Remote Sensing

Sun Position and Cloud Effects on Reflectance and Vegetation Indices of Corn

Eduardo G. de Souza, Peter C. Scharf,* and Kenneth A. Sudduth

ABSTRACT

The reflectance characteristics of plants and plant canopies far from solar noon (i.e., at large solar zenith angles) or with cloudy skies are not well known. This is an obstacle to making real-time, variable-rate N fertilizer applications based on canopy reflectance because such a system must work under cloudy skies and at all times of day. Our objective was to develop spectral radiometer reflectance corrections for variations in incoming sunlight so that the same reflectance reading would be obtained (and the same N recommendation made) for the same plants regardless of time of day or cloud conditions. Passive spectral radiometers were mounted in a stationary position about 25 cm above the corn (*Zea mays* L.) canopy. Readings were taken from morning until night over several days with a range of sky conditions (sunny, overcast, and partly cloudy). Experiments were done in the field in April and May on greenhouse-grown corn ranging from V10 to R2 growth stages. Sun angle, time of day, and cloud cover all influenced reflectance measured from the corn canopy. When regression models were applied to correct reflectance values to reference conditions for these variables, coefficients of variation were reduced by 29 to 56% for vegetation indexes and by 43 to 56% for reflectance values. The near-infrared/green ratio and the green normalized difference vegetation index were the indices most sensitive to N deficiency among six analyzed indices.

The reflectance characteristics of plants and plant canopies under conditions considerably different than those found around solar noon and with clear skies are not well known (Tumbo et al., 2002). However, Davis (1957) showed that the reflectance of grass varied with solar elevation, from 22% at noon to about 43% at sunrise and 48% at sunset. Gardener (1983) stated that one major unresolved issue in using reflectance measurements to estimate crop canopy development is the effect of diurnal changes in solar insolation and canopy reflectance characteristics on vegetative indices for estimating leaf area, phytomass, or phenology.

Canopy reflectance characteristics are complex. The interaction between canopy geometry, solar zenith angle, solar azimuth angle, shadows, and view angle influence observed reflectance (Jackson et al., 1979; Ranson et al., 1985). Even individual leaves display complex bidirectional reflectance behavior (Walter-Shea et al., 1989). Reflectance measurements in crop canopies are thus sensitive to environmental conditions, and care must be taken in interpreting such measurements for use in crop management or other applications.

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A sensor-based, real-time, variable-rate application system for N fertilizer has the potential to reduce input costs, improve yields, and reduce N loss to the environment (Tumbo et al., 2002; Raun et al., 2002). The system must work under cloudy skies and at all times of day. Past studies with reflectance sensors have mostly used data collected around solar noon with clear skies (e.g., Bausch and Duke, 1996; Blackmer et al., 1996). Newer active-light "reflectance" sensors are designed to be less sensitive to environmental conditions, but evidence proving this is unavailable, and limited evidence suggests that diurnal variations for these sensors aimed at plant targets are substantial (Scharf et al., 2007). Knowledge of reflectance behavior is important to enable practical application of real-time, variable-rate application systems for N fertilizer based on canopy reflectance.

Traditionally, soil testing, plant tissue analysis, and long-term field trials have been used to assess N availability for crops (Kitchen and Goulding, 2001). Since the early 1990s, hand-held chlorophyll meters have been available to monitor plant N status by measuring the transmittance of radiation through a leaf in two wavelength bands centered near 650 and 940 nm (e.g., Peterson et al., 1993; Blackmer et al., 1994; Wood et al., 1993).

Previous research has shown that corn reflectance of green and near-infrared (NIR) light measured with a radiometer is sensitive to N status (Bausch and Duke, 1996) and can be used to predict the amount of N fertilizer needed by the crop (Dellinger et al., 2008; Scharf and Lory, 2009). Walburg et al. (1982) confirmed that corn spectral properties associated with N deficiency are likely to be apparent by the V12 growth stage,

Abbreviations: CV, coefficient of variation; fR, flat receiver reflectance; GNDVI, green normalized difference vegetation index; ICI, instantaneous clearness index; NDVI, normalized difference vegetation index; NIR, near-infrared; OSAVI, optimized soil-adjusted vegetation index; rR, reference panel reflectance; SAVI, soil-adjusted vegetation index.

when the crop still has the potential for large yield responses to added N (Russelle et al., 1983; Scharf et al., 2002). Blackmer et al. (1996) measured reflected radiation from R5-growth-stage corn canopies using reference areas with nonlimiting N to calculate relative reflectance. They concluded that the reflected radiation around 550 and 710 nm provided the best detection of N deficiency in the 400- to 1000-nm spectral range.

Clouds may also influence reflectance measurements. Gao and Li (2000) reported normalized difference vegetation index (NDVI) errors of 15% due to the presence of thin cirrus clouds in spectral imaging data. There is much research investigating the influence of clouds in satellite or airborne imagery (Simpson et al., 2000; Gao and Li, 2000), but there are few reports about the influence of clouds on remote sensing data acquired at the earth's surface. Tumbo et al. (2002) investigated the effect of cloud cover on corn plant reflectance and found that, as cloud cover increased and solar irradiance decreased, graphs of the spectral irradiance as a function of wavelength stayed almost parallel to each other. This observation implies that an irradiance value at one particular wavelength can be used for relative comparison of spectral irradiance patterns obtained under different conditions. It was also reported that the percent reflectance did not remain constant for different irradiances.

Total radiation reaching the ground depends mainly on sun position and cloud cover (Campbell and Norman, 1998). On time scales of a few minutes, the presence of scattered clouds, especially towering cumulus, can reflect additional solar radiation onto small areas to cause irradiance measurements in excess of those obtained under clear skies.

Because of the complex three-dimensional geometry of a plant canopy, light returned from the canopy is a complex mixture of multiple reflected and/or transmitted components (Daughtry et al., 2000). The overall brightness of the canopy and the shape of the spectral signature (e.g., the red to NIR ratio) are strongly dependent on the illumination and viewing geometry. For example, Jackson et al. (1979) studied the dependence of wheat spectral reflectance on crop configuration, sun elevation, and azimuth angle. The authors concluded that row direction relative to sun azimuth is a major determinant of visible reflectance of wheat that has not reached full canopy cover.

Vegetation indices (VI) are useful to minimize variations due to extraneous factors and maximize sensitivity to the variable of interest, in this case the corn leaf chlorophyll concentration (Daughtry et al., 2000). These indices take advantage of the low reflectance in the visible wavelengths and the high reflectance in the NIR wavelengths that are characteristic of living vegetation. The VIs reported in the literature are numerous and may be broadly grouped into three categories: (i) intrinsic indices, (ii) soil-related indices, and (iii) atmospherically adjusted indices. Daughtry et al. (2000) concluded that some VIs (e.g., optimized soil-adjusted vegetation index [OSAVI] and NIR/red ratio) minimized background reflectance contributions, whereas others (e.g., the modified chlorophyll absorption in reflectance index and the NIR/green ratio) responded more to leaf chlorophyll concentrations. Tumbo et al. (2002) found a strong correlation ($r^2 = 0.94$) between the NIR/green ratio and chlorophyll concentration in V6 growth stage corn at constant solar irradiance.

Our objective for this project was to develop spectral radiometer reflectance corrections for variations in incoming sunlight so that the same reflectance reading would be obtained (and the same N recommendation made) for the same plants regardless of time of day or cloud conditions. Greenhouse-grown corn was used to make it possible to carry out this experiment early in the growing season (April and May 2001). It was assumed that greenhouse-grown corn, when moved into a typical field setting, could substitute for corn grown in natural field conditions.

