RELATIONSHIPS BETWEEN REMOTELY SENSED REFLECTANCE DATA, ACALA COTTON GROWTH, AND YIELD

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Abstract

The objective of this study was to determine whether measurements based on the NDVI could provide information useful for site-specific management of cotton. Aerial photographs were taken of replicated Acala cotton field experiments in California in which the treatment was water or nitrogen stress level. NDVI integrated over time showed a significant correlation with lint yield in those experiments in which there was a significant stress effect on yield. The spatiotemporal pattern of NDVI reflected stress factors and was approximately coincident with the onset of measurable water stress. NDVI tended to indicate the presence of nitrogen stress even in those cases where the stress did not result in a significant yield reduction. In a study of the correlation of NDVI with late season plant mapping indices NDVI was correlated with nodes above white flower and strongly correlated with nodes above cracked boll.

Introduction

Remotely sensed reflectance data, obtained either by satellite or aircraft, can provide at relatively low cost a set of detailed, spatially distributed data on plant growth and development. Crop canopy reflectance in the red and near infrared regions of the electromagnetic spectrum provides a means of estimating the vegetative status of the crop (Perry and Lautenschlager, 1984). Remotely sensed electromagnetic reflectance data are generally expressed in the form of vegetation indices, which are algebraic combinations of the measured canopy reflectances of different wavelength bands. Several such indices have been developed. One of the most commonly used vegetation indices is the normalized difference vegetation index, or NDVI (Tucker, 1979).

The objective of this research was to determine the relationship between crop reflectance properties and vegetative and reproductive status in California cotton. We analyzed chronological sequences of false color infrared aerial photographs of cotton fields. In order to achieve a controlled range of sources and levels of plant stress, we photographed fields containing ongoing, replicated experiments involving either nitrogen or water stress. This not only provided a precisely defined set of treatments that could be subjected to statistical analysis but also permitted precise recording of yields without a yield monitor. In this paper we report on the analysis of two years of aerial photography data collected from Acala cotton fields in the San Joaquin Valley, California. This study had three principal objectives: (1) determine whether water and nitrogen stress effects can be detected from NDVI data; (2) determine whether a relationship exists between lint yield and NDVI-based remote sensing data; and (3) determine whether NDVI data can be related to standard plant mapping indices.

With regard to the third objective, we focused our attention on late season plant mapping since this is the time when the crop canopy is most developed. Two of the most important late season management decisions in California cotton production are the timing of the final irrigation and the timing and amount of chemical defoliation (Kerby and Hake, 1996). The recommended management decision making process for each of these involves the use of plant mapping data (Hake et al., 1996). Determining the appropriate time of the final irrigation makes use of nodes above white flower (NAWF). The recommended means of determining the date of defoliant application uses nodes above cracked boll (NACB).

Materials and Methods

A sequence of false color infrared aerial photographs was taken of replicated field experiments on cotton conducted at four sites in 1997 and at five sites in 1998. One of the 1997 sites and two of the 1998 sites were located on approximately 85 m by 325 m plots at the University of California West Side Research and Extension Center (WSREC) near Five Points, CA (latitude 36.3°N, longitude 120.1°W). The soil at this location is relatively uniform and is classed as a Panoche clay loam. The other sites were located on commercial Acala cotton fields in the San Joaquin Valley, California. These fields were generally about 700 m by 700 m in size. The experimental trials generally extended over approximately 150 m in width and covered the entire length of the fields. The treatment in each experiment involved either nitrogen or

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 1:429-432 (2000)
National Cotton Council, Memphis TN

water stress. With the exception of the stress treatments, each field was maintained as stress free as possible using University of California management methods described in Hake et al. (1996). False color infrared aerial photographs were taken of the sites using Kodak 2443 film. Photographs were taken from an altitude sufficient to include the entire field in the image Photographs were taken at mid-day, and skies were generally cloud-free.

