COINCIDENT DETECTION OF CROP WATER STRESS, NITROGEN STATUS AND CANOPY DENSITY USING GROUND-BASED MULTISPECTRAL DATA

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ABSTRACT

Remotely sensed data has been identified as an important tool for precision crop management (PCM). The data has been used to assist in the identification of management zones, map crop nutrient status, and detect pest infestations. However, in many of the examples cited, the correlation between a multispectral signature and the variation of interest was limited to single factor experiments (i.e., only one factor was primarily responsible for the variability in crop condition). A water by nitrogen experiment was conducted during the 1999 cotton season near Phoenix, Arizona, where one objective was to test the ability of remotely sensed data to distinguish between water and nitrogen stress. Multispectral (visible, near infrared and thermal) data were collected using a prototype sensor mounted on a linear move irrigation system. Neutron probe data were used to quantify crop water status, and petiole samples were used to determine crop N status. Analysis of this data indicated that it is possible to use remotely sensed data to develop maps of water stress, N status and canopy density when variations in all of these factors are simultaneously present. Additional data analysis is needed before we can determine how accurately these factors can be quantified across the growing season.

Keywords: Remote sensing, water stress, nitrogen stress, plant density

INTRODUCTION

Precision farm management requires timely, georeferenced information on crop and soil conditions. Remote sensing has been cited as a technology to meet many of these information needs (Moran et al., 1997). One limitation to this technology is that changes in canopy density can dominate spectral response, making it difficult to relate spectral variations to other crop properties, especially before the crop reaches full cover. Therefore, in single factor experiments, it is difficult to determine if the relationship between a spectral response and crop condition that alters canopy density (e.g., nitrogen or water status) is truly a unique spectral signature or simply an artifact of changes in canopy density. The objective of this paper was to examine the ability of remotely sensed data to distinguish between water and N stress using data collected during a cotton field experiment conducted near Maricopa, Arizona.

One of the first applications of remotely sensed data has been the detection of relative differences in plant canopy density (Jordan, 1969). Reflectance data have been related to plant characteristics such as plant biomass or fraction of intercepted photosynthetically active radiation (Pinter et al., 1994). The red and near-infrared portions of the spectrum have been found particularly useful in vegetation monitoring. Korobov and Railyan (1993) found the near-infrared (NIR) and red portions of the spectrum had the highest correlation with plant variables (height, density, and percent cover). Gupta (1993) noted that the ratio of the NIR to Red channels provided a higher correlation with crop development in the early and late stages of growth, while the Normalized Difference Vegetation Index (NDVI) had a near linear correlation to crop growth over plant covers of 15 to 80%.

The primary method of remote water stress detection has been through the use of the thermal part of the spectrum. Early studies showed a relationship between plant canopy temperature and water status (Jackson et al., 1977). These relationships were later refined to define a crop water stress index (CWSI) based on canopy temperature and meteorological conditions (e.g., Idso et al., 1981). One limitation in the application of this technique is that a pure canopy temperature is needed, and any measure of the soil background can result in false detection of water stress. Moran et al. (1994) and Clarke (1997) refined the CWSI for partial canopy conditions by integrating an estimate of percent crop cover from a vegetation index. Non-thermal techniques to assess plant water use include establishing the relationship between vegetation indices and crop coefficients

(Bausch, 1995) and changes in the near infrared area of the spectrum (Peñuelas et al., 1997).

A direct means of remotely sensing absolute levels of soil or plant nutrients has yet to be established; however, plant responses to nutrient deficiency can be detected using remote sensing techniques. Several nutrient deficiencies are known to reduce plant chlorophyll levels (e.g., Evans, 1989). Many studies have shown that leaf reflectance in the visible spectrum (particularly the green region ~550 nm) can be related to chlorophyll content (e.g., Thomas and Gausman, 1977). As leaf N and chlorophyll contents have been established for a variety of C3 plants (Evans, 1989), reflected light at 550-nm has also been shown to be sensitive to plant N content (Blackmer et al, 1986). Another spectral area of considerable interest has been the region between the strong red light absorption by chlorophyll (~680 nm) and the highly reflective near infrared wavelengths (~780 nm). This wavelength region is often referred to as the "red edge." Gates et al. (1965) found that the red edge shifts to slightly longer wavelengths as leaf chlorophyll content increased. Horler et al. (1983) related spectral measurements in the red edge area to chlorophyll concentration in leaves of various species. Vegetation indices based on red and NIR reflectance have also been used to infer fertilizer application rates (e.g., Stone et al., 1997).

MATERIALS AND METHODS

A water by nitrogen experiment was conducted during the 1999 cotton season at the University of Arizona's Maricopa Agricultural Center located approximately 40 km south of Phoenix (33^o 04' 21" N; 111^o 58' 45" W) at an elevation of 360 m. This is an arid area, receiving only 185 mm of rainfall per year and average summer temperatures ranging from 25 to 42 ^oC. A Latin square experimental design was used to apply four treatments: 1) control (**WN**, optimal conditions); 2) low nitrogen (**Wn**, 50% optimal plant requirements); 3) low water (**wN**, decreased irrigation frequency, allowing the plants to become water stressed five times during the season); 4) low water and low nitrogen (**wn**). A summary of the irrigation and N applications for each treatment is given in Table 1. The high water treatments were typically irrigated at 3d intervals from June to August at levels determined by a combination of measured soil-water content and crop demand based on meteorological conditions from a near-by weather station. Water and N were applied using a linear move irrigation system adapted to allow control of irrigation quantities over individual plots. Note that on day of years (DOY) 214, 216 and 250, additional irrigations were applied to the low water plots to return these plots to similar soil water status as the high treatments. The goal of these treatments was to simulate stress levels that may be encountered in production agriculture, not to induce severe cumulative stress conditions over the course of the season.

