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S.L. Osborne
University of Nebraska-Lincoln

James S. Schepers
University of Nebraska-Lincoln, james.schepers@gmail.com

D.D. Francis
University of Nebraska-Lincoln

Michael R. Schlemmer
University of Nebraska-Lincoln, michael.schlemmer@bayer.com

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Use of Spectral Radiance to Estimate In-Season Biomass and Grain Yield in Nitrogen- and Water-Stressed Corn

S. L. Osborne*, J. S. Schepers, D. D. Francis, and M. R. Schlemmer

ABSTRACT

Current technologies for measuring plant water status are limited, while recently remote sensing techniques for estimating N status have increased with limited research on the interaction between the two stresses. Because plant water status methods are time-consuming and require numerous observations to characterize a field, managers could benefit from remote sensing techniques to assist in irrigation and N management decisions. A 2-yr experiment was initiated to determine specific wavelengths and/or combinations of wavelengths indicative of water stress and N deficiencies, and to evaluate these wavelengths for estimating in-season biomass and corn (*Zea mays* L.) grain yield. The experiment was a split-plot design with three replications. The treatment structure had five N rates (0, 45, 90, 134, and 269 kg N ha^{-1}) and three water treatments [dryland, 0.5 evapotranspiration (ET), and full ET]. Canopy spectral radiance measurements (350–2500 nm) were taken at various growth stages (V6–V7, V13–V16, and V14–R1). Specific wavelengths for estimating crop biomass, N concentration, grain yield, and chlorophyll meter readings changed with growth stage and sampling date. Changes in total N and biomass in the presence of a water stress were estimated using near-infrared (NIR) reflectance and the water absorption bands. Reflectance in the green and NIR regions were used to estimate total N and biomass without water stress. Reflectance at 510, 705, and 1135 nm were found for estimating chlorophyll meter readings regardless of year or sampling date.

Available water is one of the most limiting factors in crop production; while in non-leguminous crops, low available soil N can be an additional yield reduction factor. Denmead and Shaw (1960) found water stress reduced corn grain yield by 25, 50, and 21% prior to, during, and after silking, respectively, compared with the nonstressed plots. Claasen and Shaw (1970) concluded that water stress at 75% silking resulted in greater reduction in corn grain yield (53% of the nonstressed), compared with stress during vegetative periods or 3 wk after silking (15 and 30% of the nonstressed, respectively).

Over the past decade, the increased use of irrigation and concern over environmental contamination has brought about an awareness of efficiently utilizing our limited resources and decreasing the negative environmental impacts of fertilizer leaching and runoff. Irrigation management techniques involve several different methods, including soil-, meteorological-, and crop-based techniques. Soil-based techniques target irrigation events based on soil water content in the rooting zone; meteorological-based approaches depend on air temperature, net radiation, vapor pressure, and wind speed, as well as crop coefficients, to estimate daily ET. Direct plant-based measurements are limited to leaf water potential by pressure chamber, stomatal conductance by porometry, other leaf water content measurements, and canopy temperature by infrared thermometry. Visual indications of water stress include morphological characteristics such as leaf rolling at midday. These measurements are very time-consuming and require a number of observations to characterize a field (Jackson, 1982). Because of limitations to the above methods, it would be beneficial to use remote sensing techniques to help managers determine when and/or where a water stress exists. Early detection of a water stress could trigger irrigation before yield loss occurs.

Recent research has examined technologies involving remote sensing to quantify water stress. Moran et al. (1989) investigated the effect of water stress on canopy architecture in alfalfa (*Medicago sativa* L.) and the sequential effect on canopy reflectance. They found water-stressed canopies to have a lower spectral reflectance in the NIR and red wavebands when compared with unstressed canopies. A ratio of the two wavebands was most successful in estimating the onset of stress. Moran et al. (1994) investigated the concept of a water deficit index, which is defined as the ratio of actual to potential ET. This index exhibits the ability to predict ET rate and relative field water deficit for both full-cover and partially-vegetated sites. The measurement can be calculated from remotely sensed data (red and NIR) gathered with ground, aircraft, or satellite-based sensors. On-site measurements used in the calculation include net radiation, air vapor pressure deficit, air temperature, and wind speed. Work by Bowman (1989) with cotton (*Gossypium hirsutum* L.) showed reflectance in the infrared spectra (810, 1665, and 2210 nm) increased as relative water content decreased. Hope et al. (1986) integrated canopy reflectance, stomatal resistance, and energy dynamics into a modeling system that was suited to investigate the relationship between canopy temperature and spectral indices, that is, simple spectral ratio (NIR/red) and normalized difference vegetation index (NDVI) of green vegetation. The results indicate this relationship may be useful for parameterizing the surface moisture available for ET and the subsequent need for irrigation. Jackson et al. (1983) used several ratios and linear combinations of bands similar to those measured by sensors on the Landsat satellite. They determined water stress could not be detected until after there was a stress-induced retardation in growth. The ability of all ratios to detect water stress was dependent