MATERIALS AND METHODS

General Procedures

Corn (*Zea mays* L.) was grown in a greenhouse using a growing medium of 10% potting soil, 30% peat, and 60% sand (by volume) to provide a low N level. Corn was planted on 3 Mar. 2001, and ammonium nitrate (NH_4NO_3) was applied after planting to supply 150, 100, and 50% of the recommended rate of N (180 kg ha^{-1}) and to establish a range of leaf chlorophyll levels. To convert the N rate from kg ha^{-1} to kg plant^{-1}, a corn population of 58,400 plants ha^{-1} was used. Each treatment had 10 pots (10 replications), with each pot receiving approximately 5 kg of growing medium with the pH adjusted to between 6 and 7. Four seeds per pot were planted at a depth of 2.5 cm, but only one plant was left after thinning. Ammonium nitrate was applied up to three times, with applications 1 wk apart. Each application was 4.6 g pot^{-1}, but each treatment received a different number of applications. Treatment 1 (N1 = 270 kg ha^{-1}) received applications in Weeks 1, 2, and 3; Treatment 2 (N2 = 180 kg ha^{-1}) received applications in Weeks 1 and 2; and Treatment 3 (N3 = 90 kg ha^{-1}) received one application in Week 1.

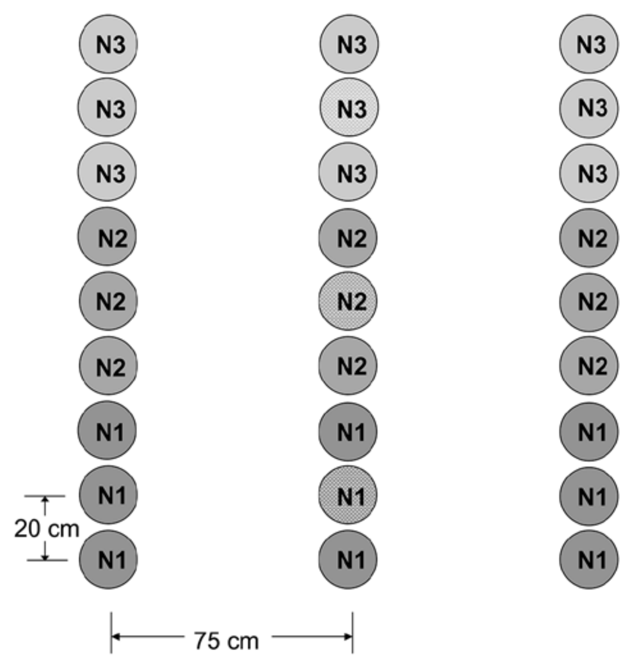

Fig. 1. Arrangement of plants during reflectance measurements. Each circle represents one plant. Reflectance was measured on the center plant (indicated by stippling) of each nitrogen rate treatment. Nitrogen rate treatments are N1 = 270 kg N ha^{-1}, N2 = 180 kg N ha^{-1}, and N3 = 90 kg N ha^{-1}. Darker gray color signifies higher nitrogen rate.

Macronutrients (P, K, Ca, and Mg) and micronutrients (Fe, Mn, Zn, Cu, and B) were applied to all treatments at rates sufficient to ensure that these nutrients did not limit growth. For spectral measurements, the potted corn plants were transported to a research field at Columbia, Missouri (38°57' N, 92°19' W). Spectral data were obtained during the period of 27 Apr. 2001 to 27 May 2001 on corn at the V10 to R2 growth stage. One randomly selected corn plant from each of three treatments was used to measure spectral reflectance. All data were taken on the same plant surrounded by plants from the same treatment. The corn plants were arranged in three north-south rows with plants spaced 20 cm apart within a row and 75 cm apart from row to row. Treatments were arranged contiguously so that each row contained three plants from treatment N1, then three plants from treatment N2, and then three plants from treatment N3, all spaced 20 cm apart (Fig. 1).

Spectral data were obtained on a 2-s interval from 0700 to 1900 h each day and smoothed using a 60-measurement moving average. Due to the large increase in reflectance as solar zenith angle approaches 90°, only data with solar zenith angles <70° were analyzed, corresponding roughly to 0800 to 1800 h. Crop Circle passive radiometers (Holland Scientific, Lincoln, NE) were used for measuring spectral reflectance response and global irradiance. (These radiometers are no longer available from Holland Scientific, and current Crop Circle reflectance sensors have an active pulsed light source.) These radiometers are cylindrical, with approximately 10 cm diameter and 10 cm height. For reflectance calibration, a Spectralon reference panel (Labsphere Inc., North Sutton, NH) was used. Spectral reflectance response was measured for 10-nm-wide bands centered at 460 nm (blue), 550 nm (green), 680 nm (red), and 800 nm (NIR). Spectral radiometers were mounted in a stationary position about 25 cm above the corn canopy, having a nadir view. The radiometers had a field-of-view of 28°, providing a 12.5-cm-diameter view area at that distance, which on V10 corn was filled almost entirely with leaves. This narrow field-of-view sensor ensured that measurements accurately represented plant spectral properties and minimized interference by background scenes. Three radiometers were positioned over corn plants, one for each N treatment. A fourth radiometer was placed 25 cm above a reference panel. Before the tests, the down-looking radiometers were normalized over the Spectralon reference panel.

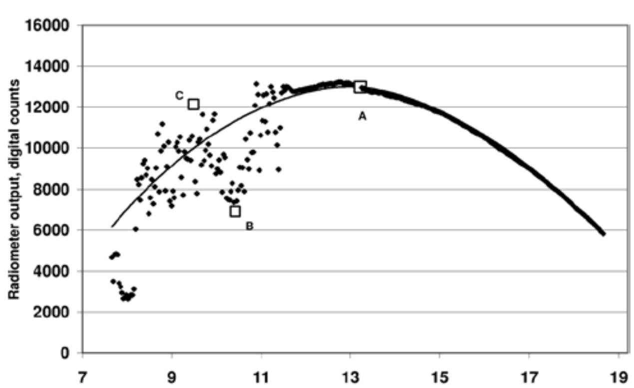

Fig. 2. The actual global spectral radiation incident on a horizontal surface in the 800-nm band (points) and the corresponding expected clear-sky radiation (solid line) for Columbia, Missouri on 15 June 2001. Point A represents clear sky. Point B represents clouds in the irradiation path. Point C represents a situation whereby scattered clouds reflected additional solar radiation onto the radiometer, causing a 21% increase in the observed radiation above the expected level.

The global irradiation was estimated using a 180°-wide field of view up-looking radiometer with four sensors, also centered at the same wavelengths. Reflectance values (R_{460}, R_{550}, R_{680}, and R_{800}) were calculated using the following two methods.

The Flat Receiver Method estimated the reflectance (fR) using the global irradiation incident on a horizontal surface, measured with the up-looking radiometer, and the radiation reflected by the target and was calculated by:

$$fR_i = \frac{\pi \times Rad_{ji}}{Rad_{Ui}} \quad [1]$$

where fR_i is flat receiver reflectance in the band i; Rad_{ji} is radiation measured by radiometer j (1, 2, and 3) in band i; and Rad_{Ui} is radiation measured by the up-looking radiometer in band i.

The reference panel method (also called the relative reflectance method) estimated the reflectance (rR) using the radiation reflected by a horizontal Spectralon reference panel compared with the radiation reflected by the target and was calculated by:

$$rR_i = \frac{Rad_{ji} \times R_{Si}}{Rad_{4i}} \quad [2]$$

where rR_i is relative reflectance in band i; Rad_{ji} is radiation measured by radiometer j (1, 2, and 3) in band i; R_{Si} is reflectance of the spectralon panel in band i; and Rad_{4i} is radiation measured by radiometer 4 (over reference reflectance panel) in band i.