The field size was 1 ha and was divided into 16 (4 treatments by 4 replicates) 22 x 22 m plots. An Upland cotton variety (*Gossypium hirsutum* L. cv Delta Pine 90b) was planted on 16 April (DOY 106) in east to west raised beds. The beds had a 1-m spacing and the plant population was 10 plants m^{-2} after stand establishment. The crop had reached maturity by mid-September; however, rain at

Table 1. Irrigation or rainfall depths, and nitrogen application rates during the 1999 cotton season.

Date	DOY	Water Treatment High (W)	Water Treatment Low (w)	N Treatment High (N)	N Treatment Low (n)
		---- mm ----		--- kg N ha^{-1} ---	
7-Apr (pre-plant)				34	34
16 Apr. to 7 Jul	106 to 189	475	475	142	59
12-Jul	193	29	-		
14 to 23-Jul.	196 to 204	75	75	46	19
27-Jul	208	28	-		
29-Jul	210	38	38		
2-Aug	214	-	28		
3-Aug	215	25	25		
4-Aug	216	9	39		
5 to 9-Aug	217 to 221	58	58		
11-Aug	223	43	-		
13-Aug	225	38	38		
16-Aug	228	28	-		
19 to 26 Aug	231 to 238	88	88		
31-Aug	242	28	-		
2-Sep	245	38	38		
7-Sep	250	-	29		
19 to 22 Sep	262 to 265	66	66		
	Season Totals:	**1066**	**998**	**222**	**112**

[†] DOY is day of year (1 to 365).

this time delayed defoliation until 15 October and final harvest occurred 12 November.

Soil moisture levels were monitored in every plot using a neutron probe at a minimum of weekly intervals (2 access tubes per plot) from planting through crop maturity. The plots were destructively sampled weekly to determine N status from petiole and leaf samples, leaf area index (LAI), and leaf, stem, and boll dry weights from DOY 160 to 243. Average canopy height and width measurements, and hand-held chlorophyll meter (SPAD) readings were also taken at the time samples were harvested. Canopy width was used to approximate the fraction of canopy cover.

The linear move irrigation system also served as a remote sensing platform (named Agricultural Irrigation Imaging System, AgIIS, i.e., "Ag Eyes"). AgIIS uses a single downward looking sensor package that measures a 1-m diameter area. As the sensor traveled along the length of the linear move, measurements were taken at 1-m intervals. A differentially corrected global positioning system receiver (GPS) was located at one end of the linear move and processing algorithms were developed that assigned a UTM coordinate to every sensor measurement. The linear was operated at a speed so that sensor measurements could be gathered at approximately 1-m intervals in the direction of travel. Thus, when the data was displayed spatially, the "pixel" resolution was 1x1-m. AgIIS data collection typically began at solar noon and the entire field was measured in approximately 2 h. The AgIIS sensor package was composed of four silicon detectors filtered to narrow wavelength intervals (~10 nm) in the red (670 nm), green (555 nm), red-edge (720 nm), and near infrared (NIR, 790 nm) portions of the spectrum, and an infrared thermometer. Images were obtained at a minimum of weekly intervals, with as many as three images per week during the period of rapid crop development. The reflective bands of AgIIS were calibrated to units of reflectance by taking the ratio of downward looking sensor mV readings to mV readings from an upward-looking sensor measuring the same spectral bands. The output of the upward looking sensor was found to be very temperature sensitive and a procedure to temperature correct the upward sensor has not been finalized at this time. The results presented are based on upward sensor readings calculated as a function of solar zenith angle at the time of the downward sensor reading. Therefore, the current calibration procedure will not account for changes in atmospheric transmittance or cloud cover.

An adaptation of the two-dimensional CWSI developed by Clarke (1997) was calculated on selected days when the low water treatments were in effect. The two-dimensional CWSI is illustrated in Fig. 1a. The method of Idso et al. (1981) was used to predict crop canopy temperature under well-watered and water-stressed, full cover conditions (points 1 and 2, respectively in Fig. 1a) as a linear function of vapor pressure deficit. Surface temperature measurements of a dry bare soil were used rather than predictive equations to determine point 4 on Fig. 1a. Fractional vegetative cover was estimated from the NDVI. The NDVI uses reflectance (_) of a near infrared band (790nm, 10nm bandwidth) and a red band (670nm, 10nm bandwidth):

$$\mathrm{NDVI} = \frac{\rho_{790\mathrm{nm}} - \rho_{670\mathrm{nm}}}{\rho_{790\mathrm{nm}} + \rho_{670\mathrm{nm}}}. \qquad (1)$$

The ratio of NIR to red reflectance (ratio vegetation index, RVI) was also computed from the 790 and 670 nm bands.

