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Nitrogen Deficiency Detection Using Reflected Shortwave Radiation from Irrigated Corn Canopies

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ABSTRACT

Techniques that measure the N status of corn (*Zea mays* L.) can aid in management decisions that have economic and environmental implications. This study was conducted to identify reflected electromagnetic wavelengths most sensitive to detecting N deficiencies in a corn canopy with the possibility for use as a management tool. Reflected shortwave radiation was measured from an irrigated corn N response trial with four hybrids and five N rates at 0, 40, 80, 120, and 160 kg N ha^{-1} in 1992 and 0, 50, 100, 150, and 200 kg N ha^{-1} in 1993. A portable spectroradiometer was used to measure reflected radiation (400–1100 nm in 1992, 350–1050 nm in 1993) from corn canopies at approximately the R5 growth stage. Regression analyses revealed that reflected radiation near 550 and 710 nm was superior to reflected radiation near 450 or 650 nm for detecting N deficiencies. The ratio of light reflectance between 550 and 600 nm to light reflectance between 800 and 900 nm also provided sensitive detection of N stress. In 1993, an inexpensive photometric cell, which has peak sensitivity to light centered at 550 nm, was also used to measure reflected radiation from a corn canopy. Photometric cell readings correlated with relative grain yield ($P < 0.001$, $r^2 = 0.74$), but more research will be required to develop procedures to account for varying daylight conditions. These results provide information needed for the development of variable-rate fertilizer N application technology.

THE DEVELOPMENT of variable-rate fertilizer application technology creates the need for better methods of assessing variability in crop N status within a field. Assessment of N availability is traditionally based on soil testing and plant analysis. These techniques can be effective, but substantial expense and effort are required to adequately characterize the variability within a field. These constraints lead to uncertainty as to how variability in fields should be sampled and characterized.

Chlorophyll meter technology has potential for rapidly assessing crop N availability by measuring transmittance of light through a leaf at about 650 and 940 nm. These meters can identify N deficiency of corn because an N deficiency reduces chlorophyll content of leaves, which in turn increases the amount of light transmitted through a leaf. Chlorophyll meters have been used in several ways, with varying degrees of success (Yadava, 1986; Marquard and Tipton, 1987; Dwyer et al., 1991; Piekielek and Fox, 1992; Schepers et al., 1992; Wood et al., 1992; Blackmer and Schepers, 1995). These meters are most effective when readings are expressed relative to an in-field reference area having nonlimiting amounts of N. A major advantage of this technique is that it provides N assessments without time-consuming laboratory analysis. The meter allows one to detect N deficiencies for 30 leaves in a few minutes by sequentially clamping the meter on the same relative leaf of representative plants and recording the average value (Peterson et al., 1993). Nonetheless, even this approach can be time consuming when characterizing variability within large fields.

An alternative technique to chlorophyll meters is to measure light reflected from the plant canopy. A major advantage is that a single measure of reflected radiation can characterize the N status of many plants within a selected area. Walburg et al. (1982) indicated that spectral measurements of corn canopies could be used to detect N treatment differences. They attributed N treatment effects to differences in leaf area, crop biomass, soil cover, and plant height, as well as chlorophyll content. Canopy spectral measurements and chlorophyll meters both rely on how chlorophyll interacts with light, but canopy reflectance is influenced by many additional factors. Stanhill et al. (1972) made observations in wheat (*Triticum aestivum* L.) and concluded that the major cause of altered spectral response from N-deficient wheat was differences in total biomass. They further concluded that altered leaf properties or changed canopy configuration were of secondary importance. Canopy architecture also influences reflected radiation (Jackson and Pinter, 1986). Stanhill et al. (1972) and Walburg et al. (1982) postulated that canopy reflectance could be a valuable tool for assessing variability in N status within fields, but did not consider interpreting variability in canopy reflectance using nonlimiting N reference areas (as is done with the chlorophyll meter).