Similar to the clearness index of Liu and Jordan (1960), but as a function of time of day, sky clearness for each 2-min interval was estimated using the instantaneous clearness index (ICI) (Souza et al., 2006). We defined ICI as the ratio of the global spectral radiation incident on a horizontal surface (I, W m^{-2}), measured with the up-looking sensor of the radiometer, to the expected clear-sky global spectral radiation incident on a horizontal surface (I_o, W m^{-2}).

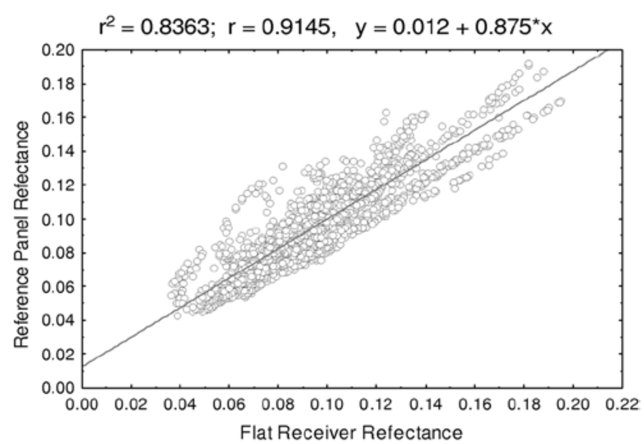

Fig. 3. Reference panel reflectance in the 550-nm band as a function of the flat receiver reflectance (fR) in the same band (r^2 = 0.84). Data from 8 to 19 May 2001.

$$ICI = I/I_o \quad [3]$$

I_o was estimated ($R^2 > 0.97$) for each of the four radiometer channels as a polynomial function of sun zenith angle, time of day, and day of year, using data obtained at the same locations under clear-sky conditions. Details of the model fitting process are given by Souza et al. (2006).

To better understand the practical meaning of the ICI, three points were selected in Fig. 2. This figure presents radiation incident on a horizontal surface in the 800-nm band and the corresponding expected clear-sky radiation as a function of time of day. The ICI values were 1.0, 0.61, and 1.21 for the points A, B, and C, respectively. Point A represents clear sky, whereas point B represents clouds in the irradiation path, reducing observed radiation by about 39% relative to the expected clear-sky radiation. Point C represents a situation whereby scattered clouds reflected additional solar radiation onto the radiometer, causing a 21% increase in the observed radiation above the expected level. All three conditions are likely to occur in any given day. If sunlight reflectance measurements are to be used in agricultural applications, the effects of clouds on radiation reaching the earth's surface must be understood for different wavelengths.

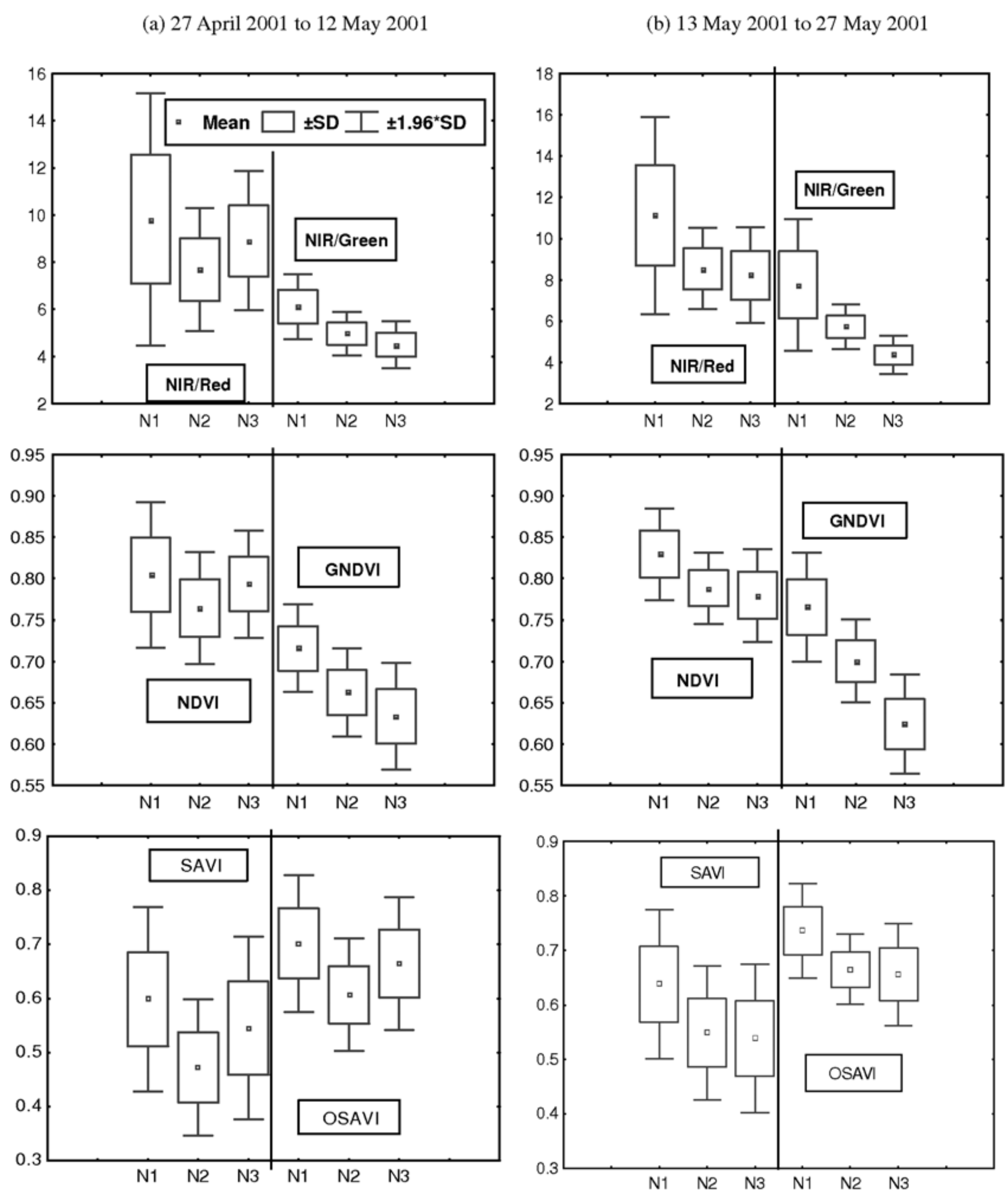

Fig. 4. Dispersion of six vegetation indices (near-infrared [NIR]/red, NIR/green, normalized difference vegetation index [NDVI], green normalized difference vegetation index [GNDVI], soil-adjusted vegetation index [SAVI], and optimum soil-adjusted vegetation index [OSAVI]) for three nitrogen treatments (N1 = 270, N2 = 180, and N3 = 90 kg N ha^{-1}) and two time periods. Measurements were obtained in the field using greenhouse-grown corn in pots. The test periods were (a) 27 Apr. 2001 to 12 May 2001 (growth stage V10–V14) and (b) 13 May 2001 to 27 May 2001 (growth stage V15–R2). All data with sun zenith angle <70° are included.

Vegetation Indices

Based on results reported by Daughtry et al. (2000) and Tumbo et al. (2002), the following vegetation indices were selected for consideration: (i) the NIR/red ratio (R_{800}/R_{680}), (ii) the NIR/green ratio (R_{800}/R_{550}), (iii) the normalized difference vegetation index (NDVI) ($[R_{800} - R_{680}]/[R_{800} + R_{680}]$), (iv) the green normalized difference vegetation index (GNDVI) ($[R_{800} - R_{550}]/[R_{800} + R_{550}]$), (v) the soil-adjusted vegetation index (SAVI) ($1.5 \times [R_{800} - R_{680}]/[R_{800} + R_{680} + 0.5]$), and (vi) the optimized soil-adjusted vegetation index (OSAVI) ($1.16 \times [R_{800} - R_{680}]/[R_{800} + R_{680} + 0.16]$).