Based on the points labeled A, B, and C in Fig. 1a, the CWSI for a particular percent cover was calculated as

$$\mathrm{CWSI} = \frac{C - A}{B - A}. \qquad (2)$$

where points A and B represent the surface minus air temperature difference at a particular percent cover for a non-stressed and completely stressed crop, respectively, with a dry soil background. Points to the left of the line formed between points 1 and 4 represent a moist soil background and no water stress is assumed under these conditions. Point C was determined based on the measured NDVI and surface – air temperature difference. From Eq. [2], a CWSI of 0 corresponds to a well-watered crop with a dry soil background, while 1 represents a water-stressed crop.

The Canopy Chlorophyll Content Index (CCCI) was developed empirically for cotton using data this data set by Clarke et al. (2000). It is similar to the 2D-CWSI in that it uses the Normalized Difference Vegetation Index (NDVI) as an estimate of percent cover. Rather than using a temperature as a stress indicator as with the CWSI, the CCCI uses a normalized difference red edge index (NDRE):

$$\mathrm{NDRE} = \frac{\rho_{790\mathrm{nm}} - \rho_{720\mathrm{nm}}}{\rho_{790\mathrm{nm}} + \rho_{720\mathrm{nm}}}. \qquad (3)$$

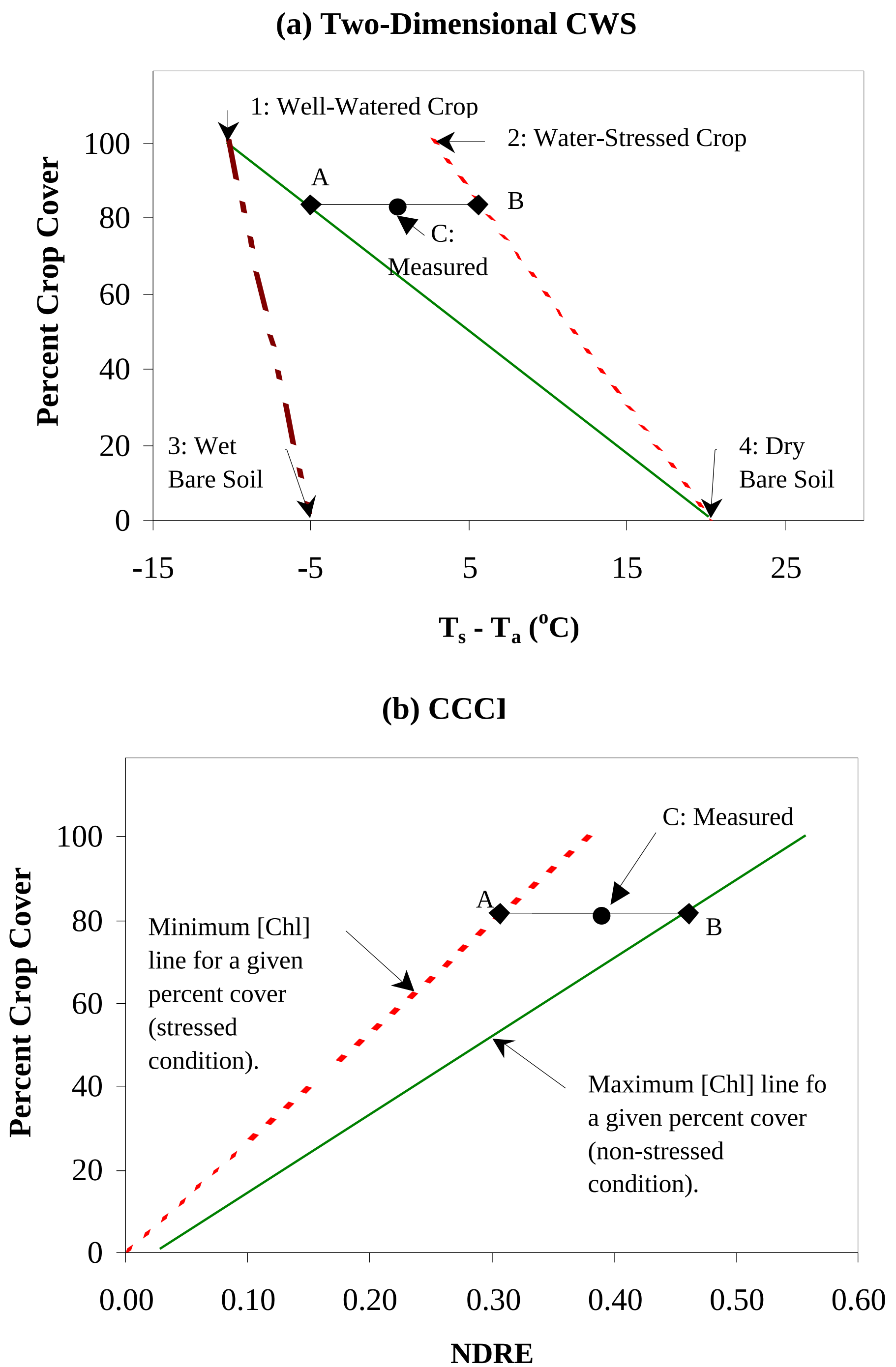


Fig 1. Illustration of (a) the two-dimensional CWSI and (b) the Canopy Chlorophyll Content Index (CCCI).