The nitrogen stress experiments were part of an ongoing fertilizer rate study. All of these experiments were identical in design. The variety was Acala Maxxa and the treatments were nitrogen rate. Total soil N level in the upper 0.6 m was measured just prior to fertilization and sufficient N fertilizer was applied to bring available soil N to the treatment levels, which were 55, 110, 165, and 220 kg ha^{-1}. Aerial photographs were taken of two experimental nitrogen sites in 1997 and three sites in 1998.

Two of the experiments in 1997 and one in 1998 involved water stress. The treatments in 1997 were the dates of the final irrigation. One experiment was conducted at the WSREC. This involved four final irrigation dates (June 18, July 21, August 8, and August 29) and four varieties (Acala Maxxa, Acala Phytogen 33, Acala GC-510, and Pima S-7). The experiment was laid out as a split plot with four replications in which final irrigation date was the main plot factor and variety was the subplot factor. There were 4 replications. Each plot consisted of 6 1.02-m rows. The second experiment was located in a commercial cotton field. The variety was Acala Maxxa. The experiment involved three final irrigation dates (August 11, August 25, and September 5). It was laid out as a randomized complete block with four blocks and four treatments per block (there were 2 September 5 treatments in each block). The field was maintained according to normal commercial production practices. The 1998 irrigation experiment was conducted at the WSREC. The treatments were the number of times the field was irrigated: either 0, 1, 2, or 3 times at evenly spaced intervals. The Acala portion of the experiment was laid out as randomized complete block in which number of irrigations was factor. There were three replications

Positive images were scanned at 600 dpi using an Agfa Argus II scanner, which separated the bands into TIFF image files. These files were imported into the Idrisi geographic information system (Clark University, Worcester, MA) and georegistered. Data were analyzed using Idrisi, Microsoft Excel (Microsoft Corp, Redmond, WA), and Minitab (Minitab, Inc., State College, PA). In analysis of plot data only the values from the middle rows of cells from each plot were used so that edge effects and mixed pixels could be avoided. Normalized difference vegetation index (NDVI) was computed on a cell-by-cell basis according to the formula:

$$NDVI = \frac{IR - R}{IR + R},$$

where *IR* is the infrared digital number value of the cell and *R* is the red digital number value. Accumulated NDVI according to the season was measured as NDVI-days, the integral of NDVI over time. This was estimated according to the trapezoidal rule:

$$NDVI - days = 0.5 \sum_{j=1}^{n-1} (NDVI_j + NDVI_{j+1})(D_{j+1} - D_j),$$

where $NDVI_j$ is the NDVI value on day j and D_j is the number of elapsed days on day j.

Results

Effect of Crop Stress on NDVI

Water Stress. Figure 1 shows a plot of mean NDVI vs. date for each of the four irrigation termination dates for Acala Maxxa cotton in the 1997 WSREC trial. Results were similar for the other varieties. Error bars indicate 95% confidence intervals. The treatment with the June 18 termination date shows a clear trend toward reduced NDVI by July 28, when the first aerial photo was taken. The mean NDVI in response to second earliest irrigation termination date is significantly reduced in the August 26 image. Plots receiving the August 8 termination treatment do not have a significantly different NDVI from those receiving the August 29 treatment, although the August 8 plots show a trend to lower NDVI in the September 15 image. Figure 2 shows a plot of absolute leaf water potential vs. time. Cotton plants are generally considered to be in a condition of water stress when the absolute leaf water potential exceeds approximately 1.8 to 2 MPa (Hake et al, 1996). The June 18 treatment reached 1.8 MPa on August 1 and 1.92 MPa on August 25. The July 21 treatment reached its maximum absolute leaf water potential,1.7 MPa, on August 25.

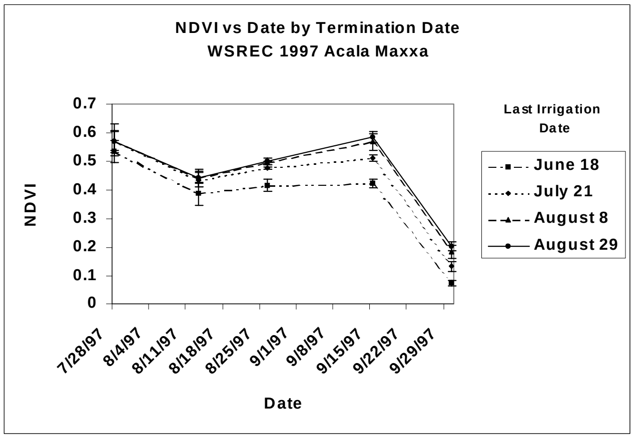

Figure 1. Mean NDVI vs. date for each of the four irrigation termination dates for Acala Maxxa cotton in the 1997 WSREC trial. Error bars represent 95% confidence intervals.