Statistical Procedures

Regression analysis was performed to model observed reflectance as a function of sun zenith angle (ψ, degrees), time of day (t, hour), and ICI.

To reduce expected multicollinearity, the independent variables were transformed to centered sun zenith angle (ψ_C), centered time of day (t_C), and centered ICI (ICI_C)

$$\psi_C = \psi - 45 \quad [4]$$

$$t_C = t - 13 \quad [5]$$

$$ICI_C = ICI - 0.9 \quad [6]$$

where the centered constants were chosen to provide symmetry to the data [i.e., 45 is half of the maximum possible ψ, 13 is the approximate time of solar noon (1310 during the data collection period), and 0.9 is a typical average value of ICI for a partly overcast day, as estimated from a 15-d test dataset].

Three different regression methods were used: forward stepwise, backward stepwise, and best-subset search procedures. A 0.05 P value of the F distribution was selected to control entry and removal of effects from the model. The adjusted R^2 value was used as the criterion to find the best models of all possible subsets of effects specified.

After an exploratory analysis, we decided to fit the data to the following model:

$$\hat{Y} = a + (b \times t_C) + (c \times t_C^2) + (d \times \psi_C) + (e \times \psi_C^2) + (f \times ICI_C) + (g \times ICI_C^2) + (h \times t_C \times \psi_C) + (i \times t_C \times ICI_C) + (j \times \psi_C \times ICI_C) \quad [7]$$

After finding the model that best fit the data set for each variable, values for 550 nm reflectance, 800 nm reflectance, NIR/green, and GNDVI were corrected to standard reference conditions using the following equation:

$$CorrY = (Y - \hat{Y}) + Y_R \quad [8]$$

where CorrY is the corrected observation, Y is the original (raw) observation, $\hat{Y}$ is the estimated Y from the model for the conditions of the initial observation, and Y_R is the expected value (fitted with the model) for the selected reference condition: solar noon (1310 at our latitude and longitude), minimum sun zenith angle of the day, and clear sky (ICI = 1). In a practical sense, the final user would use this type of model to reduce an observed variable, like reflectance, to a reference condition so that observations and fertilizer recommendations would not be influenced by time of day, sun zenith angle, or clouds.

RESULTS AND DISCUSSION

Figure 3 presents the reference panel reflectance (also called relative reflectance, rR) in the 550-nm band as a function of the flat receiver reflectance (fR) in the same band (data from 8–19 May 2001). The nearly 1:1 linear behavior and high coefficient of determination ($R^2 = 0.84$) confirm the similarity of both methods in converting data to reflectance. The scatter in this relationship appears to be caused by a tendency for rR to be higher in mid-day and lower early and late in the day at a given value of fR. Herein we report only the flat receiver data and refer to flat receiver reflectance as reflectance. This correction method was selected for further analysis because it would be better suited for real-time use on a variable-rate fertilizer applicator. The dispersion of six VIs (NIR/red, NIR/green, NDVI, GNDVI, SAVI, and OSAVI) for three N treatments (90, 180, and 270 kg N ha^{-1}) and two time periods is presented in Fig. 4. The total data collection period was divided to reduce the influence of changing growth stages on the VI means. The first period (27 Apr. 2001–12 May 2001) included corn growth stages from V10 to V14 (Fig. 4a), and the second period (13 May 2001–27 May 2001) included corn growth stages from V15 to R2 (Fig. 4b). Although visual differences between N Treatments 2 and 3 were small, the NIR/green and GNDVI indices were sensitive to N treatment in both periods. NIR/green and GNDVI ratio were positively correlated with N input. Combinations of NIR and green reflectance have also shown the greatest sensitivity to N status in past research (Bausch and Duke, 1996; Gitelson et al., 1996). For this reason, the NIR/green and GNDVI indices were selected for further analysis of the effects of changing sun angle and cloud conditions.

Data from the first 6 d of data collection illustrate that green reflectance and the NIR/green ratio were generally higher early and late in the day (Fig. 5a and 5b). This finding is in agreement with Davis (1957). Ranson et al. (1985) also found higher reflectance at higher solar zenith angle in full-canopy situations and attributed this observation to increased specular reflectance.

The degree of fluctuation was much greater on some days (28 and 29 April) than on others (27 April and 1 May). The reason for this is not known, but greater fluctuation does not appear to correlate with more changes from clear to cloudy. Rapid changes in the instantaneous clearness index (Fig. 5c) indicate changes in cloud cover, and these changes in cloud cover do not appear to cause rapid changes in green reflectance or NIR/green ratio (Fig. 5a and 5b) (e.g., 27 April; some green reflectance data on 29 April appear to fluctuate with ICI, but NIR/green data do not). The extended clear periods on 28 and 29 April (Fig. 5c) may be causally related to the large variability in green reflectance and NIR/green on these dates. Data in Fig. 5 represent corn growth stages from V10 (27 Apr. 2001) to V12 (2 May 2001) and an N input of 180 kg N ha^{-1}. This period was selected because spectral properties associated with N deficiency are likely to be apparent by this growth stage (Walburg

