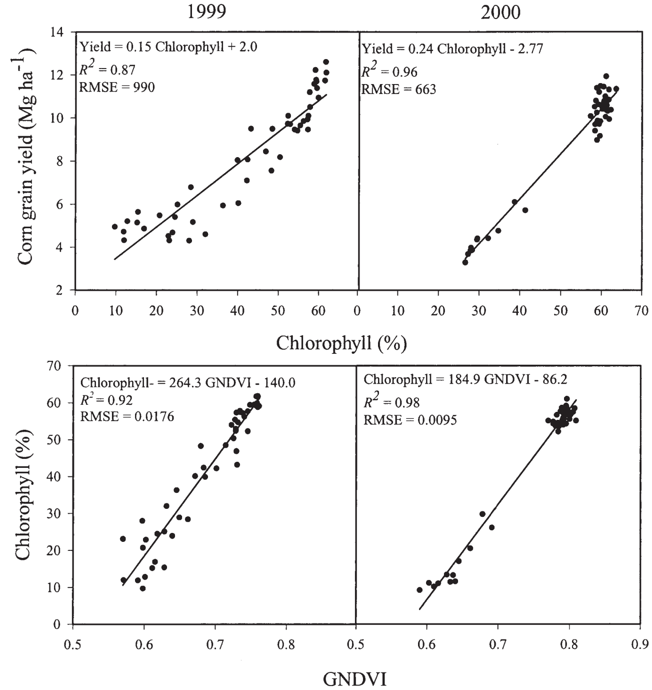

Fig. 5. The relationship between corn grain yield and corn leaf chlorophyll and GNDVI and corn leaf chlorophyll on 12 Aug. 1999 and 9 Aug. 2000. GNDVI, green normalized difference vegetation index.

Using Eq. [1], LAI was modeled as a function of SVI for NDVI, SAVI, and GNDVI for combined N treatments. The fit of Eq. [1] to all three SVIs was very good with high R^2 and similar RMSEs (Table 3). The equation for each SVI was used to predict LAI for the same dates LAI was measured in 2000. The NDVI predicted LAI best overall (lowest RMSE) but deviated from the 1:1 line when LAI exceeded 2.3 (Fig. 6). The underprediction of LAI at higher LAI is expected and is consistent with other reports (Westgate et al., 1997). The SAVI, which accounts for exposed soil influences on reflected light at low LAI, deviated from the 1:1 line at LAI < 1.3 when soil influences on reflectance should have been present and at LAI > 2.3 as was the case with NDVI. The GNDVI did not perform well as it overestimated at LAI < 1.3, similar to SAVI, but underestimated LAI > 2.0. Based on these results for 1 yr, NDVI did better in predicting LAI than SAVI or GNDVI below LAI of 2.3.

CONCLUSIONS

Either selected single wavelengths in the 510 to 760 nm range or SVIs can be used to estimate corn grain yields if the measurements are obtained near the R5 dent stage of corn development. The SVIs were also highly correlated to leaf chlorophyll. These data support the use of green reflectance-based SVIs, specifically GSRI and GNDVI, over red reflectance-based SVIs for corn grain yield estimation because they performed better based on R^2 and RMSE. In contrast, LAI was best estimated by NDVI while GNDVI performed poorly. Therefore, it is important to calibrate SVIs with specific plant attributes before assuming general applicability.

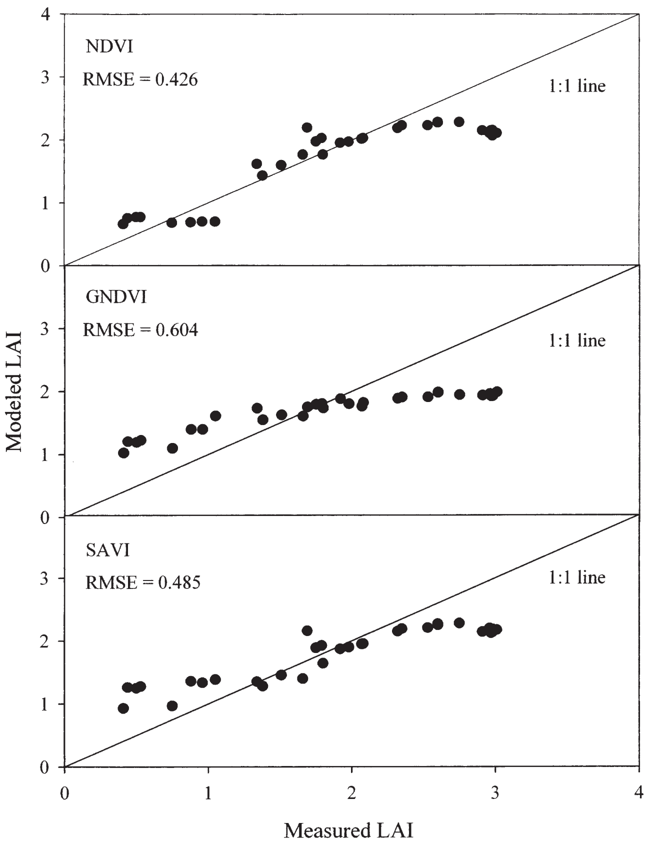

Fig. 6. The relationship between modeled leaf area index (LAI) from vegetation indices and measured LAI for all N treatments for 2000 growing season. GNDVI, green normalized difference vegetation index; NDVI, normalized difference vegetation index; SAVI, soil adjusted vegetation index.

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