RESEARCH, REVIEWS, PRACTICES, POLICY AND TECHNOLOGY

Relationship Between Hyperspectral Reflectance, Soil Nitrate-Nitrogen, Cotton Leaf Chlorophyll, and Cotton Yield: A Step Toward Precision Agriculture

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The authors wish to acknowledge Dr. Allan Zipf and Ms. Karnita Golson of the Department of Plant and Soil Science, Alabama A&M University, Normal, AL for their assistance in editing the manuscript.

The authors gratefully acknowledge the support from National Aeronautics and Space Administration (NASA), Washington, DC (Grant No. NCC*-140) in the research reported herein.

Contributed by the Agricultural Experiment Station, Alabama A&M University, Journal No. 496.

Mention of a trade name does not imply endorsement by the authors or Alabama A&M University.

Journal of Sustainable Agriculture, Vol. 22(3) 2003
http://www.haworthpress.com/store/product.asp?sku=J064

10.1300/J064v22n03_03

ABSTRACT. Modern agriculture uses large amounts of organic and inorganic nutrients to optimize productivity. Excessive nutrient applications sometime lead to adverse effects on the environment and human health. Precision agriculture is evolving with the objectives of minimizing these adverse effects by enabling farmers to manage nutrient applications more efficiently while sustaining precious environmental resources. To develop a method that uses nutrients more efficiently on cotton, a field experiment involving three sources and three rates of nitrogen with and without nitrification inhibitor was carried out in four replications at Belle Mina, AL during the 1994-97 crop seasons. In 1997, these plots were used to determine if there was a relationship between remotely sensed hyperspectral reflectance data and three field measurements that included cotton leaf chlorophyll (defined as measurements of five leaves using a Minolta Chlorophyll SPAD Meter to represent cotton canopy), soil nitrate-nitrogen, and cotton yield. Our results showed that hyperspectral reflectance in the 807.6 nm region had the highest significant correlation with cotton leaf chlorophyll. Cotton leaf chlorophyll correlated significantly with soil nitrate-nitrogen and cotton yield. Because leaf chlorophyll is an indicator of nitrogen deficiency, our results suggest that hyperspectral reflectance may be used as a tool to help farmers determine nitrogen deficiency, which may subsequently lead to increased crop productivity and reduced environmental pollution.

KEYWORDS. Remote sensing, hyperspectral data, GIS, poultry litter, precision agriculture

INTRODUCTION

High nitrogen inputs are commonly used in modern crop production. This has translated into high levels of productivity that would have seemed improbable a few decades ago (van Es et al., 1991). In the past thirty years, for example, the average annual yields of cotton in the United States have doubled. This increase in yield is primarily due to the use of fertilizers, irrigation, pesticides, and herbicides. Unfortunately, these technological advances, if not carefully managed can, and in some cases have, incurred environmental costs. For example, fertilizers applied to improve crop production have been found in surface and/or groundwater, with possibly damaging consequences. Nitrate-nitrogen from fertilizers is a widespread contaminant of ground and surface waters worldwide (Keeney, 1986). Furthermore, nitrate-nitrogen leaching from different point and non-point sources has been found to exceed the US drinking water standard of 10 ppm nitrate-nitrogen per liter of water (U.S. EPA, 1970; Keeney, 1986; Gold et al., 1990).

However, precision agriculture, site-specific application of inputs tailored to the needs of the crop, is one of the new ways that modern agriculture could potentially maintain or enhance crop yields and minimize environmental pollution. One method of precision agriculture is to use multispectral and hyperspectral remote sensing. Multispectral and hyperspectral remote sensing can be used to program variable-rate technology equipment in applying production inputs such as water, pesticides, and fertilizers (Wallace, 1994). Multispectral and hyperspectral remote sensing assess crop conditions by their spectral signature, a measure of electromagnetic energy reflected from the crop. Leaf chlorophyll content is a major factor that dictates the amount of energy reflected and can be good indicator of crop health; a stressed leaf would have low chlorophyll content. The disadvantage of most multispectral sensors is that they take one measurement over a wide portion of each major wavelength band, such as visible blue, near infrared, etc., whereas hyperspectral remote sensing measures energy in numerous narrow units of each band, which allows for detection of small changes in crop chemical and physical characteristics. More importantly, hyperspectral remote sensing is less researched than multispectral remote sensing technology. Therefore, the objectives of this research project were: (1) to determine the relationships between hyperspectral reflectance data, cotton leaf chlorophyll, soil nitrate-nitrogen, and cotton yield, (2) to evaluate if the spatial relationship of one field measurement can be used to determine the other, and (3) to determine the optimum fertilizer rate to achieve optimum cotton yield.