This approach requires upper and lower limits for NDRE to be determined as a function of NDVI as depicted in Fig. 1b. The high chlorophyll- and low chlorophyll-content limits of NDRE for various NDVIs were determined empirically by plotting NDRE vs. NDVI data from DOYs 176, 182, 185, 202 and 231. Lines representing the minimum and maximum chlorophyll content limits were drawn by eye along the edges of the space occupied by the NDRE values and then defined as linear functions of NDVI. The CCCI was then derived using the same form as the CWSI (Eq. 2). Note that unlike the CWSI, a CCCI of 0 will typically represent a condition of crop stress (low chlorophyll content) and 1 will correspond to high chlorophyll, low stress conditions. Thus, it is expected that the index will be positively correlated with chlorophyll content.

The analysis of the results in this paper is limited to trends in treatment or plot averages. Most of the data collected in the experiment was georeferenced, which will eventually allow a more precise comparison between the AgIIS data and measures of crop and soil condition.

RESULTS AND DISCUSSION

In this section, season trends in selected measured crop parameters and multispectral data are first examined. This is followed by an evaluation of qualitative relationships between the multispectral data and measures of crop condition.

Seasonal Trends

Fig. 2 shows the seasonal trends in leaf area index and petiole nitrate content based on the treatment averages. The difference in water treatments began on DOY 193, after which point there was a definite decrease in the LAI for the low water treatments (wN and wn). By DOY 236 there is little difference in the LAI between the Wn and wN treatments. There was not a clear response in LAI to the N treatments until DOY 215 at which point petiole analysis indicate a significant difference between high and low N treatments.

Fig. 3 shows the season trends in the stressed treatment averages (Wn, wN, and wn) relative to the control treatment (WN) for the RVI, surface temperature and CCCI. The relative differences in RVI follow similar trends as LAI with some exceptions (Fig. 3a). The sharp relative decrease in RVI on DOYs 194, 202 and 209 was due to a combination of a wet soil background in the high-water treatments (WN and Wn) and some leaf wilting in the low water treatments due to water stress. Note that from DOY 233 to 259 the RVI for the wN treatment becomes higher than the Wn. This illustrates the difficulty in interpreting the differences of simple vegetation indices as a measure of a single stress. As will be illustrated later, indices based on combinations of the NIR and red areas of the spectrum are strongly correlated with canopy density; therefore, any stress that alters canopy density will impact these indices.

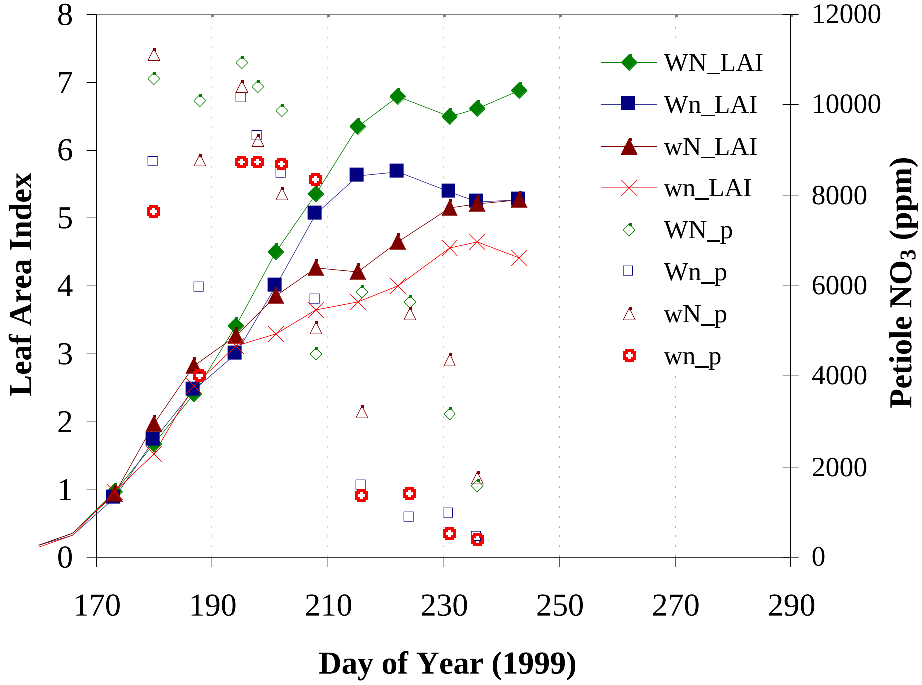


Fig. 2. Seasonal trends in treatment average leaf area index (LAI) and petiole NO_3-N concentration (p).

In Fig. 3b, the periods after which water was withheld (DOYs 194, 202, 209 and to a lesser extent 231 and 245) are identified by the relative increase in surface temperature in the low water (wN, wn) treatments. While some of these events also decreased the RVI in the low water plots with respect to the high, the RVI trends are not as related to water treatment levels as those in surface temperature later in the season, particularly on DOY 251, after the water treatments were purposely reversed (i.e., water was not applied to the WN and Wn treatments on DOY 250). Also note that on dates after all of the plots were irrigated (e.g., DOY 215), there was little difference in the surface temperature between water treatments, unlike the RVI.