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S.L. Osborne, USDA-ARS, Northern Grain Insects Research Laboratory, 2923 Medary Ave., Brookings, South Dakota 57006; J.S. Schepers, D.D. Francis, and M.R. Schlemmer, Dep. of Agronomy and USDA-ARS, Univ. of Nebraska-Lincoln, Lincoln, NE 68583. Received 12 Dec. 2000. *Corresponding author (sosborne@ngirl.ars.usda.gov).

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Abbreviations: ET, evapotranspiration; MIDIR, midinfrared; NIR, near-infrared.

on the plant growth stage, soil background, and atmospheric changes.

In order to efficiently apply N, in-season methods must be developed to assess the crop fertilizer N needs. Methods used to detect N deficiencies during the cropping season include: chlorophyll meter readings, destructive plant sampling, and soil sampling. Blackmer and Schepers (1994) found the chlorophyll meters were useful for monitoring N status in irrigated corn. Normalizing the readings to those from the highest N treatments was a practical way to prescribe N application within the growing season. They also discussed the post-harvest stalk nitrate test as a quick and reliable means of identifying excessive N availability during the later part of the growing season. The stalk nitrate test is not practical during the growing season. Blackmer and Schepers (1996) found photographic data collected at R4 (dough) were more highly correlated with grain yield than was chlorophyll meter data. They also found photographic data could detect N deficiencies, which were later verified using stalk nitrate-N sampling. Although these methods have proven to be good indicators of N stress, they require large amounts of time and labor for sample collection. The use of effective remote sensing techniques would eliminate the need for extensive field sampling, giving good deficiency detection capability.

Increased scientific understanding of spectral responses of crops is increasing the potential for using remote sensing to detect nutrient stresses. Recent research has focused on determining the appropriate wavelength or wavelength combinations to characterize crop N deficiency. Blackmer et al. (1994) and Thomas and Oerther (1972) found light reflectance near 550 nm was best for separating N-deficient from non-N-deficient corn and sweet pepper (*Capsicum annuum* L.) leaves, respectively. Bausch and Duke (1996) investigated using a ratio of NIR/green reflectance as an N-sufficiency index. Comparison of this method to the SPAD chlorophyll meter measurements (Minolta Corp., Ramsey, NJ) demonstrated that the NIR/green ratio and SPAD measurements exhibited a 1:1 relationship and that the ratio could be used to determine fertilization need for irrigated corn. Walburg et al. (1982) showed that N-deficient corn canopies had increased red reflectance and decreased NIR reflectance when compared with N-sufficient corn canopies. A ratio of the average reflectance from 760 to 900 nm divided by reflectance from 630 to 690 nm exhibited a good separation between N treatments. Aase and Tanaka (1984) reported a relationship between green leaf dry matter and NIR/red ratios, and suggested that reflectance measurements could be used to estimate leaf dry matter or leaf area measurements in spring and winter wheat (*Triticum aestivum* L.). Work by Stone et al. (1996) demonstrated that total plant N could be estimated using spectral radiance measurements at the red (671 nm) and NIR (780 nm) wavelengths. They calculated a plant-N-spectral-index for the amount of fertilizer N required to correct in-season N deficiency in winter wheat.

The objectives of this work were to determine specific wavelengths and/or combinations of wavelengths indicative of water stress and N deficiencies, and to evaluate these wavelengths for estimating in-season biomass and corn grain yield.