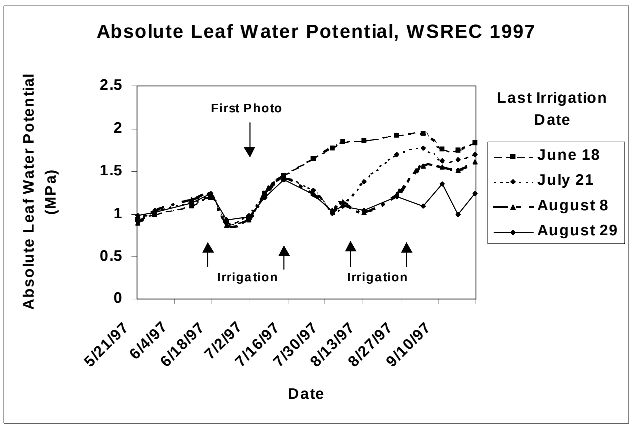

Figure 2. Plot of mean leaf water potential (MPa) vs. time for Acala Maxxa in the 1997 WSREC trial. Arrows indicate irrigation applications. Each application is the last one for one treatment.

The commercial site used in the 1997 irrigation experiment, which was located in Fresno County, had very heterogeneous soil properties. The field soil type was predominantly Traver sandy loam with two large sandy streaks. The sandy soils are classed as Hesperia sandy loam. A portion of each experimental plot was located in a sandy streak on the east side of the plots. Fig 3 shows plots of mean NDVI vs. date for the loamy and sandy areas of the experiment. Two properties are evident from a comparison of NDVI values from the two soil textures on the same dates. The first and most obvious is that the NDVI in the sandier area was considerably less than that in the loamy area. The second is that the end-of-season decline in NDVI occurred earlier in the sandy area than it did in the loamy area. Both of these phenomena may be attributed to the reduced water holding capacity of the sandy soil on the east side of the plots, although other differences in soil properties may play a role as well. The cotton plants on the sandy soil were visually observed to be stunted in growth throughout the season. There was no significant yield response to irrigation termination date ($p > 0.1$) among the three treatments. There was also no significant NDVI response to irrigation treatment in either soil texture ($p > 0.1$). Leaf water potential measurements indicated that no treatment reached a stress condition during the growing season. Table 1 shows a summary of ANOVA results for the variety Acala Maxxa for all the irrigation treatments. The table gives treatment means and significance groupings for yield and NDVI-days for each of the three irrigation experiments.

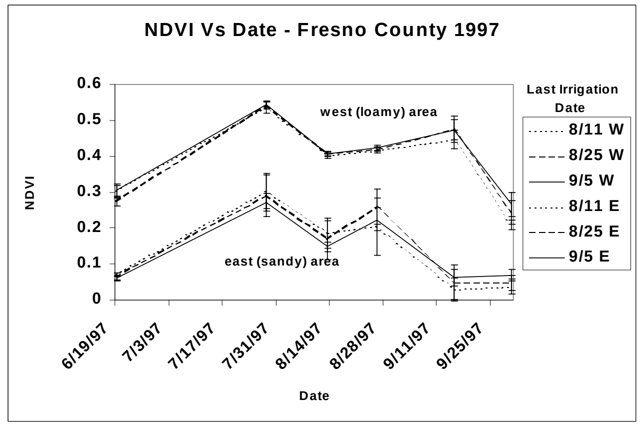

Figure 3. NDVI vs. date for the 1997 Fresno County irrigation experiment. West side and east side of the field are shown separately. Legend indicates date of last irrigation. The west side of the field (indicated by the W) is loamy soil, and the east side (indicated by E) is sandy soil.