The CCCI begins to show a clear distinction between the low N treatments (Wn, wn) after DOY 214 (Fig. 3c), about the same time the petiole data indicated a strong difference between the high and low N treatments (Fig. 2). Unlike the RVI, the CCCIs of the low N treatments are consistently less than the control from DOY 214 to 270. After DOY 270 the CCCI for the WN plot declined to low values (< 0.3), thus the ratio with the WN treatment becomes sensitive to small changes in the index. While this index does appear to minimize the impact of canopy density, it was sensitive to changes in the wetness of the soil surface background under partial canopy conditions as indicated by the increase in the index on DOYs 198 and 209. On both of these dates, the soil background in the low water treatments was dry, but wet in the high water plots. This resulted in a false indication that the chlorophyll content was higher in these treatments than the control.

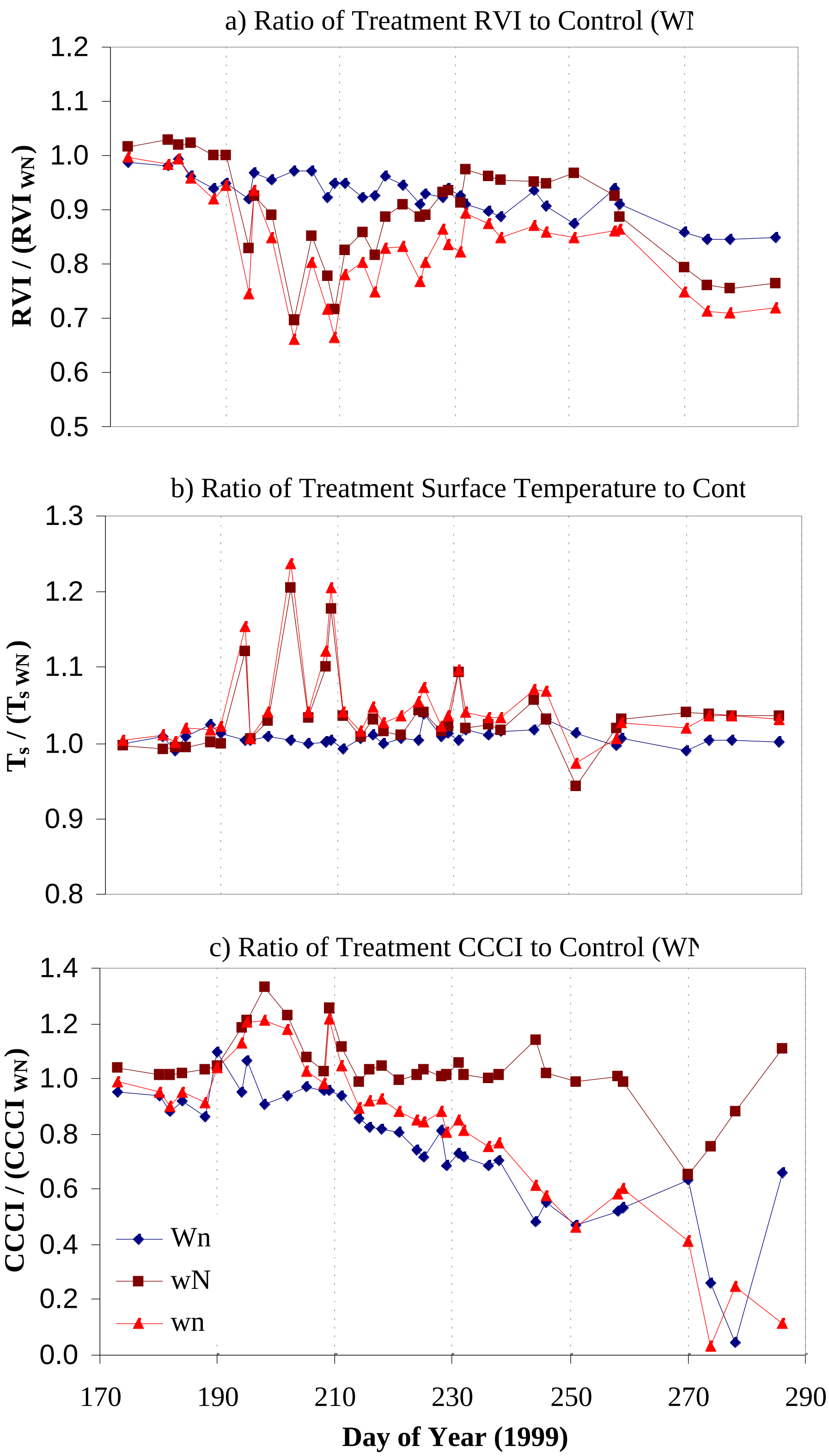


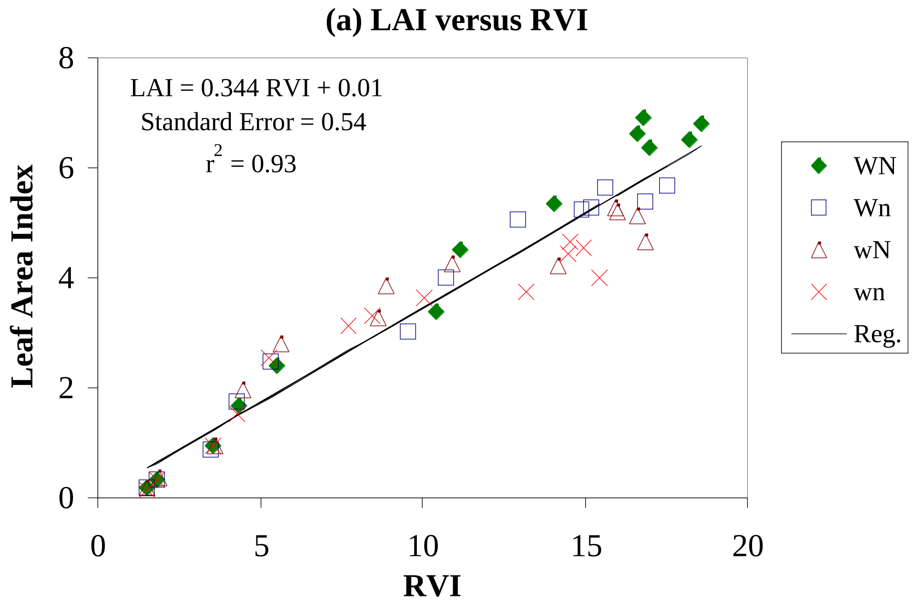
Fig. 3. Seasonal trends in the ratio of (a) ratio vegetation index (RVI), (b) surface temperature (T_s), and (c) canopy chlorophyll content index (CCCI) in the high water, low N (Wn), low water, high N (wN) and low water, low N (wn) treatments to the respective index in the control treatment (WN).

Quantitative Relationships

The ability to detect differences in canopy density in terms of LAI and percent crop cover is illustrated in Fig. 4. A fairly linear trend between LAI and RVI is evident. There is some evidence that a different relationship may be appropriate for LAI < 3.0 (about the time of full cover in this experiment), as the RVI seems to increase at a greater rate compared to its change after LAI > 3.0. The scatter can be attributed to several factors, including: LAI was determined based on three point samples within the plots and the multispectral data was based on data averaged across the entire plot, variations in the RVI due to changes in surface soil moisture under partial canopy conditions, and final calibration routines for the multispectral data have not been applied.