MATERIALS AND METHODS

A field experiment was conducted at the Management Systems Evaluation Area (MSEA) project near Shelton, NE, on a field of irrigated continuous corn. Soil type was a Hord silt loam (fine-silty, mixed, mesic Cumulic Haplustolls). The production system utilized conventional tillage with a linear-move irrigation system. Planting occurred on 7 May 1997 and 5 May 1998 with Pioneer brand hybrid 3489 at a seeding rate of 74 000 plants ha^{-1}. The experimental design was a split-plot with three replications. The treatment design was a three by five factorial arrangement, with water treatment being the whole-plot treatment and N rate as the split-plot treatments. Plots were 7.32 m × 22.86 m with 0.91-m row spacing. Starter fertilizer (13 kg N ha^{-1} and 19 kg P ha^{-1} as ammonium polyphosphate) was applied at planting. The three water treatments consisted of dryland (no additional irrigation except that needed to avoid complete crop loss), irrigation based on 0.5 ET, and irrigation based on 1.0 (full) ET. Nitrogen treatments were applied as NH_4NO_3 at rates of 0, 45, 90, 134, and 269 kg N ha^{-1}. Nitrogen treatments were applied as a split application (1/2 sidedress at V1–V2 and 1/2 sidedress at V4–V5). Applications dates were 21 May and 10 June 1997, and 22 May and 16 June 1998. Guardsman [Dimethenamid (2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide) + Atrazine (2-chloro-4-ethylamino-6-isopropyl-amino-s-trazine)] 53.2% a.i. were applied to all plots at a rate of 3.5 L ha^{-1} in early May for weed control. Irrigation time and application amounts are reported in Table 1. Irrigation water contained <1 mg L^{-1} nitrate-N. Phenology data according to Ritchie et al. (1997) were taken weekly from early June to late August. Chlorophyll meter readings (SPAD 502, Minolta Corp., Ramsey, NJ) were taken on the uppermost collared leaf until the ear leaf was present. Once the ear leaf was collared, it was used for the remainder of the growing season. Readings were collected half way between the edge of the leaf and the mid-rib and mid-way between the stalk and tip of the leaf. Chlorophyll meter readings were collected weekly from the middle of June until the middle of August, according to Peterson et al. (1993).

Hyperspectral reflectance measurements were collected

Table 1. Irrigation time and application amounts, Shelton, NE, 1997 and 1998.

Date	Water treatment		
	Dryland	**0.5 ET†**	**1.0 ET**
		mm	
30 June 1997	**22**	**22**	**22**
9 July 1997	**14**	**14**	**14**
10 July 1997	–	**14**	**29**
15 July 1997	–	–	**28**
18 July 1997	–	**27**	**33**
23 July 1997	–	–	**36**
31 July 1997	**37**	**36**	**38**
8 Aug. 1997	–	**25**	**30**
		mm	
29 June 1998	–	–	**16**
3 July 1998	–	–	**14**
21 July 1998	–	–	**30**
22 Aug. 1998	–	–	**24**
5 Sept. 1998	–	**5**	**22**

† ET = evapotranspiration.

from the 350- to 2500-nm range, collected at 1-nm intervals using a FieldSpec spectroradiometer (Analytical Spectral Devices, Boulder, CO). Measurements were taken at heights of 4.5 m and 10.6 m above the canopy, in 1997 and 1998, respectively, with an 18° field of view foreoptic. Measurement dates were 17 July and 17 September in 1997, and 15 June and 17 July in 1998. Five canopy measurements were taken randomly throughout each plot. Individual readings were averaged to get a representative reading for the entire plot. Canopy measurements were taken on cloud-free days at solar noon ±2 h. All measurements were transformed into percentage reflectance using a Spectralon[1] reference panel (CEREX, Cantonment, FL) (representing maximum reflectance) for total incoming radiance. Reference panel measurements were taken before the initial canopy reading and repeated about every 15 min.

Spectral readings collected on the specified dates were averaged across 5-nm intervals to decrease the amount of data for analysis. Stepwise regression was performed, using the REG procedure in SAS (SAS, 1988) on all data to develop multiple regression equations for predicting plant N, biomass, grain yield, grain N concentration, and chlorophyll meter readings. All individual wavelength coefficients used in the regression equations had a significance level of 0.05 or less. Each regression equation developed had a significance level of 0.001.

Biomass samplings were performed during the growing season by randomly collecting 12 plants from the east quarter of the plots. Whole plants were weighed and ears were separated once distinguishable. Sampling dates were 15 July and 19 August in 1997, and 13 July and 16 September in 1998. Whole plants were weighed and then chopped with a chipper-shredder in the field to facilitate subsampling. Subsamples and ear samples were weighed and then oven dried at 50°C before being reweighed to determine water content. All subsamples were ground in a Wiley Mill to pass a 2-mm sieve. Nitrogen concentration was determined on all subsamples using dry combustion (Schepers et al., 1989). Grain yield was estimated by hand harvesting a 3.05-m length from each of the four middle rows. Ears were shelled and water content determined. Grain samples were oven dried at 50°C, ground and analyzed for N concentration, as previously described for biomass. Grain yield was calculated and corrected to 155 g kg^{-1} moisture.