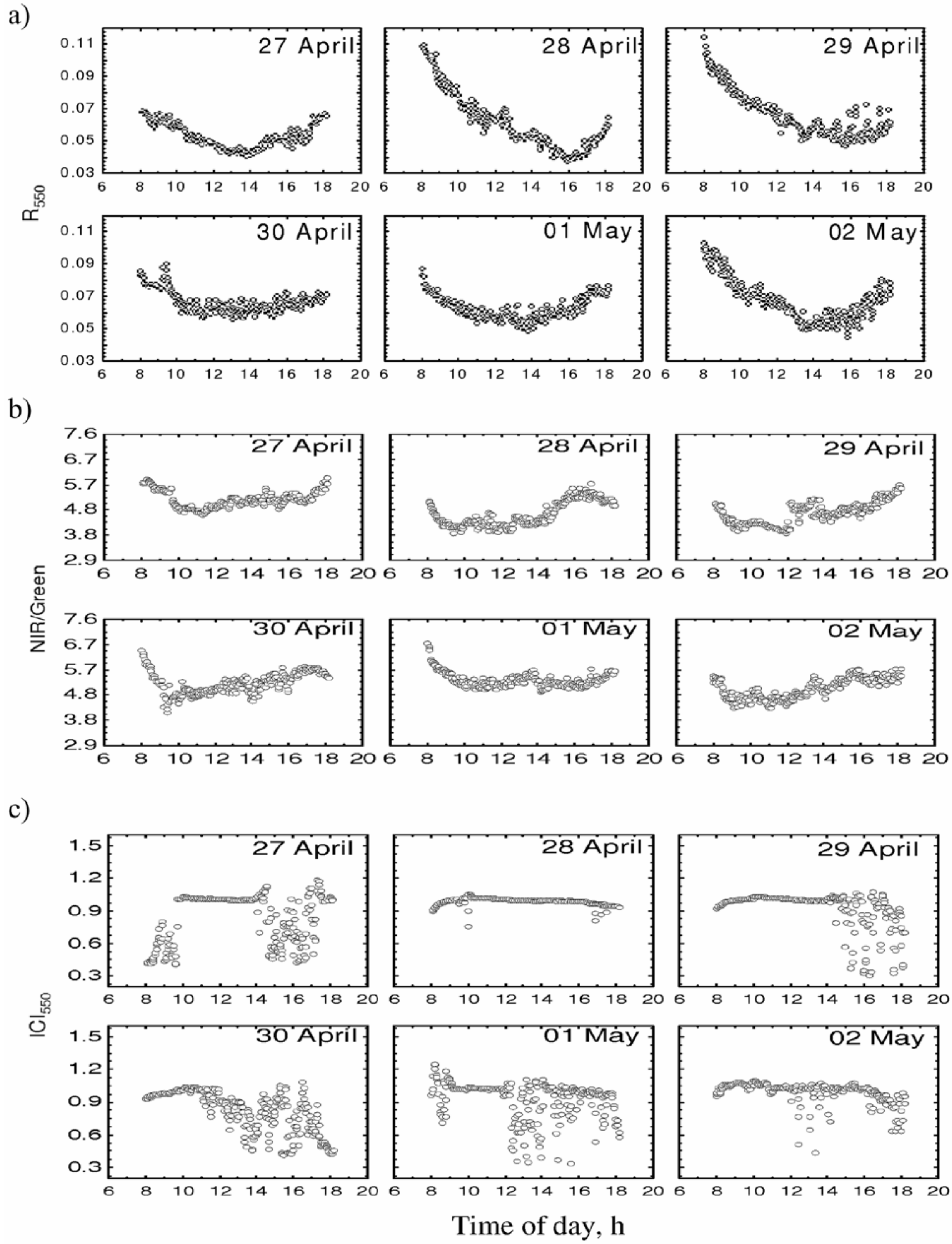

Fig. 5. (a) Corn reflectance measured in the green band (R_{550}), (b) near-infrared (NIR)/green ratio, and (c) instantaneous clearness index at 550 nm (ICI_{550}), all plotted vs. time of day. The corn growth stage during the test period (27 Apr. 2001–2 May 2001) was from V10 to V12. Measurements were obtained in the field using greenhouse-grown corn in pots. Data shown are from the N2 (180 kg N ha^{-1}) treatment.

et al., 1982), but the crop still has the potential for large yield responses to added N (Russelle et al., 1983; Scharf et al., 2002).

Observed fluctuations in reflectance were large enough to cause large and unacceptable fluctuations in reflectance-based N rate recommendations. Using the relationship between relative green/NIR and optimal N rate developed by Scharf and Lory (2009), the fluctuations in NIR/green in Fig. 5b represent fluctuations in predicted N rate of 98, 135, 155, 91, 58, and 102 kg N ha^{-1} on 27, 28, 29, and 30 April and 1 and 2 May, respectively. This is an unacceptable level of error to introduce into N rate decisions.

Reflectance of green and NIR light during this period was most clearly a function of time of day, less strongly a function of sun angle, and not clearly influenced by ICI or cloud cover (Fig. 6). Data spread at sun angles from 50° to 70° is considerably wider than at 30° (Fig. 6b) due to lower reflectance at the same sun angle in the afternoon than in the morning (Fig. 6a). Data in Fig. 6 are from the same dates and N treatment as Fig. 5. The modest dependence of measured reflectance on sun angle may reflect a causal relationship or may merely be collinear with the true causal variables that also progress smoothly through the day. The wide day-to-day variability in this progression (Fig. 5) suggests weather dependence and results in a wide data spread when all days are pooled (Fig. 6). Weather-dependent factors that might cause diurnal variation in measured reflectance include canopy geometry (e.g., leaf angle or orientation), water content (Carlson et al., 1971; Myers et al., 1983), wind (Lord et al., 1985), dew (Pinter, 1986), pigment content, or factors affecting the efficiency of light absorption by pigments (Hoel and Solhaug, 1998; Brugnoli and Björkman, 1992). It appears that such factors influence reflectance observations far more than sun angle or cloud cover. This suggests that using active light reflectance sensors to minimize sensitivity to changes in sun angle and cloud cover may not solve the problem of diurnal variation in reflectance. A better understanding of the causes of diurnal variation in canopy

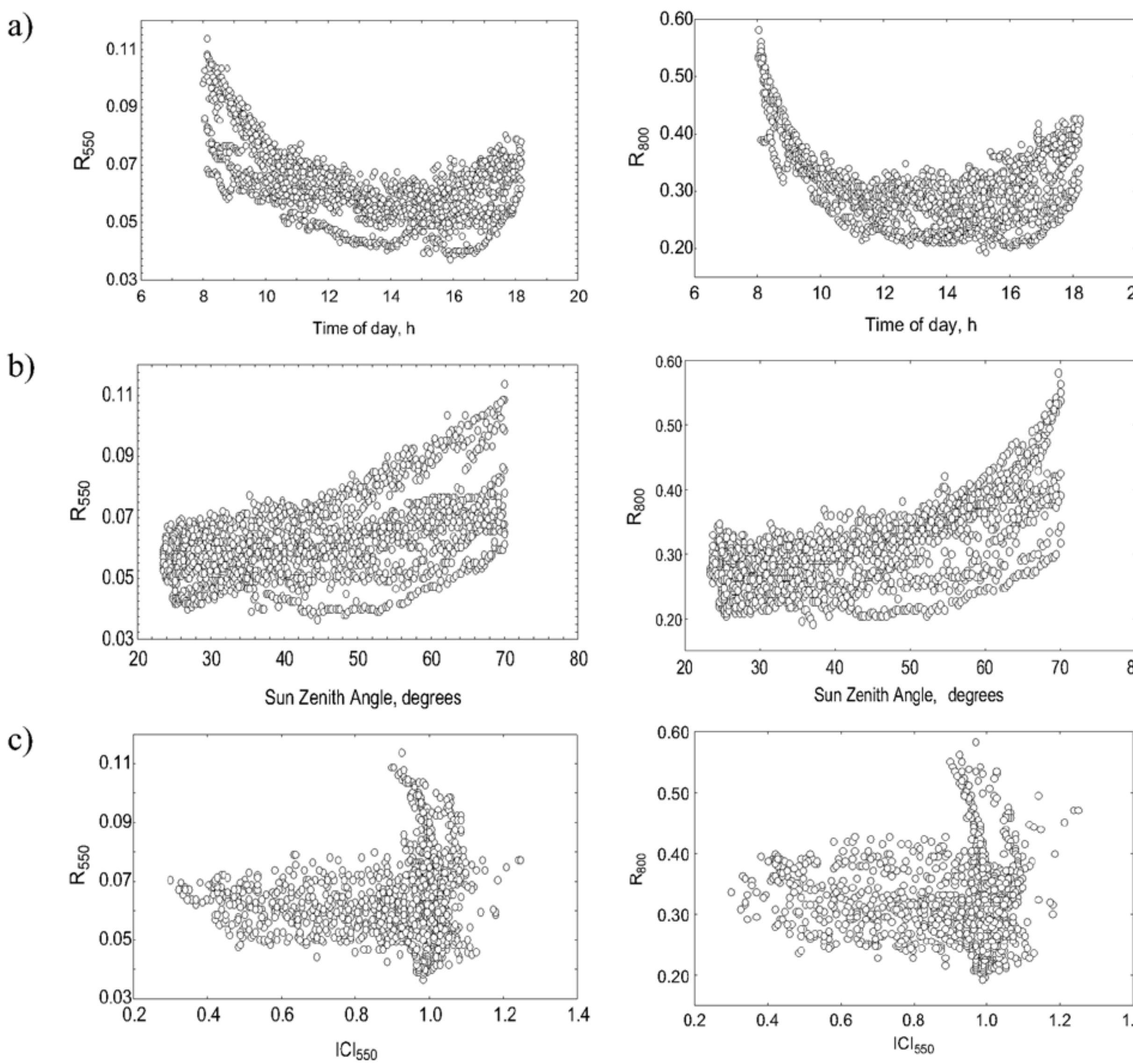

Fig. 6. Corn reflectance measured in the green band (R_{550}) and near-infreared band (R_{800}) vs. (a) time of day (h), (b) sun angle (degrees), and (c) the instantaneous clearness index at 550 nm (ICI_{550}, dimensionless). Nitrogen input was 180 kg N ha^{-1}. The corn growth stage during the test period (27 Apr. 2001–2 May 2001) was from V10 to V12. Measurements were obtained in the field using greenhouse-grown corn in pots.

reflectance may help to devise strategies to minimize errors in fertilization decisions based on reflectance measurements.