Research to develop applications for crop canopy reflectance has focused on wide bandwidths. High spectral res-

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olution devices recently have improved in sensitivity, decreased in cost, and increased in availability. Improved technology and increased interest in site-specific management encourage close examination of optimal wavelengths and designs of appropriate sensors to detect crop N stress.

Evidence that an N deficiency influences reflectance from individual corn leaves was provided by Al-Abbas et al. (1974). Thomas and Gausman (1977) subsequently showed that leaf reflectance at 550 nm was a good indicator of chlorophyll and carotenoid concentrations for eight different crops, including corn. More recently, light reflectance at wavelengths near 550 nm from individual leaves was found to be a good indicator of N stress in corn (Blackmer et al., 1994). These observations suggest that measurements of canopy reflectance should enable assessment of variability in crop N status within fields. As with chlorophyll meters, interpretation of such assessments can be improved by use of in-field reference areas having nonlimiting N.

Our objective was to use canopy reflectance for estimating the crop N status within fields, but with reflectance calculated using reference areas with nonlimiting N availability rather than a calibrated reference panel. More specifically, this research was conducted to identify wavelengths that are most sensitive for detection of crop N status differences. In conducting the work, we evaluated a relatively inexpensive light reflectance sensor that is most sensitive at 550 nm.

MATERIALS AND METHODS

Studies were conducted in 1992 and 1993 on N response trials for four equally irrigated corn hybrids at the Nebraska Management Systems Evaluation Area (MSEA) project near Shelton, NE. Corn was planted in plots of eight rows (15.2 m long, 91-cm spacing) in an east-west direction and fertilized at planting with NH_4NO_3 at rates of 0, 40, 80, 120, and 160 kg N ha^{-1} in 1992 and 0, 50, 100, 150, and 200 kg N ha^{-1} in 1993. Pioneer brand hybrids 3162, 3379, 3394, and 3417 were planted at $\approx$65 000 seeds ha^{-1} in four replications. In 1993, grain yields were significantly reduced by severe wind damage on 8 July, at or just prior to tasseling. The experimental design was a split plot randomized complete block, with hybrids as the whole plot and N treatments as subplots.

Canopy reflected radiation was measured in late August over the 400- to 1100-nm range in 1992 and the 350- to 1050-nm range in 1993 using portable spectroradiometers. The instrument used in 1992 was a Model SE-590 manufactured by Spectron Engineering[1] (Denver, CO) with a 15° field of view. The instrument used in 1993 was a Personal Spectrometer II manufactured by Analytical Spectral Devices (Boulder, CO) with a 10° field of view. In 1993 only, canopy reflected radiation measurements at about 550 nm were also measured using a photometric cell (Li-Cor, Lincoln, NE) that follows a photopic curve similar to the CIE Standard Observer Curve. Plants were sampled at the R5 (dent) growth stage (Ritchie et al., 1992) to minimize changes in N status between the time of sampling and physiological maturity while still measuring live vegetation. All sensors were mounted on top of a 5-m vertical pole, viewing at a 40° angle from the vertical. The sensor was oriented parallel to the corn rows, resulting in an elliptical spot size about 2.7 m long in 1992 and about 2.0 m long in 1993 as determined on the ground. Corn plants were approximately 2.4 m tall at the time of measurement. All measurements were made in triplicate on days with no visible cloud cover. Measurements proceeded from N rates within hybrids to hybrids within blocks. A complete set of measurements required about 5 h (900 to 1400 h) in 1992 and 2 h (1300 to 1500 h) in 1993. The reference plot (the plot with the highest N rate) and the four other N rates within a hybrid for a given replication were randomly sampled within a 10-min time period. Three readings per plot were collected by sampling three different portions of the plot. Spectral measurements reported from this study in Fig. 2, 3, and 4 are expressed as the *relative reflectance*, which is defined as the ratio of reflected radiation from treated plots to that from the highest N rate treatment within a hybrid. Traditionally, reflected radiation from a target is standardized to reflected radiation from a calibrated reference panel (i.e., the reflected radiation from the reference panel approximates the incident radiation at the time of measurement) (Walter-Shea and Biehl, 1990).