RESULTS AND DISCUSSION

Grain Yield

There was a significant linear and/or quadratic response to applied N each year for grain yield and total plant N content (Table 2). A water stress was only present in 1997, which affected both grain yield and N concentration. The presence of a water stress (measured from canopy temperature and neutron probes, data not shown), occurring prior to silking in 1997, decreased yields by 22.1 and 15.8% for the dryland and 0.5 ET irrigation treatments (averaged across N treatments), respectively, compared with the full ET treatment in 1997 (Table 2). These results are similar to previous findings from Denmead and Shaw (1960), who found a 25% reduction in yield with water stress prior to silking. The dryland irrigation treatment resulted in a higher N

Table 2. Analysis of variance, single-degree-of-freedom contrasts, and mean for grain yield and grain N concentration, Shelton, NE, 1997 and 1998.

			Grain yield		Grain N	
Source		**df**	**1997**	**1998**	**1997**	**1998**
			MS			
Replication		2	2.99	5.08	0.0378	0.0022
Water		2	16.84**	0.98	0.1321*	0.0499
Linear		1	31.74**	1.64	0.2489**	0.0889
LOF†		1	1.94	0.33	0.0153	0.0110
Error (a)		4	0.63	0.10	0.0089	0.0094
N rate		4	34.86***	58.16***	0.3018***	0.3563***
Linear		1	97.01***	120.88***	0.9844***	1.4150***
Quadratic		1	33.68***	107.77***	0.2059***	0.0063
N rate* water		8	1.01*	1.20	0.0256*	0.0109
Error (b)		24	0.39	0.53	0.0081	0.0218
			Treatment means			
N Rate, kg ha^{-1}	**Water level**		**Grain yield (Mg ha^{-1})**		**Grain N (g kg^{-1})**	
0	0		4.98	3.67	1.12	1.01
45	0		6.76	5.76	1.40	1.12
90	0		8.16	8.85	1.58	1.20
134	0		7.44	10.40	1.67	1.18
269	0		8.96	8.27	1.77	1.57
0	0.5		4.38	4.08	1.11	0.94
45	0.5		7.25	6.49	1.25	0.95
90	0.5		8.99	9.17	1.41	1.09
134	0.5		8.60	8.59	1.54	1.18
269	0.5		10.02	8.87	1.57	1.50
0	1		5.48	3.56	1.25	0.94
45	1		9.03	6.17	1.17	0.98
90	1		10.11	9.39	1.31	1.05
134	1		10.97	1.039	1.45	1.23
269	1		11.01	9.77	1.44	1.35

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† LOF, lack of fit.