The same data presented as NIR/green or GNDVI shows that these indices are less sensitive to time of day, sun angle, and clouds than the individual green and NIR reflectances (Fig. 7, note scale changes from Fig. 6). All four dependent variables (R_{550}, R_{800}, NIR/green, and GNDVI) had greater variance for ICI near 1. The reflectance peak near ICI = 1 appeared to occur because morning skies were generally clear (Fig. 5c) on the days with the highest reflectance early in the day (Fig. 5a). Under cloudy conditions (ICI <1), the influence of, and variance due to, sun angle would be minimized, and apparently time of day effects that were independent of sun angle were also minimized under cloudy conditions.

Models were developed to describe the influence of time of day, sun angle, and cloud cover on green and NIR reflectance and the derived indices (Table 1). To reduce the effect of day-to-day variation due to changing corn growth stage, the dataset used for regression analysis was reduced to the three most similar days in terms of reflectance distribution—28, 29, and 30 April (growth stage V10). Data with an N input level of 180 kg ha^{-1} were used. The model was fitted with two randomly

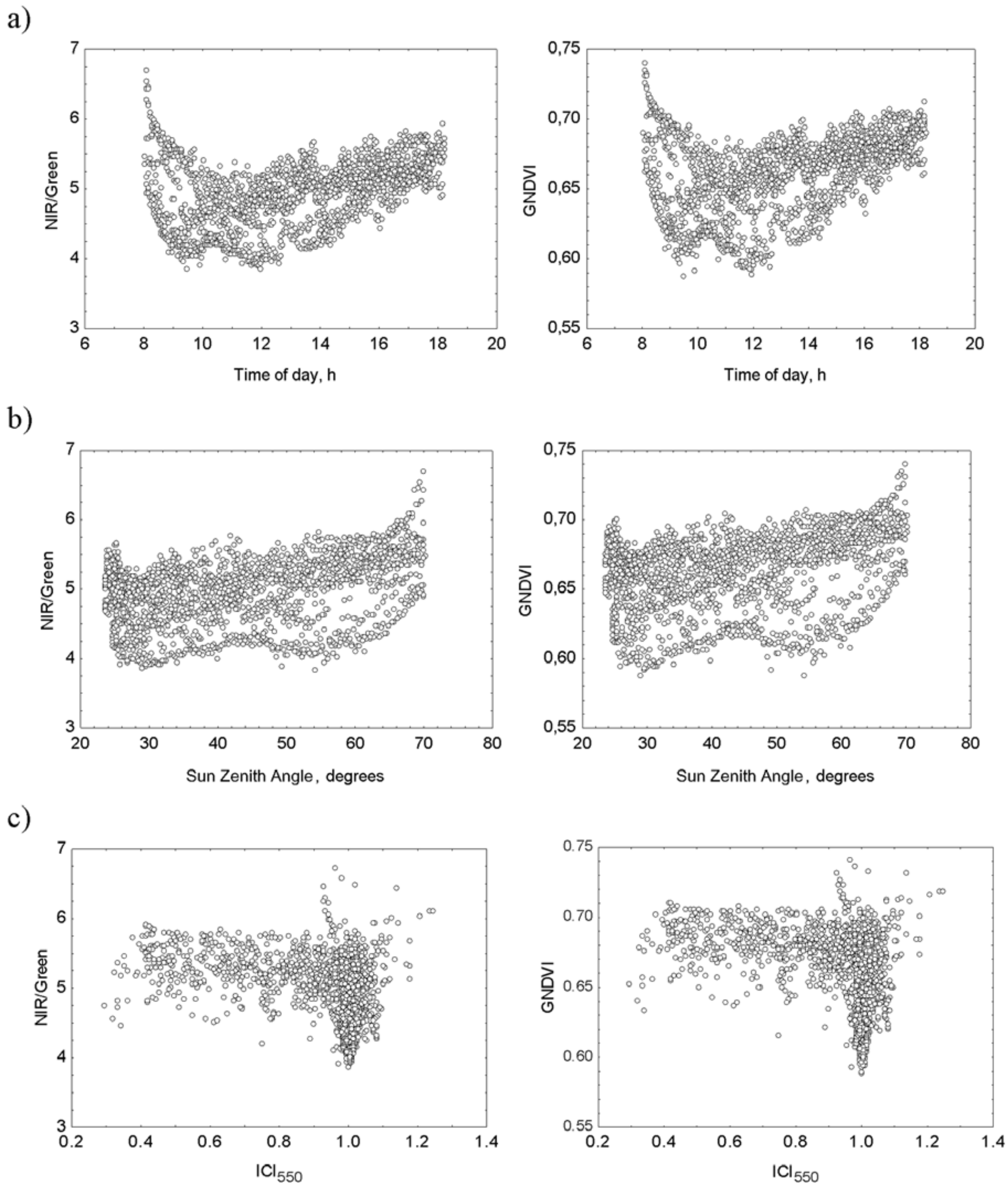

Fig. 7. Near-infrared (NIR)/green and green normalized difference vegetation index (GNDVI) vegetation indices vs. (a) time of day (h), (b) sun angle (degrees), and (c) the instantaneous clearness index at 550 nm (ICI_{550}, dimensionless). Nitrogen input was 180 kg N ha^{-1}. The corn growth stage during the test period (27 Apr. 2001–2 May 2001) was from V10 to V12. Measurements were obtained in the field using greenhouse-grown corn in pots.

Table 1. Regression coefficients for corn reflectance measured in the green band and the near-infrared band and for the vegetation indices near-infrared/green and green normalized difference vegetation index as a function of time of day, sun zenith angle, and sky clearness (28 Apr. 2001 and 30 Apr. 2001).

Regression variable	R_{550}†	R_{800}	NIR/green	GNDVI
Intercept	0.207637	–0.768691	–19.267985	–0.789350
t_C		–0.038818	–0.554245	–0.033511
t_C^2	–0.017258	0.130416	2.923481	0.175240
ψ_C	0.009452	–0.066816	–1.533359	–0.091947
ψ_C^2	0.000115	–0.000770	–0.018389	–0.001105
ICI_{550}	–0.049401	–0.268124	–0.895550	–0.058324
ICI_{550}^2	–0.102932	–0.563636		
$t_C \times \psi_C$		–0.000360	–0.003019	–0.000160
$t_C \times ICI_{550}$	–0.008899	–0.032192	0.411465	0.027559
$\psi_C \times ICI_{550}$				
R^2	0.808	0.876	0.820	0.823

† GNDVI, green normalized difference vegetation index; ICI_{550}, instantaneous clearness index (a measure of sky clearness assessed at 550 nm); NIR/green, near-infrared/green ratio; R_{550}, reflectance in the green band (550 nm); R_{800}, reflectance in the near-infrared band (800 nm); t_c, centered time (difference from approximate solar noon); ψ_c, centered sun zenith angle.