Grain yields were determined by hand harvesting 3.2 m of row from each plot and were adjusted to 155 g kg^{-1} moisture. Statistical analyses were performed on relative reflectance values at the 450-, 550-, 650-, and 710-nm wavelengths using analysis of variance. Because there was a significant hybrid × N rate interaction for all four wavelength intervals, linear regression analysis was performed by hybrid each year. Photometric cell data were regressed against relative grain yield using a linear relationship. Relative yields were calculated by dividing grain yields by the mean yield of the three highest N rates (the N response plateau) in 1992, and by the yield of the highest N rate in 1993, because no yield response plateau was observed. For 1992, the denominator was the mean of the highest three N rates; for 1993, it was the value for the highest N rate.

RESULTS AND DISCUSSION

Reflected radiation in the 400- to 1000-nm range (presented in raw measurement counts) showed sensitivity to corn N treatment in a broad wavelength region centered at 550 nm and in two narrow regions centered at approximately 750 and 800 nm (Fig. 1). However, data reported in raw counts makes identification of all wavelengths that respond to N treatments difficult, because instrument response is not uniform over all wavelengths. Reflected radiation (absolute scale) is dependent on many factors, including sensor and illumination angles, solar irradiance, and canopy architecture (row direction, row

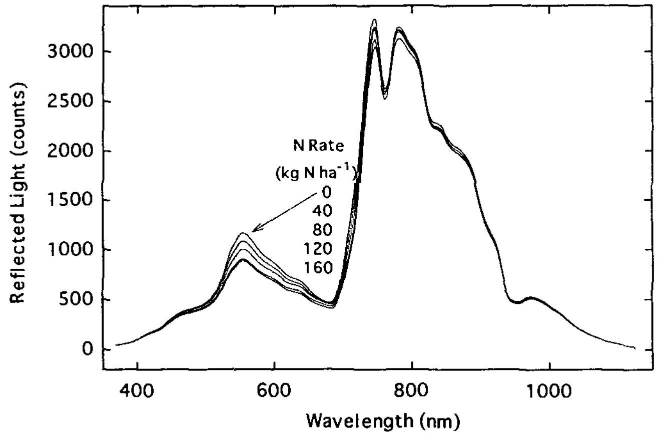

Fig. 1. Reflected radiation in instrument counts at wavelengths between 350 and 1050 nm for Pioneer brand hybrid 3379 in 1992.

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[1] Mention of trade name or proprietary products does not indicate endorsement of USDA and does not imply its approval to the exclusion of other products that may also be suitable.