MATERIALS AND METHODS

Experimental Design and Soil Data Collection

A cotton field experiment was conducted at the Alabama Agricultural Experiment Station, Belle Mina, AL, situated at 34° 41′ latitude and 86° 52′ 30″ longitude on a Decatur silt loam (Ultisol) during the 1994-1997 crop seasons. The experiment was laid out in a randomized complete block design (RCBD) with 20 treatments and four replications. The treatments included three sources of nitrogen [urea, fresh poultry litter (FPL), and composted poultry litter (CPL)], and three nitrogen rates (40, 80, and 120 kg N ha^{-1}), with and without a nitrification inhibitor, carboxymethyl pyrazole (CMP) application. In addition to this ($3 \times 3 \times 2$ treatments), two control plots, (i) no nitrogen and no CMP and (ii) no nitrogen and CMP treatment, were included, thus forming a total of 20 treatments. This variation in nitrogen addition creates various health conditions for cotton, ranging from stressed to over fertilization. These treatments were initiated in 1994. Based on initial soil chemical analysis in 1994, a blanket application of 336 kg ha^{-1} of 0-20-20 NPK fertilizer was applied as a basal dose to all plots (resulting in 67.2 kg ha^{-1} of P_2O_5 and K_2O). It was applied to minimize the effects of P and K additions through poultry litter application. Also, to correct Ca and Mg deficiencies, 3359 kg ha^{-1} of dolomite limestone was applied in 1994.

All treatments were applied on the same plots each year. Fertilizer and poultry litter were hand-broadcast and mixed into the soil by a cultivator at about 5-10 cm depth. After cotton was harvested, plants were chopped and disked back into the soil.

Each year, fresh poultry litter was collected from nearby poultry farms and CPL was prepared at the Tennessee Valley Authority (TVA) facilities at Muscle Shoals, Alabama. The poultry litter was composted for a total of 9 months. Availability of nitrogen from both CPL and FPL during the first year was estimated at 60% (Keeling et al., 1995). The nitrogen content in FPL was 2.8%, 2.6%, 2.4%, and 2.2%, respectively, in 1994, 1995, 1996, and 1997. Similar results in CPL were 1.8%, 2.3%, 1.9%, and 2.1%. The nitrification inhibitor, CMP, was applied at 0.56 kg ha^{-1} a.i. in a 50/50 solution of ethanol and acetone resulting in a total of 116 mL solution per plot. Urea, FPL or CPL were mixed thoroughly with CMP before application.

Cotton cultivar DPL-33B was planted on May 8, 1997. Cotton lint yield was estimated from the two central rows of each plot.

In 1997, four sampling points were established per plot. Hyperspectral reflectance data, cotton leaf chlorophyll content, and soil samples were taken at two of the four sampling points.

Soil cores were collected at the second growth stage of cotton (15 weeks after planting) using a two-inch diameter Giddings probe at 0-15 cm. These samples were sealed in plastic bags, returned to the laboratory, and placed in the refrigerator before performing nitrate analyses. Nitrate analyses were measured using the procedure developed by Dick and Tabatabai (1979).

Cotton Leaf Chlorophyll Data Collection

Using the Minolta Chlorophyll SPAD Meter (Chapman and Barreto, 1997), cotton leaf chlorophyll content was measured on five randomly selected leaves (which represented the canopy). An average of the five readings from the SPAD meter was taken to evaluate the relationship between hyperspectral reflectance data, soil nitrate-nitrogen, and cotton yield. Cotton leaf chlorophyll measurements were taken during the second stage of cotton growth.

A nitrogen sufficiency index was performed from each treatment. The 120 kg N ha^{-1} treatment was used as the reference treatment. The equation is as follows:

$$\text{N sufficiency index} = \text{average bulk reading/average reference reading} \times 100.$$

Hyperspectral Data Collection and Analyses

A 252-band portable radiometer (SE 590) was used to collect the hyperspectral reflectance data approximately 1 ½ meter above the cotton canopy. The specific parameters of the SE-590 portable field spectroradiometer are as follows: wavelength −400 to 1100 nm, spectral resolution −4.0 nm, and field of view 15°.

Two readings were taken in each plot simultaneously with the leaf chlorophyll data collection. Calibration data was collected using a reflectance panel after every forty readings. The hyperspectral data was stored in a data logger and taken back to the remote sensing laboratory at Alabama A&M University for analyses. These analyses included correcting the hyperspectral reflectance data by referencing it to the calibrated data and performing statistical analyses, i.e., correlations (Pearson) between hyperspectral reflectance data and cotton leaf chlorophyll from each plot using SAS (SAS Inst., 1987), and spatial distribution hyperspectral reflectance data and the three field measurements using Geographical Information Systems (GIS) software.