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

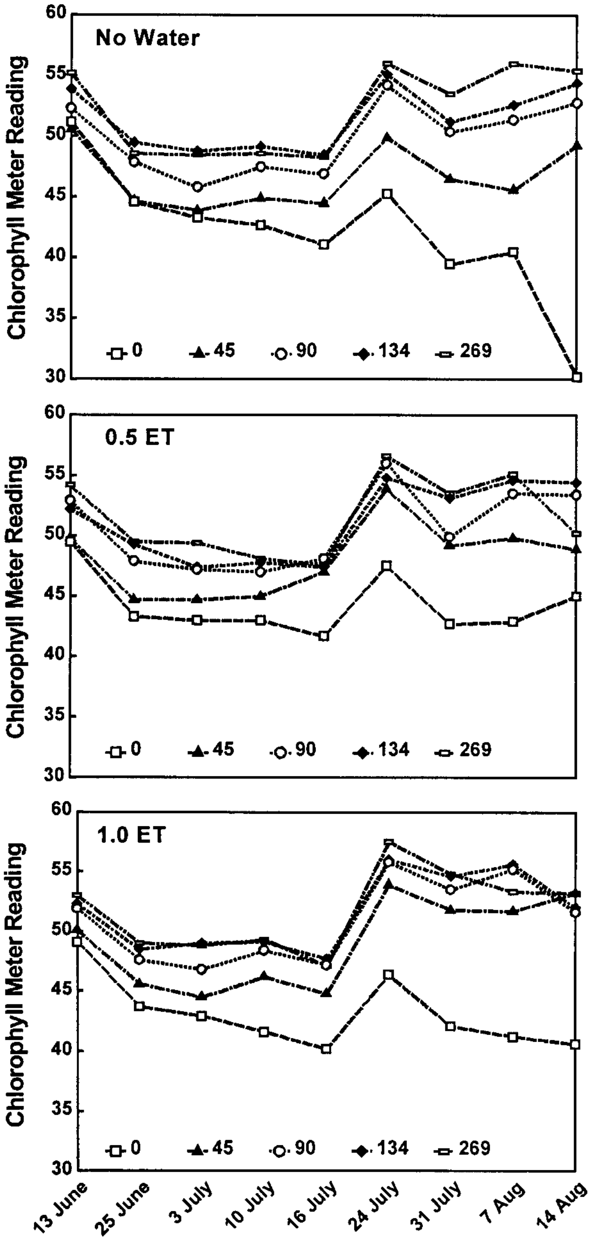

Fig. 1. Chlorophyll meter readings for each N rate (kg N ha⁻1) by water level, Shelton NE, 1997.

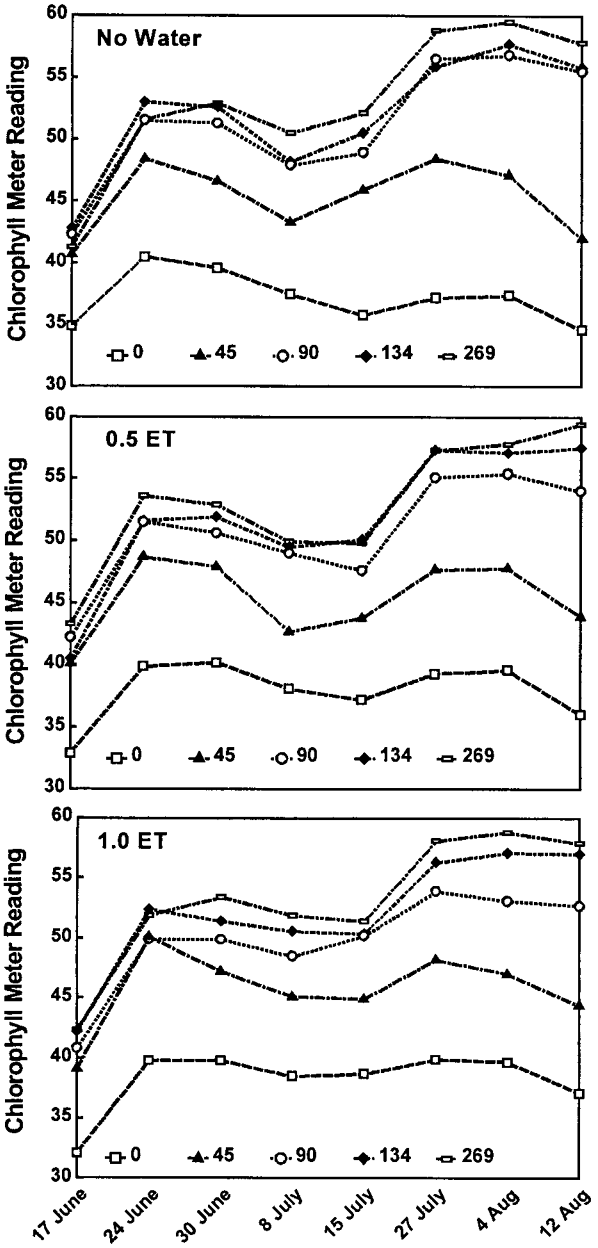

Fig. 2. Chlorophyll meter readings for each N rate (kg N ha⁻1) by water level, Shelton NE, 1998.

concentration relative to the 0.5 and full ET treatments. There was no water stress present during the 1998 season, thus no effect of water on grain yield or total N. Rainfall amount for the 1997 season was 247 mm, compared with 457 mm in the 1998 season. The 1997 season had a significant water × N interaction for grain yield and total N (Table 2).

Chlorophyll Meter Readings

Past research has shown that chlorophyll meter measurements were correlated with changes in leaf N concentration. Problems associated with comparing readings from different growth stages, different hybrids, or different locations make it difficult to make comparisons throughout the season (Schepers et al., 1992). Chlorophyll meter readings from this experiment were used to help illustrate differences between years and the different N rates rather than make seasonal comparisons (Fig. 1, 2). In the 1998 growing season, the different N rates had a larger effect on chlorophyll content, regardless of water treatments. Differences in chlorophyll content for three water treatments were greatest between the 0 N rate compared with the remaining N rates (Fig. 1, 2).