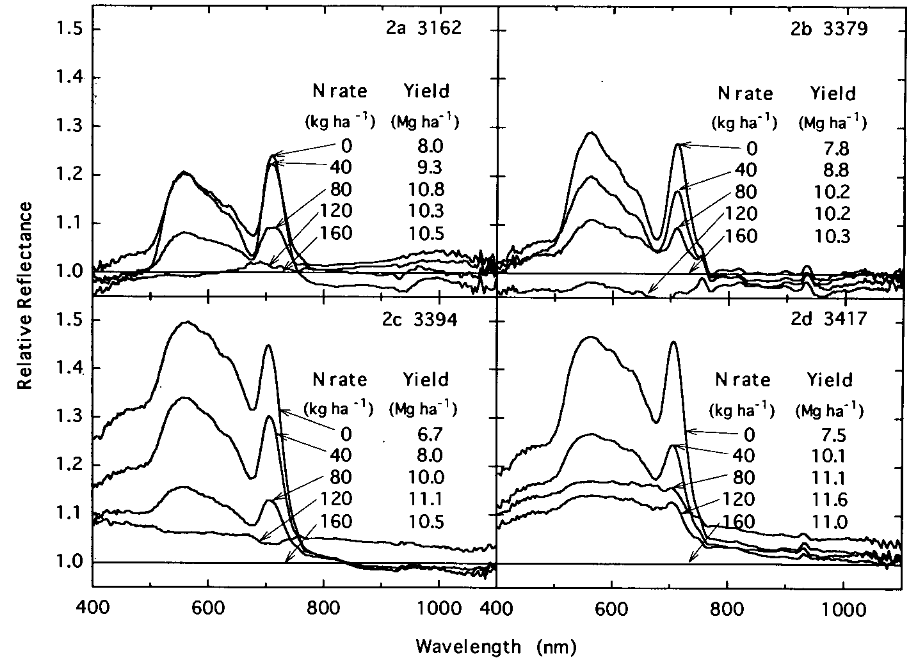

Fig. 2. Relative corn canopy reflectance ratios (ratio of reflected radiation from various N treatments to reflected radiation from the reference canopy at 160 kg N ha^{-1}) for Pioneer brand hybrids (3162, 3379, 3394, and 3417) and five N rates in 1992 vs. wavelength. Grain yields for each N treatment are also given.

spacing, leaf area index, and plant population) (Norman et al., 1985). Potential problems due to illumination differences can largely be avoided by referencing data to incident or incoming radiation. Assuming little change in solar irradiance within a 10-min period on clear days, all data were referenced to reflected radiation from a high-N-rate plot, yielding values of relative reflectance. That is, a ratio between traditional reflectance values from a treatment plot and reflectance from a control plot will yield a similar value as the ratio between reflected radiation from a treatment plot to reflected radiation from a control plot if there is little change in solar irradiance.

The relationship between relative reflectance and wavelength demonstrates unique differences between hybrids and N rates (Fig. 2 and 3). Wavelength regions that appeared to be the best indicators of N deficiency were cen-

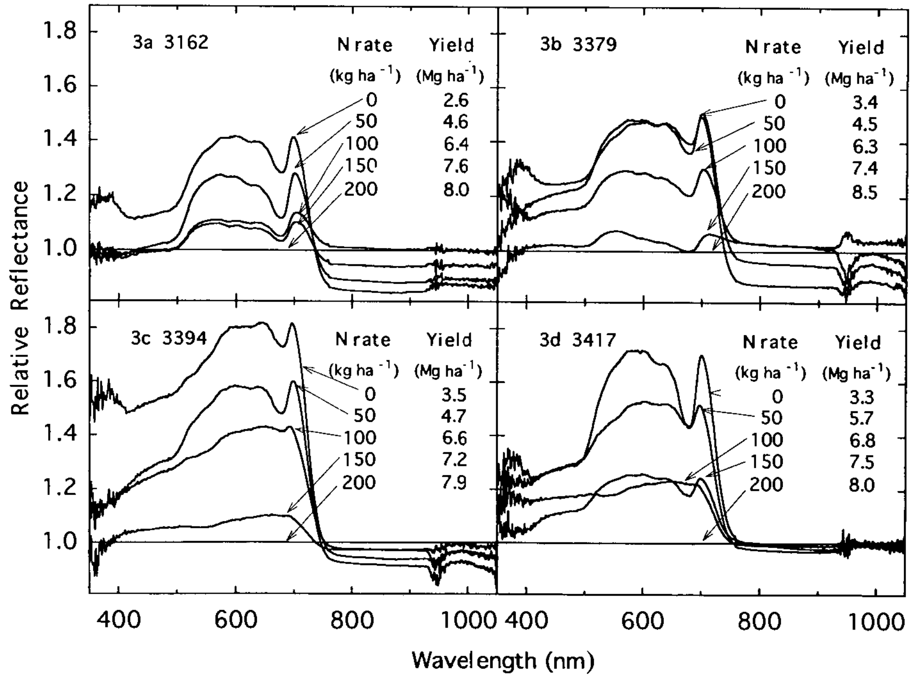

Fig. 3. Relative corn canopy reflectance ratios (ratio of reflected radiation from various N treatments to reflected radiation from the reference canopy at 200 kg N ha^{-1}) for Pioneer brand hybrids (3162, 3379, 3394, and 3417) and five N rates in 1993 vs. wavelength. Grain yields for each N treatment are also given.