The NDVI demonstrates a very strong linear relationship with percent crop cover (Fig. 4b) up to percent covers of 90. After this point, the NDVI reaches a plateau as percent cover increase. This relationship is the basis for the two dimensional indices (CWSI and CCCI) used in this study. As with the RVI, the relationship between NDVI and percent cover must be reevaluated after the final calibration procedures have been executed. Note the fact that RVI shows a linear correlation with LAI and NDVI with percent cover does not imply that the two indices contain independent information as both are functions of the same reflectance data (NIR and red). The different relationships between these indices and LAI and percent cover are a mathematical artifact, as NDVI can be calculated from RVI (NDVI = [RVI-1]/(RVI+1]) and vice versa.

Fig. 5 illustrates the relationship between the CWSI calculated on three dates and the percent depletion of available soil moisture determined from the neutron readings. On the chart, a linear relationship is presented between percent depletion and the CWSI for CWSI > 0. The negative CWSI values indicated a wet soil background and the assumption was made that the crop did not experience stress under these conditions. This assumption may not be valid under all conditions, such as after a light rain. The relationship between positive CWSI and soil moisture was not particularly strong, with CWSI only explaining about 30% of the variation in soil water depletion in the root zone. A partial explanation for this lack of agreement is that the CWSI will only increase when the crop cannot keep up with evaporative demand. As long as there is sufficient soil moisture in the root zone to allow the crop to meet evaporative demand, the CWSI will be independent of soil moisture. The point at which the CWSI will begin to correlate with soil moisture will also depend on the distribution of soil moisture and the crop's root density with depth. In Fig. 5, it appears that the CWSI does not start to respond to changes in soil moisture until approximately 50% of the moisture has been depleted from the root zone. Other factors that may contribute to the lack of correlation are that estimates of soil moisture in the top 20 cm of the soil profile have not been incorporated into the estimates of available water (TDR data are being processed).