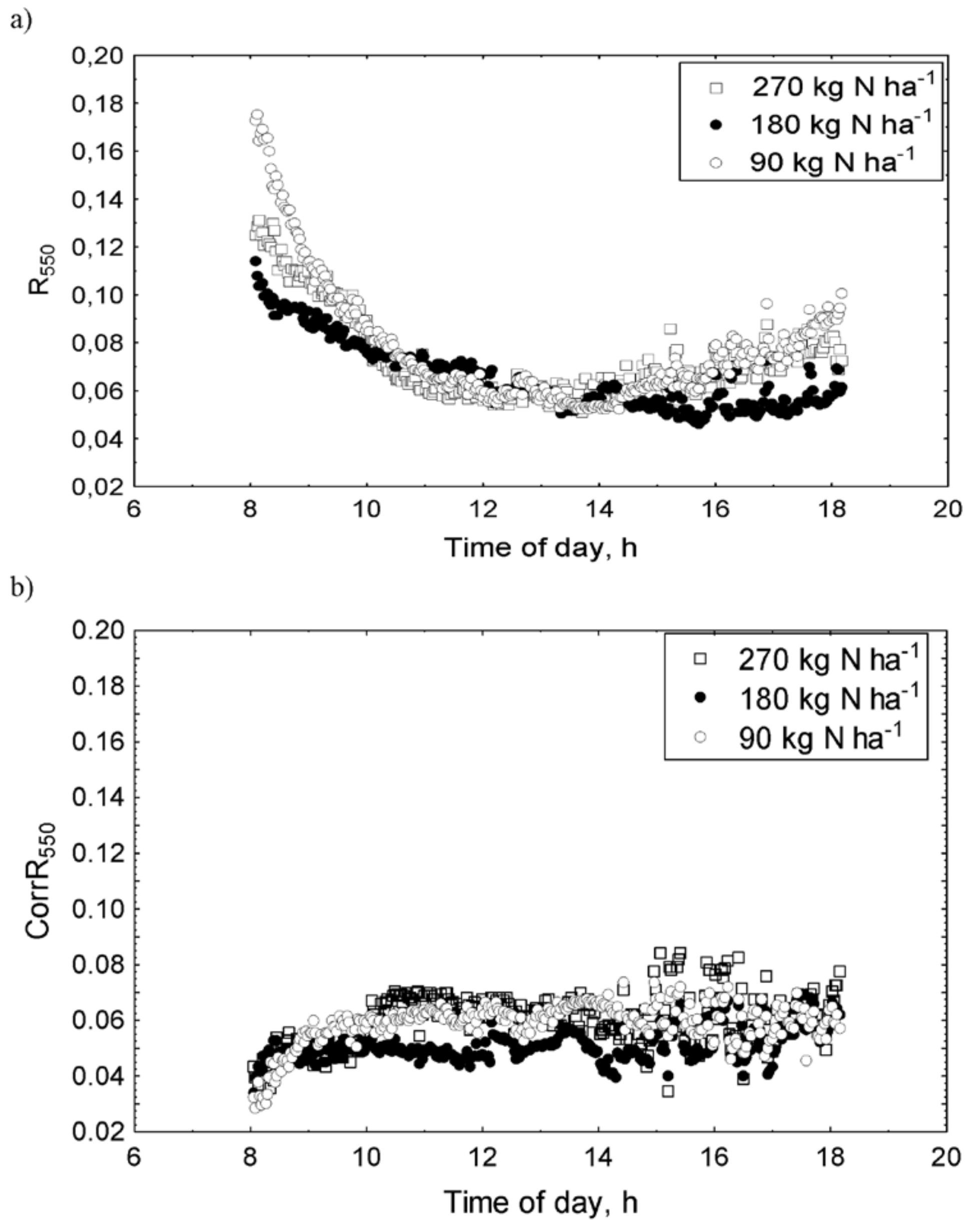

Fig. 8. Corn reflectance measured in the green band (R_{550}; Fig. 7a) and after regression model correction ($CorrR_{550}$; Fig. 7b) vs. time (h) for three N treatments (N1 = 270, N2 = 180, and N3 = 90 kg N ha^{-1}) for 29 April (the validation day). The corn growth stage was V10. Measurements were obtained in the field using greenhouse-grown corn in pots.

Table 2. Descriptive statistics of raw and regression-corrected variables in the calibration data set (28 Apr. 2001 and 30 Apr. 2001).

Reflectance variable†	Mean	Minimum	Maximum	SD	CV‡	CV reduction
					%	%
R_{550}	0.0639	0.0370	0.1090	0.0136	21.3	
$CorrR_{550}$	0.0550	0.0231	0.0671	0.0060	10.9	49.1
R_{800}	0.3105	0.1950	0.5530	0.0695	22.4	
$CorrR_{800}$	0.2499	0.1030	0.3003	0.0244	9.8	56.3
NIR/Green	4.8823	3.8602	6.4519	0.5350	11.0	
CorrNIR/Green	4.4902	3.7606	5.3899	0.2273	5.1	53.8
GNDVI	0.6572	0.5885	0.7316	0.0315	4.8	
CorrGNDVI	0.6339	0.5948	0.6902	0.0132	2.1	56.4

† CorrGNDVI, corrected green normalized difference vegetation index; CorrNIR/green, corrected near-infrared/green band ratio; $CorrR_{550}$, corrected reflectance in the band 550 nm; $CorrR_{800}$, corrected reflectance in the band 800 nm; GNDVI, green normalized difference vegetation index; NIR/green, near-infrared/green ratio; R_{550}, reflectance in the band 550 nm; R_{800}, reflectance in the band 800 nm.

‡ CV, coefficient of variation.

selected days (28 and 30 April) and tested with the third day (29 April). The R^2 for the best fitting model ranged from 0.81 (R_{550}) to 0.88 (R_{800}). On average, the regression models represented 82% of the total variation in vegetation indexes and 84% of the total variation in the reflectances. Model fit for the indices was slightly poorer because the indices remove some of the variability present in reflectance measurements and thus have less variability to describe (see coefficient of variation [CV] values in Table 2).

For R_{550}, NIR/green, and GNDVI, sun zenith angle, its square, and time squared were the three most important terms in the model with approximately equal sums of squares. For R_{800}, time and ICI were the most important terms, followed closely by sun zenith angle, its square, and time squared.

Correcting observations for time, sun angle, and cloud cover reduced the CV by 55% for the vegetation indices and by 53% for the reflectances when the models generated from 28 Apr. 2001 and 30 Apr. 2001 was applied to the same days. When applied to data from 29 April, the correction model reduced CV by 29% for the vegetation indices and 45% for the reflectances. Initial CV values were somewhat lower for data from 29 April (Table 3) than from pooled data from 28 and 30 April (Table 2), which may partially account for the fact that correction reduced CVs less on 29 April. After correction, measurements were much less dependent on time of day (Fig. 8). Eliminating the large amount of reflectance variability associated with diurnal fluctuations will make it much easier to diagnose N status, distinguish N rate treatment, and make N rate decisions accurately. In this example, statistical difference between treatments was greatly increased because error sums of squares was greatly decreased, whereas model sums of squares remained nearly the same. However, treatments were still not different at $\alpha = 0.05$, and the treatment with the lowest reflectance was the middle N rate. Neither NIR/green nor GNDVI was able to statistically separate N rates in the 29 April (V10) data, with or without correction. It appears that the differences between treatments shown in Fig. 4 (NIR/green and GNDVI) were not detectable at the V10 stage.