Table 1. Coefficients of determination between relative grain yields and relative reflectances at various wavelengths at the R5 growth stage for corn.

	r^2		
Wavelength	1992	1993	Combined
nm			
450	0.24†‡	0.45†‡	0.44
550	0.66†‡	0.74†‡	0.74
650	0.45†‡	0.66†‡	0.67
710	0.68†	0.74†‡	0.76
(760–900)/(630–690)	0.60	0.75‡	0.60
(550–600)/(800–900)	0.86†	0.75†	0.86
(710)/(800–900)	0.68	0.87†‡	0.68

† Denotes significant hybrid effect ($P \le 0.05$).
‡ Denotes significant N rate × hybrid interaction ($P \le 0.05$).

Table 2. Coefficients of determination between grain yields and reflectance ratios at various wavelengths at the R5 growth stage for four corn hybrids.

	r^2			
Wavelength	3162†	3379	3394	3417
nm				
		1992		
450	0.05	0.28	0.85	0.56
550	0.71	0.85	0.94	0.77
650	0.63	0.71	0.93	0.70
710	0.77	0.80	0.96	0.81
(760–900)/(630–690)	0.70	0.78	0.95	0.72
(550–600)/(800–900)	0.82	0.93	0.96	0.81
(710)/(800–900)	0.72	0.85	0.96	0.80
		1993		
450	0.72	0.96	0.89	0.63
550	0.93	0.91	0.94	0.94
650	0.93	0.95	0.92	0.86
710	0.89	0.91	0.94	0.95
(760–900)/(630–690)	0.99	0.97	0.87	0.73
(550–600)/(800–900)	0.99	0.98	0.96	0.92
(710)/(800–900)	0.98	0.99	0.95	0.93

† Pioneer brand hybrids.

tered around 550, 650, and 710 nm. The relatively wide window of N sensitivity centered around 550 nm and merged with sensitivity around 650 nm decreases the need for specific wavelength precision. In contrast, the narrow peak at about 710 nm requires more precise control of the bandwidth measured. The 650-nm wavelength coincides with the value where chlorophyll strongly absorbs light. Chlorophyll also absorbs light strongly near 450 nm, but this area of the spectrum does not appear to be a good indicator of N status.

Relative reflectance values at 550 and 710 nm were most highly correlated with grain yield (Table 1). The apparent merits and sensitivity of measurements around 710 nm would be reduced if only wide-band measurements could be made. Walburg et al. (1982) used a ratio of two wavebands (760–900 nm)/(630–690 nm), which separated most treatments over the season, but the single 550- to 600-nm band provided the best separation in this study for late-season comparisons (R5). One might expect spectral ratio data to be less sensitive for variable lighting conditions if reflectance at both wavebands were measured simultaneously and both wavebands were affected the same by the variable lighting. Results of our study showed little difference between the performance in distinguishing N status with relative reflectance at the 550-nm wavelength and the ratio of relative reflectances reported by Walburg et al. (1982) [i.e., (760–900)/(630–690); Table 1]. Because of the inverse relationship observed for wavelengths longer than 800 nm (Fig. 3) compared with those in the vicinity of 550 nm, the ratio of relative reflectance for the two most sensitive individual wavelengths (550 and 710 nm) and an 800- to 900-nm interval were calculated (i.e., 575/850 and 710/850). The ratio of the data for the 550- to 600-nm interval to the 800- to 900-nm interval provided equal or superior predictability compared with relative reflectance at any individual wavelength (Table 1). The ratio of data for 710 nm to the 800- to 900-nm interval also provided good predictability compared with data at any individual wavelength within a year, but predictability decreased when data from both years were combined.