Nitrogen Stress. ANOVA was carried out on each of the yield and NDVI responses in all five nitrogen rate experiments. Tukey's test was used to isolate differing responses in cases where a significant treatment effect was observed. Table 2 shows the mean yields and NDVI-days and the significance groups for each of the experimental sites. In both of the 1997 trials the NDVI groups matched those of yield. In 1998 the Kings County site had an unexpectedly low mean yield response to the 110 kg ha^{-1} treatment that was not matched by the NDVI-days. At the other two sites, however, the NDVI-days had a low response to the 55 kg ha^{-1} treatment that was not matched by yield. Plants in the 55 kg ha^{-1} plots were visually observed to be stunted. Fig. 3 Shows NDVI vs. date for the 1998 WSREC experimental site, which is typical of those in which a significant difference in NDVI-days exists. Mean NDVI in response to the lower treatment level is reduced during all of the growing season except at the end of the season. Table 2 indicates that only the 1997 Fresno County site had a significant yield difference attributable to nitrogen level. This site also had a significant correlation between yield and NDVI-days.

Relationship between NDVI and Plant Map Indices

Nodes Above White Flower. In three of the fields studied there were sufficient NAWF data to determine whether a relationship existed between NDVI and NAWF. In each of these the results were the same: a relatively weak positive correlation in which the variability is sufficiently great that the relationship is not statistically significant. In order to pool the data across sites we normalized both NDVI and NAWF data. The NDVI data were normalized so that for any given site the minimum NDVI was 0 and the maximum was 1. The values of NAWF were scaled in the same way. One NAWF value appeared to be an outlier and was removed. The regression equation for the pooled data is:

$$NAWF = -0.06 + 0.93\ NDVI \quad (r^2 = 0.65,\ p < 0.01).$$

Nodes Above Cracked Boll. Nodes above cracked boll data were recorded in five of the fields, one in 1997 and four in 1998. Table 3 shows a summary of the results of these regression analyses. In every case but one there was a strong correlation, as measured by the coefficient of determination, between NACB and NDVI. In one of the cases the small sample size ($n = 4$) prevented the relationship from being statistically significant, but in all of the others the relation was significant.

Discussion

Yield had a significant, consistent relation with NDVI-days in each of the experiments in which there were significant variations in yield that were consistent with the order of both the irrigation and nitrogen treatment levels. Thus, to the extent that crop yield is consistent with vegetative biomass (i.e., that harvest index is constant) the relation between yield and NDVI-days is consistent with expectation. Factors such as pest consumption that reduce reproductive growth but not vegetative growth would reduce the harvest index and therefore distort the yield - NDVI-days relationship. Therefore, NDVI-days may be better considered as a measure of spatial variability in yield potential, that is, of the yield capable of being produced by the vegetative canopy.

In the 1997 WSREC irrigation experiment, the absolute leaf water potential of the June 18 termination date treatment reached 1.85 MPa on August 8, and the absolute leaf water potential of the July 21 termination date treatment reached 1.70 MPa on August 25. As indicated in Fig. 1, the NDVI for the June 18 termination date treatment differed significantly from the other treatments by August 11, and the NDVI for the July 21 treatment differed significantly from the others some time shortly after August 25. Based on these results it appears that in the case of water stress significant NDVI effects appear approximately coincidentally with the stress effects themselves.

There are several reasons why NDVI might be dependent on water stress. These include effects on leaf optical properties, canopy structure (e.g. due to wilting), reduction in LAI, and so forth. It is also possible that the wetness of the soil has an influence, although the impact of soil reflectance is reduced by the closed canopy in most of these trials. It must also be emphasized that the effect of water stress on NDVI may be primarily an effect of cumulative water stress rather than instantaneous stress. Thus, remotely sensed reflectance data may be of more use in strategic design of irrigation systems to achieve uniform crop moisture level than in day-to-day irrigation scheduling.