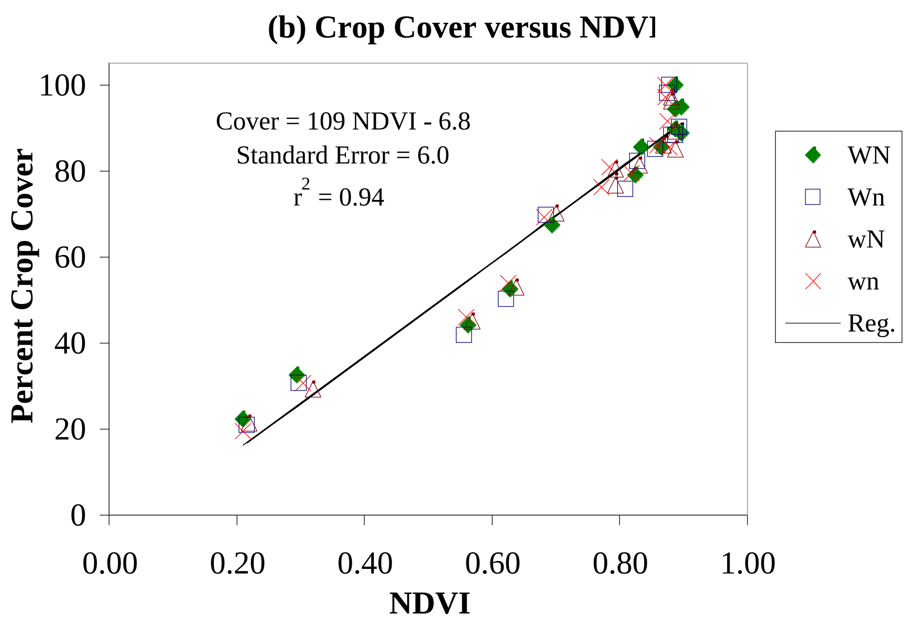


Fig. 4. Relationship between (a) leaf area index and the ratio vegetation index and (b) relationship between percent crop cover and NDVI.

Figure 6 shows the relationship between plot averaged values of the CCCI and total N on DOY 236. This date was selected, as the N treatments were established by this date, resulting in a range of crop nitrogen conditions. There was a strong linear relationship between the CCCI and total N on this date; however, the correlation with petiole nitrate levels was not as strong (Table 2). The CCCI had a stronger correlation with total N, petiole N and SPAD meter readings than did RVI, and the CCCI had a similar level of correlation with petiole nitrate as the SPAD readings on this date. Note that it is currently hypothesized the CCCI is sensitive to chlorophyll content. The correlation seen with plant N status is likely related to the fact that N was the only limiting nutrient in this study. Further data analysis is needed to determine how well the CCCI can predict N levels during the season.

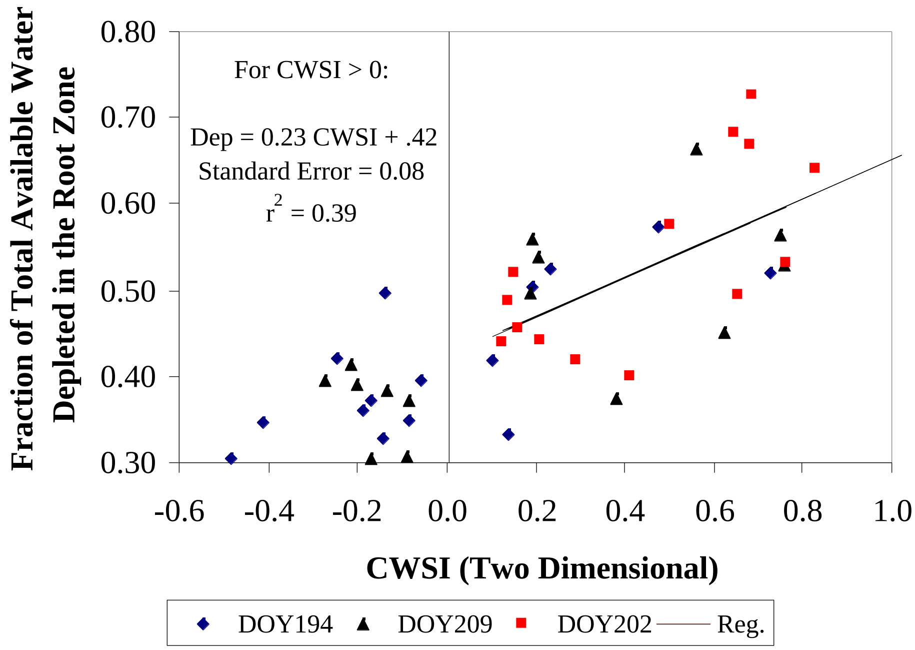


Fig. 5. Relationship between available water in the root zone and the two-dimensional crop water stress index (CWSI) based on plot averages on day of years (DOY) 194, 202 and 209.