Linear and/or quadratic single-degree-of-freedom contrasts for applied N were significant for all weekly readings (Table 3 and 4). Chlorophyll meter readings from 31 July 1997 suggested a significant effect of N rates on chlorophyll content due to the extreme water stress present at that date. Immediately following chlorophyll meter readings, all plots were irrigated to prevent total crop loss for the dryland treatments (Table 1).

Table 3. Significance level from the analysis of variance, and single-degree-of-freedom contrasts for chlorophyll meter readings, Shelton, NE, 1997.

Source	df	13 June	25 June	3 July	10 July	16 July	24 July	31 July	7 Aug.	14 Aug.
Replication	2	ns†	ns	ns	ns	ns	ns	ns	ns	ns
Water	2	ns	ns	ns	ns	ns	ns	*	ns	ns
Linear	1	ns	ns	ns	ns	ns	ns	*	ns	ns
LOF‡	1	ns	ns	ns	ns	ns	ns	ns	ns	ns
Error (a)	4									
N rate	4	***	***	***	***	***	***	***	***	***
Linear	1	***	***	***	***	***	***	***	***	***
Quadratic	1	ns	***	***	***	***	***	***	***	***
Cubic	1	ns	ns	ns	ns	*	***	***	**	ns
LO	1	ns	ns	ns	ns	ns	ns	ns	ns	ns
N rate × water	8	ns	ns	ns	ns	ns	ns	ns	*	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† ns = not significant.
‡ LOF, lack of fit.

Table 4. Significance level from the analysis of variance, and single-degree-of-freedom contrasts for chlorophyll meter readings, Shelton, NE, 1998.

Source	df	17 June	24 June	30 June	8 July	15 July	27 July	4 Aug.	12 Aug.
Replication	2	ns†	ns	ns	ns	ns	ns	ns	ns
Water	2	ns	ns	ns	ns	ns	ns	ns	ns
Linear	1	ns	ns	ns	ns	ns	ns	ns	ns
LOF‡	1	ns	ns	ns	ns	ns	ns	ns	ns
Error (a)	4								
N rate	4	***	***	***	***	***	***	***	***
Linear	1	***	***	***	***	***	***	***	***
Quadratic	1	***	***	***	***	***	***	***	***
Cubic	1	***	***	***	ns	**	**	ns	ns
LO	1	ns	**	ns	ns	ns	ns	ns	ns
N rate × water	8	ns	ns	ns	ns	ns	ns	ns	ns

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† ns, not significant.
‡ LOF, lack of fit.

Hyperspectral Readings

Two separate analyses were performed for the 17 July 1997 sampling due to differences between water stress treatments. One analysis was performed for all treatments, while the other analysis was performed on only the highest water treatment with varying N rates. This was to determine the reflectance wavelength for predicting total N and biomass with and without a water stress. Results from water-stressed plants indicated reflectance in the red (600 and 700 nm) and a number of different wavelengths in the midinfrared (MIDIR), between the water absorption bands (1400, 1900, and 2700 nm), were important for predicting biomass ($R^2 = 0.87$) and total N ($R^2 = 0.87$) (Table 5). Reflectance in the MIDIR region is considered to be a function of leaf thickness and water content (Lillesand and Kiefer, 1987). These wavelengths are similar to wavelengths used by past researchers to detect water stress (Moran et al., 1989; Carter, 1991). In contrast, results from plants adequately supplied with water indicated wavelengths in the green region (550 nm) and the MIDIR (1425, 1465, 1490, and 2120 nm) were important in the prediction of total N, having an $R^2 = 0.95$ (Table 6). Biomass was best predicted by wavelengths in similar narrow waveband regions (505, 515, 545, 1455, 2045, 2180, and 2190 nm) with an $R^2 = 0.94$ (Table 6). This is similar to work by Blackmer et al. (1994) who found reflectance near 550 nm was best for detecting N deficiencies in corn. Everitt et al. (1985) found plant leaf N content was associated with reflectance at 500 nm.

Regression equations for estimating total biomass and total N in 1997 and 1998 are reported in Table 5. Estimation of biomass for the 1998 season did not produce very reliable information, although prediction of total N was somewhat better and accuracy of estimating chlorophyll was similar between 1997 and 1998. Various wavelengths in the MIDIR region were used for predicting total N (Table 5).