Differences in conditions between years, hybrids, soil fertility level, and instrumentation appeared to be partially accounted for by using the relative reflectance, as shown by the higher coefficients of determination for data combined from both years (Table 1). This is important, because most of the single-wavelength reflectance measurements had significant ($P \le 0.05$) hybrid effects and hybrid × N rate interactions for each year (Table 1). Hybrid and hybrid × N rate interactions for each year would detract from the ability to predict yield response when comparing across hybrids. However, comparisons made within a management area containing a single hybrid would not be affected by these confounding factors. Assuming that a management unit contained a single hybrid, the suggested way to evaluate the reliability in using relative reflectance to detect N differences would be to calculate the coefficient of determination for N rates within a hybrid and within a year. Relationships between relative grain yield and reflectance values within each hybrid were generally better in 1993 than 1992 (Table 2). Improved correlations in 1993 are attributed to the greater yield response to N fertilization. High regression coefficients for all hybrids at 550 nm for both years suggest that a photometric cell with a maximum sensitivity at 550 nm could be used to detect N deficiencies within N management units.

Data collected using a photometric cell in 1993 showed a significant ($P \le 0.05$) hybrid effect, but not a hybrid × N rate interaction. The strength of the relationship between relative reflectance and relative grain yield obtained using the photometric cell (Fig. 4) was comparable to that obtained using the spectroradiometer (Table 1). The larger regression coefficient for the photometric cell can be attributed to the slightly larger sampling area of the photometric cell compared with that of the spectroradiometer. Efforts to optimize the angle, height, and sampling area may substantially increase the performance of the photometric cell and enable effective detection of N stress at minimal cost; the cost of the photometric cell is about 1% that of the spectroradiometer and about 25% the cost of a chlorophyll meter.

CONCLUSIONS

Differences in N status were detected using reflected shortwave radiation from corn canopies. Reflected radi-

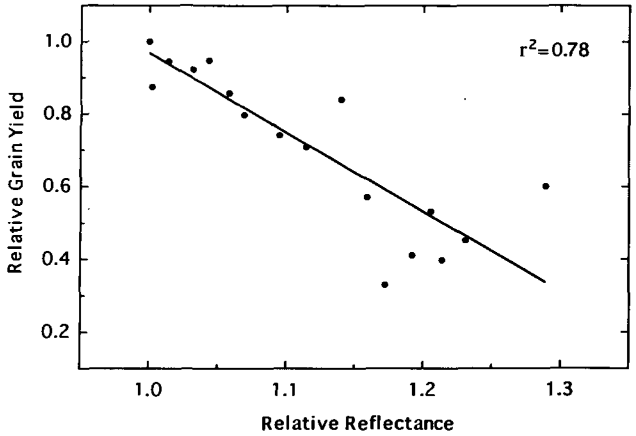

Fig. 4. Relative grain yield in 1993 vs. relative canopy reflectance ratio (ratio of reflected radiation from various N treatments to reflected radiation from the reference canopy at 200 kg N ha^{-1}) measured using a photometric cell.

ation (expressed as relative reflectance) around 550 and 710 nm provided the best detection of N deficiency in the 400- to 1000-nm spectral range. The spectral region responsive to N status around 710 nm was relatively narrow compared with that around 550 nm. A ratio of relative reflectance at either 710 or 550 nm to the relative radiation at around 800 to 900 nm also provided good relationships. The use of relative reflectance and a nonlimited-N reference plot makes it possible to utilize less expensive instrumentation by internally calibrating the instrument to a field situation. The data suggest that sensors for individual wavebands could be developed to detect N stress in corn, as demonstrated by the spectral ratio of (550–600)/(800–900). The use of ratios may have the advantage of compensating for fluctuating light conditions. More research is needed to further optimize canopy reflectance measurements and account for other sources of variability. Despite numerous sources of variation, results suggest that a relatively inexpensive sensor can be used to detect N deficiency, but additional research is needed to evaluate this technology. These results do, however, provide a practical and economically acceptable means of assessing crop N status by using an inexpensive sensor and standardizing the reflectance measurements to an in-field reference. Sensors of this type could be mounted on high-clearance vehicles and used in conjunction with global positioning systems or could possibly be mounted on center-pivot irrigation systems. Thus, characterization of the spatial distribution of canopy reflectance can be the basis for developing technologies for variable N rate application over a field.

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