CONCLUSIONS

Spectral radiometer reflectance measurements were influenced by time of day, to a lesser extent by sun angle (morning and afternoon measurements were often different at the same sun angle), and minimally by degree of cloud cover. Correcting to standard reference conditions reduced CV for reflectance and vegetation indices by about 30 to 50%. Approaches for making N fertilizer recommendations based on canopy reflectance measurements will need to understand and compensate for diurnal variability. The NIR/green ratio and green NDVI were the indices most sensitive to corn N status, but they were not able to distinguish our N rate treatments until after stage V10.

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Table 3. Descriptive statistics of raw and regression-corrected variables in the validation data set (29 Apr. 2001).

Reflectance variable†	Mean	Minimum	Maximum	SD	CV‡	CV reduction
					%	%
R_{550}	0.0662	0.0466	0.1141	0.0143	21.5	
$CorrR_{550}$	0.0510	0.0339	0.0693	0.0058	11.4	47.1
R_{800}	0.3029	0.2254	0.5639	0.0596	19.7	
$CorrR_{800}$	0.2487	0.1907	0.3340	0.0279	11.2	43.1
NIR/green	4.6182	3.8670	5.7033	0.4152	9.0	
CorrNIR/green	4.7269	3.8858	5.2241	0.3001	6.3	29.4
GNDVI	0.6421	0.5891	0.7016	0.0262	4.1	
CorrGNDVI	0.6471	0.5961	0.6760	0.0188	2.9	28.9

† CorrGNDVI, corrected green normalized difference vegetation index; CorrNIR/green, corrected near-infrared/green ratio; $CorrR_{550}$, corrected reflectance in the band 550 nm; $CorrR_{800}$, corrected reflectance in the band 800 nm; GNDVI, green normalized difference vegetation index; NIR/green, near-infrared/green ratio; R_{550}, reflectance in the band 550 nm; R_{800}, reflectance in the band 800 nm.

‡ CV, coefficient of variation.

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REFERENCES

Bausch, W.C., and H.R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Trans. ASAE 39:1869–1875.

Blackmer, T.M., J.S. Schepers, and G.E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. Agron. J. 86:934–938.

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and E.A. Walter-Shea. 1996. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron. J. 88:1–5.

Brugnoli, E., and O. Björkman. 1992. Chloroplast movement in leaves: Influence on chlorophyll fluorescence and measurements of light-induced absorbency changes related to delta-pH and zeaxanthin formation. Photosynth. Res. 32:23–35.

Campbell, G.S., and J.M. Norman. 1998. An introduction to environmental biophysics. Springer, New York.

Carlson, R.E., D.N. Yarger, and R.H. Shaw. 1971. Factors affecting the spectral properties of leaves with special emphasis on leaf water status. Agron. J. 63:486–489.

Davis, P.A. 1957. Exploring the atmosphere's first mile. p. 377–383. *In* H.H. Lettau and B. Davidson (ed.) Proceedings of the Great Plains Turbulence Field Program, 1 August to 8 September 1953, O'Neill, Nebraska. Symposium Publications Division, Pergamon Press, New York.

Daughtry, C.S.T., C.L. Walthall, M.S. Kim, E. Brown de Colstoun, and J.E. McMurtrey, III. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sens. Environ. 74:229–239.

Dellinger, A.E., J.P. Schmidt, and D.B. Beegle. 2008. Developing nitrogen fertilizer recommendations for corn using an active sensor. Agron. J. 100:1546–1552.

Gao, B., and R. Li. 2000. Quantitative improvement in the estimates of NDVI values from remotely sensed data by correcting thin cirrus scattering effects. Remote Sens. Environ. 74:494–502.

Gardener, B.R. 1983. Techniques for remotely monitoring canopy development and estimating grain yield of moisture stressed corn [dissertation]. University of Nebraska, Lincoln, NE.

Gitelson, A.G., Y.J. Kaufman, and M.N. Merzlyak. 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens. Environ. 58:289–298.

Hoel, B.O., and K.A. Solhaug. 1998. Effect of irradiance on chlorophyll estimation with the Minolta SPAD-502 leaf chlorophyll meter. Ann. Bot. (Lond.) 82:389–392.

Jackson, R.D., P.J. Pinter, S.B. Idso, and R.J. Reginato. 1979. Wheat spectral reflectance: Interactions between crop configuration, sun elevation, and azimuth angle. Appl. Opt. 18:3730–3733.

Kitchen, N.R., and K.W. Goulding. 2001. On-farm technologies and practices to improve nitrogen use efficiency. p. 335–369. *In* R.F. Follett and J.L. Hatfield (ed.) Nitrogen in the environment: Sources, problems, and management. Elsevier Science, Amsterdam, the Netherlands.

Liu, B.Y.H., and R.C. Jordan. 1960. The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation. Sol. Energy 4:1–19.

Lord, D., R.L. Desjardins, and P.A. Dubé. 1985. Influence of wind on crop canopy reflectance measurements. Remote Sens. Environ. 18:113–123.

Myers, V.I., M.E. Bauer, H.W. Gausman, W.G. Hart, J.L. Heilman, R.B. Macdonald, A.B. Park, R.A. Ryerson, T.J. Schmugge, and F.C. Westin. 1983. Remote sensing applications in agriculture. p. 2111–2228. *In* R.N. Colwell (ed.) Manual of remote sensing, Vol. 2, 2nd ed. American Society of Photogrammetry, Falls Church, VA.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management. Nebguide G93-117A. Coop. Ext. Serv., Univ of Nebraska, Lincoln, NE.

Pinter, P.J., Jr. 1986. Effect of dew on canopy reflectance and temperature. Remote Sens. Environ. 19:187–205.

Ranson, K.J., C.S.T. Daughtry, L.L. Biehl, and M.E. Bauer. 1985. Sun-view angle effects on reflectance factors of corn canopies. Remote Sens. Environ. 18:147–161.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820.

Russelle, M.P., R.D. Hauck, and R.A. Olson. 1983. Nitrogen accumulation rates of irrigated corn. Agron. J. 75:593–598.

Scharf, P.C., and J.A. Lory. 2009. Calibrating reflectance measurements to predict optimal sidedress nitrogen rate for corn. Agron. J. 101:615–625.

Scharf, P.C., K.A. Sudduth, N. Hong, and L. Oliveira. 2007. Reflectance sensors: How stable are the values they measure? Agronomy Abstracts, ASA, Madison, WI.

Scharf, P.C., W.J. Wiebold, and J.A. Lory. 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. Agron. J. 94:435–441.

Simpson, J.J., Z. Jin, and J.R. Stitt. 2000. Cloud shadow detection under arbitrary viewing and illumination conditions. IEEE Trans. Geosci. Rem. Sens. 38:972–976.

Souza, E.G., P.C. Scharf, K.A. Sudduth, and J.D. Hipple. 2006. Using a field radiometer to estimate instantaneous sky clearness. Revista Brasileira de Engenharia Agrícola e Ambiental 10:369–373.

Tumbo, D.S., D.G. Wagner, and P.H. Heinemann. 2002. Hyperspectral characteristics of corn plants under different chlorophyll levels. Trans. ASAE 45:815–823.

Walburg, G., M.E. Bauer, C.S.T. Daughtry, and T.L. Housley. 1982. Effects of nitrogen nutrition on the growth, yield, and reflectance characteristics of corn canopies. Agron. J. 74:677–683.

Walter-Shea, E.A., J.M. Norman, and B.L. Blad. 1989. Leaf bidirectional reflectance and transmittance in corn and soybean. Remote Sens. Environ. 29:161–174.

Wood, C.W., D.W. Reeves, and D.G. Himelrick. 1993. Relationships between chlorophyll meter readings and leaf chlorophyll concentration, N status, and crop yield: A review. Proc. Agron. Soc. New Zealand 23:1–9.