In the nitrogen field experiments lint yield correlated with NDVI only in those cases in which a significant nitrogen effect was present. Indeed, two of the fields in 1998 showed significant NDVI effects in response to the lowest treatment level, but yield did not show a corresponding difference. Visual inspection of the fields indicated that the 55 kg ha^{-1} treatments were often stunted in appearance but that yield did not differ significantly in many of these sites. It appears that at least in the case of nitrogen deficiency NDVI may be prone to give false positive indications of potential yield loss. It should also be noted that the 1998 growing season was very short, which may have contributed to a reduced N response. In this sense the information may be regarded as a conservative early-warning indicator of potential problems. The timing of nitrogen stress is more difficult to measure than water stress. In those cases in which a significant NDVI difference was observed, this difference was present throughout the season except at the very end.

Of the two late season plant mapping indices tested, NDVI was correlated but not strongly so with nodes above white flower (NAWF) and it was highly correlated in most cases with nodes above cracked boll (NACB). In all tests but one the coefficient of determination was at least 0.65. The NDVI values used in this test are the plot mean values, and therefore the correlation with plant mapping indices may be even greater on a location by location basis. The positive correlation indicates that the spatial distribution of late-season NDVI may be used to determine a directed sampling scheme for plant mapping indices, which may then be used to develop a spatial map of crop maturity. This can be used to more precisely schedule late season irrigation and defoliation.

Acknowledgement

This research was supported by Cotton Incorporated and the California State Support Program. We are grateful to Jonathan Wroble, Tomé Martin-Duval, and Joe Padilla for technical assistance. We are also grateful to William Wildman, Wildman Aerial Photography, for taking the aerial photographs used in this study. Finally, we would like to express our thanks to an anonymous referee whose comments greatly improved the paper.

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Table 1. Treatment means and significance groups based analysis of variance for the three irrigation experiments. Letters next to mean values indicate significance groupings based on Tukey's test at the significance level of the difference in treatment means. Significance level of the test is shown in the last row.

	WSREC 1997		Fresno 1997		WSREC 1998	
Treatment	Yield	NDVI-days	Yield	NDVI-days	Yield	NDVI-days
1	1759 a	24.7 a	1097	42.8	835 a	34.4 a
2	2212 b	28.7 b	1145	43.2	1403 ab	64.3 b
3	2261 b	30.5 b	1210	44.2	1606 b	68.5 b
4	2236 b	31.0 b	1129	44.2	1368 ab	67.7 b
Sig. level	0.01	0.01	ns	ns	0.05	0.01

Table 2. Treatment means and analysis of variance results for the five nitrogen rate experiments for yield and NDVI-days. Letters next to mean values indicate significance groupings based on Tukey's test at the significance level of the difference in treatment means.

	Madera 1997		Fresno 1997		Kings 1998		WSREC 1998		Fresno 1998	
Treatment	Yield	NDVI-days	Yield	NDVI-days	Yield	NDVI-days	Yield	NDVI-days	Yield	NDVI-days
1	1951	29.6	1376 a	20.0 a	1303 ab	47.8 a	1333	53.4 a	1382	47.1 a
2	2002	29.3	1560 b	22.5 b	1224 a	48.8 ab	1445	68.1 b	1481	50.1 b
3	2006	29.8	1613 b	23.2 b	1420 b	55.1 b	1429	66.8 b	1496	51.4 b
4	1963	29.5	1627 b	23.4 b	1384 ab	52.0 ab	1434	69.1 b	1415	51.5 b
Sig.	ns	ns	0.001	0.001	0.001	0.01	ns	0.001	ns	0.001

Table 3. Coefficients of simple linear regression, coefficient of simple determination, and p value for nodes above cracked boll regressed against NDVI for each of the experimental sites for which data is available.

Experimental Site	n	b_0	b_1	r^2	p
WSREC Irrigation 1997	12	-6.69	24.8	0.91	<0.01
Kings County Nitrogen 1998	8	-12.3	43.7	0.89	<0.01
WSREC Nitrogen 1998	8	1.12	11.1	0.66	0.01
WSREC Irrigation 1998	4	-5.53	21	0.75	0.13
Fresno County Nitrogen 1998	14	-19.6	63.3	0.22	0.09