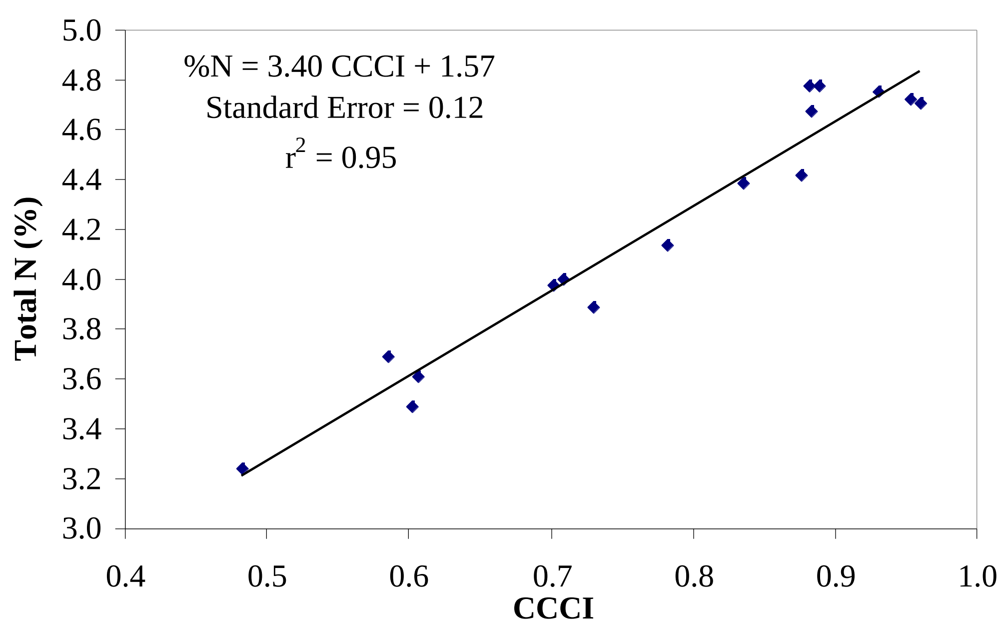


Fig. 6. Relationship between total N and the CCCI both determined from plot averages on DOY 236.

Table 2. Correlation matrix for plot averaged measurements on DOY 236.

	CCCI	RVI	Total N	Petiole NO_3	SPAD
CCCI	1				
RVI	0.803**	1			
Total N	0.975**	0.851**	1		
Petiole NO_3	0.713**	0.599*	0.805**	1	
SPAD	0.796**	0.549*	0.794**	0.687**	1

* significantly different than 0 (p = 0.05), ** p=0.01.

SUMMARY AND CONCLUSIONS

To summarize the relationships previously discussed, Fig. 7 provides two false color composite images from AgIIS on DOY 231 (19 August). This day was selected as the low N treatments were established and the high water plots were irrigated 3 d earlier, but the low water plots were not. In the standard color infrared image of Fig. 7a, most of the color patterns in the image were related to variations in canopy density (brighter red corresponds to a denser canopy) and there were no distinct signs of the experimental treatments. However, many of the color patterns in Fig. 7b can be related to the treatments. In this figure, 1-CCCI is displayed as red (higher values represent more N stress). The ratio vegetation index is displayed as green, and the crop water stress index displayed as the blue band. Therefore, the control plots (WN) appear green as 1-CCCI and CWSI are low under non-stressed conditions and RVI is higher for high canopy densities. A majority of the low N plots have an orange tint (higher 1-CCCI values), while the low water plots have a blue tint (higher CWSI values). Plot 13 (lower left corner, wn) has a strong pink tint, as this plot had a low canopy density.

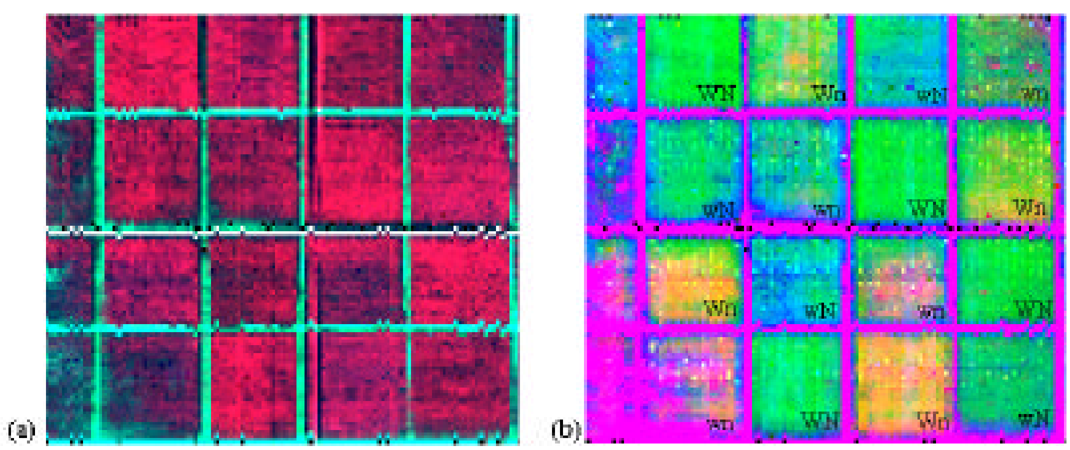


Fig 7. AgIIS images on 19 August displayed as false RGB color composites of (a) NIR displayed as red, red displayed as green, green displayed as red and (b) CCCI displayed as red, RVI displayed as green, and CWSI displayed as green.

The ability to distinguish between canopy density and two crop stresses demonstrates the progress being made in this study to extract more detailed information about crop status than was previously possible. However, the relationship between remotely sensed data and crop or soil conditions can be subject to interfering factors such as soil surface wetness. Work will continue to integrate the sensor information with simulation models (e.g., ENWATBAL of Lascano and VanBavel, 1987). The hope is that by integrating the data with models, further ambiguities can be removed from the interpretation of the remotely sensed data and improve the frequency at which crop conditions can be reported. Additionally, the remotely sensed data should make the simulation of conditions at a high spatial resolution more feasible than it has been in the past.

ACKNOWLEDGMENTS

The authors would like to thank: the Idaho National Environmental and Engineering Laboratory for funding of this project; Valmont Industries and CDS Ag Industries for donated equipment; Charlie Defer, Ed Eaton and others in the Biosystems and Agricultural Engineering Department at the University of Arizona for assembly of AgIIS; and Bill Luckett, Physical Science Technician at the US Water Conservation Lab, for image processing.

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