Hyperspectral data were compared with chlorophyll meter data gathered at the same time (±1 d). Prediction of chlorophyll meter data was significant in 1997 for blue (440 nm), green (510 nm), NIR (705 nm), and MIDIR (1135, 1145, 2095, and 2110 nm) regions, with an $R^2 = 0.91$ (Table 5). Because plants had been under a water stress for 2 wk during the 1997 growing season, the production of chlorophyll and plant growth were reduced. The decrease in growth, as well as differences in water content, could account for the contribution from reflectance in the NIR and MIDIR regions in 1997. Estimation of chlorophyll meter readings based on 1998 data involved reflectance in the green (510 nm), NIR (705 nm), and MIDIR (1135 nm) with $R^2 > 0.82$ (Table 5). Because these wavelengths were similar to those used for the 1997 data, our results indicate the potential of remote sensing for estimating chlorophyll meter readings, which in the past has been used to estimate fertil-

Table 5. Regression equations for predicting biomass, plant N, and chlorophyll meter readings in corn grown under five N levels and three irrigation levels from canopy hyperspectral data by sampling date, Shelton, NE, 1997 and 1998 ($n = 45$).

Date	Growth stage	R^2	Biomass
			Mg ha^{-1}
17 July 1997	V13-V16	0.87	$y = 10 - 122 \times R_{700} + 295 \times R_{1015} - 48 \times R_{1110} - 473 \times R_{1205} + 107 \times R_{1335} + 356 \times R_{1510} - 306 \times R_{1580} - 235 \times R_{1640} + 498 \times R_{1645} + 96 \times R_{1785} - 9 \times R_{1795} - 95 \times R_{1960} + 97 \times R_{1965} - 176 \times R_{2075} - 94 \times R_{2185} + 38 \times R_{2240}$
15 June 1998	V6-V7	0.59	$y = 4 - 1 \times R_{975} - 17 \times R_{2000} + 24 \times R_{2005} + 34 \times R_{2040} - 21 \times R_{2055} - 27 \times R_{2065} + 16 \times R_{2245} - 14 \times R_{2265}$
17 July 1998	V14-R1	0.45	$y = 7 - 35 \times R_{2240}$
			Plant N
			g kg^{-1}
17 July 1997	V13-V16	0.87	$y = 1 + 158 \times R_{600} - 91 \times R_{705} - 5 \times R_{1130} + 12 \times R_{1155} - 11 \times R_{1450} - 26 \times R_{1515} - 18 \times R_{1700} + 22 \times R_{1725} + 12 \times R_{1775} + 11 \times R_{2045} - 10 \times R_{2090} - 4 \times R_{2155} + 6 \times R_{2190}$
15 June 1998	V6-V7	0.80	$y = 5 + 5 \times R_{1150} + 53 \times R_{2045} - 37 \times R_{2060} + 51 \times R_{2065} - 80 \times R_{2110}$
17 July 1998	V14-R1	0.95	$y = 1 - 15 \times R_{715} + 2 \times R_{935} + 18 \times R_{1435} + 7 \times R_{1955} - 15 \times R_{1990} - 8 \times R_{2010} - 45 \times R_{2030} + 32 \times R_{2110} + 9 \times R_{2230}$
			Chlorophyll meter reading
17 July 1997	V13-V16	0.91	$y = 48 - 7048 \times R_{440} + 8808 \times R_{510} - 1897 \times R_{705} + 3 \times R_{1135} + 51 \times R_{1145} + 285 \times R_{2095} - 298 \times R_{2110}$
15 June 1998	V6-V7	0.82	$y = 48 + 1840 \times R_{510} - 862 \times R_{705} + 28 \times R_{1135}$
17 July 1998	V14-R1	0.87	$y = 46 + 1006 \times R_{510} - 808 \times R_{705} + 87 \times R_{1135}$

Table 6. Regression equations for predicting biomass, and plant N for corn grown at high water levels at the V13-V16 phenological growth stage, Shelton, NE, 17 July 1997 ($n = 15$).

Sample type	R^2	Equation
Biomass, Mg ha^{-1}	0.94	$y = 6 + 4214 \times R_{505} - 4436 \times R_{515} + 710 \times R_{545} + 140 \times R_{1455} + 90 \times R_{2045} - 67 \times R_{2180} - 60 \times R_{2190}$
Plant N, g kg^{-1}	0.95	$y = 2 - 60 \times R_{555} + 3 \times R_{1425} + 10 \times R_{1465} + 35 \times R_{1490} - 37 \times R_{2120}$

izer N need for a growing crop (Blackmer and Schepers, 1995).

Stepwise regression was performed to estimate grain yield and grain N using hyperspectral data for the four phenological growth stages (Table 7). Prediction of grain yield was best for the 17 July 1998 sampling (V14–R1), with an $R^2 = 0.95$ using reflectance in the green (530 nm), red (675 nm), and MIDIR (1780, 1790, 2020, and 2035 nm). The equation developed for the 17 Sept. 1997 sampling date (R5–R6) used reflectance values in similar regions of the spectrum, with an $R^2 = 0.89$. Reflectance in these spectral regions would account for differences in N content and also differences in the amount of plant biomass present. The wavelengths used in the regression equations changed throughout the growing season and especially between years, suggesting seasonal differences in the amount of soil background present, difference in vegetation stages, and presumably a number of other agronomic factors.

CONCLUSIONS

The potential for hyperspectral remote sensing to detect water stress in irrigated corn was illustrated the

Table 7. Regression equations for predicting grain yield and grain N from canopy hyperspectral data × measurement collection date, Shelton, NE, 1997 and 1998 ($n = 45$).

Date	Growth stage	R^2	Grain yields
			Mg ha^{-1}
17 July 97	V13-V16	0.88	$y = 8 + 368 \times R_{705} - 378 \times R_{715} + 46 \times R_{1025} + 16 \times R_{1440} - 98 \times R_{1970} + 35 \times R_{2170} - 53 \times R_{218}0 - 32 \times R_{2210} + 23 \times R_{2245}$
17 Sept. 1997	R5-R6	0.89	$y = 1 + 373 \times R_{585} - 1268 \times R_{655} - 2450 \times R_{660} + 3064 \times R_{685} + 202 \times R_{935} - 178 \times R_{940} + 63 \times R_{1975} - 47 \times R_{2145} + 61 \times R_{2160} - 25 \times R_{2230} - 17 \times R_{2240}$
15 June 1998	V6-V7	0.28	$y = 18 - 117 \times R_{460}$
17 July 1998	V14-R1	0.95	$y = 8 - 475 \times R_{530} + 351 \times R_{675} + 332 \times R_{1780} - 202 \times R_{1790} + 63 \times R_{2020} - 225 \times R_{2035}$
			Grain N
			g kg^{-1}
17 July 1997	V13-V16	0.84	$y = 1 - 605 \times R_{425} + 679 \times R_{430} - 10 \times R_{740} + 2 \times R_{1120} + 12 \times R_{1180} + 4 \times R_{1460} + 55 \times R_{1575} - 34 \times R_{1635} - 28 \times R_{1715} - 5 \times R_{1780} + 8 \times R_{2060} - 30 \times R_{2090} - 18 \times R_{2110} + 20 \times R_{2130} + 1 \times R_{2215} + 6 \times R_{2235}$
17 Sept. 1997	R5-R6	0.88	$y = 1 + 72 \times R_{415} - 21 \times R_{695} + 2 \times R_{810} - 3 \times R_{1425} + 9 \times R_{1450} + 13 \times R_{1455} - 13 \times R_{1720} - 4 \times R_{1960} + 4 \times R_{1970} - 8 \times R_{2155} + 10 \times R_{2180} - 3 \times R_{2190}$
15 June 1998	V6-V7	0.87	$y = 4 - 1 \times R_{865} + 3 \times R_{1945} - 14 \times R_{2005} + 29 \times R_{2020} + 30 \times R_{2080} - 54 \times R_{2085} + 22 \times R_{2145} - 49 \times R_{2150} + 45 \times R_{2155} - 13 \times R_{2210} - 6 \times R_{2220}$
17 July 1998	V4-R1	0.90	$y = 1 + 354 \times R_{540} - 233 \times R_{575} - 76 \times R_{725} + 13 \times R_{960} - 11 \times R_{1445} - 6 \times R_{1955} + 34 \times R_{2000} - 13 \times R_{2005}$

first season (1997) of this study, but these results could not be repeated due to the lack of water stress in the 1998 growing season. The presence of water stress influenced the wavelengths used for estimating plant N content compared with wavelengths used without the presence of a water stress. Predicting plant N and grain yield resulted in an R^2 of 0.80 or better for each sampling date, but the wavelengths were not always consistent across phenological stages. Reflectance in the green (510 nm), NIR (705 nm), and MIDIR (1135 nm) regions predicted chlorophyll meter readings with an $R^2 > 0.82$ for all sampling dates, indicating the potential of using hyperspectral imagery as a tool to detect and map variations in plant chlorophyll. While there are a number of different specific wavelengths that were used to estimate N content, biomass, and grain yield, and the specific equations developed may not be transferable to other areas, the range of wavelengths could be useful in determining which reflectance bands are important for detecting N content, biomass, or grain yield with and without the presence of a water stress at different times in the growing season.

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