RESULTS AND DISCUSSION

The SPAD meter uses light at two different wavelengths to determine leaf chlorophyll content. One is in the near infrared at 920 nm, which determines how much light goes through the leaf. The other is red at 650 nm, which will be impeded by chlorophyll. The ratio of the light transmittance at these two wavelengths is compared to the ratio determined with no sample. This information is then used to produce relative chlorophyll content in the leaf. When the leaf chlorophyll content data from the SPAD meter were compared to hyperspectral reflectance data, the spectral region that best indicated small changes in the amount of leaf chlorophyll was found between 776 and 817 nm. The highest correlation was observed for the spectral band of 807.6 nm. Gates et al. (1965) and Sinclair et al. (1971) have reported that internal leaf structure is the dominating factor that controls spectral responses of vegetation in the near infrared. However, there is a link between leaf chlorophyll and structure. If a leaf chlorophyll molecule is altered because of nitrogen deficiency, this changes leaf chemistry (e.g., color) and can subsequently change leaf structure (i.e., leaf moisture and air spaces).

This relationship between hyperspectral reflectance and leaf chlorophyll was significant at the 99% confidence level (Table 1). Leaf chlorophyll and soil nitrate-nitrogen correlated significantly to each other and to cotton yield. The most significant correlation was found between soil nitrate-nitrogen and cotton yield. Although the images in Figure 1 do not match exactly, some general interpretations can be made from the spatial images. The interpolation of all images was done by using the nearest neighbor method, which assigns values to each cell in the spatial output by weighting the value of each point by the distance that point is from the cell being analyzed and then taking the average of the values. Furthermore, Figure 1 indicates that there is not a visible relationship between hyperspectral reflectance data and leaf chlorophyll. However, hyperspectral reflectance does correlate significantly (0.26, $p < 0.01$) with leaf chlorophyll (Table 2). The best-fit regression model for hyperspectral reflectance (band 807.6) and leaf chlorophyll is $y = 0.11x + 0.333$, $r^2 = 0.06$. Although the r^2 value in very small, there is a significant relationship between the two variables, thus implying that hyperspectral reflectance may be used to predict leaf chlorophyll. Leaf chlorophyll can be used to predict soil nitrate-nitrogen and cotton yield, with a best-fit regression model of $y = 0.8118x - 0.32$, $r^2 = 0.33$ and $y = 0.0469x + 33.81$, $r^2 = 0.42$, respectively.

Low correlation values can be attributed to the common errors in recording hyperspectral reflectance data using the SE-590 and leaf chlorophyll content. For example, measured leaf chlorophyll was collected from the outer portion of five leaves while the hyperspectral data is collected from a number of leaves and their surroundings, which might include bare soil. This usually results in a decrease in the accuracy of

TABLE 1. Correlation between hyperspectral reflectance (wavelength) and cotton leaf chlorophyll at 15 weeks after planting, Belle Mina, AL, 1997.

Wavelength (nm)	Correlation (%)
807.6	0.27*
804.5	0.26*
792.0	0.26*
813.8	0.26*
779.5	0.26*
817.0	0.26*
785.8	0.26*
801.3	0.26*
782.6	0.26*
776.4	0.26*

*Significant at $p < 0.01$

TABLE 2. Pearson correlation coefficients between hyperspectral reflectance data, leaf chlorophyll, soil nitrate-nitrogen and cotton yield, Belle Mina, AL, 1997.

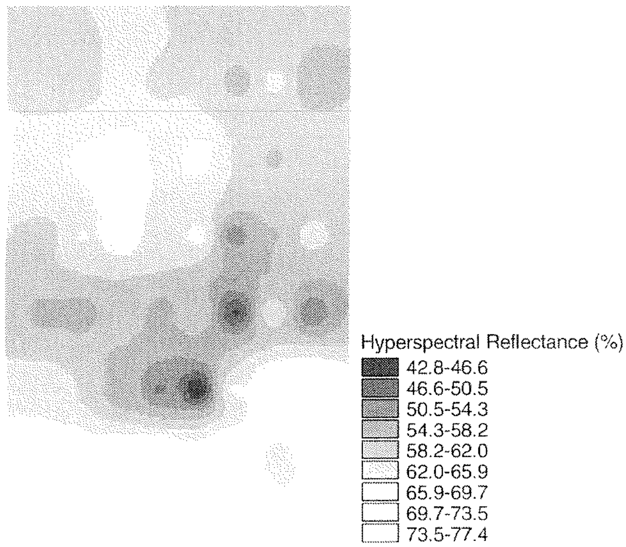
	Hyperspectral data	Leaf chlorophyll content	Nitrate-Nitrogen	Yield
Hyperspectral data		0.26*	0.09	0.25
Leaf chlorophyll			0.57*	0.44*
Nitrate-Nitrogen				0.65*

*Significant at $p < 0.01$

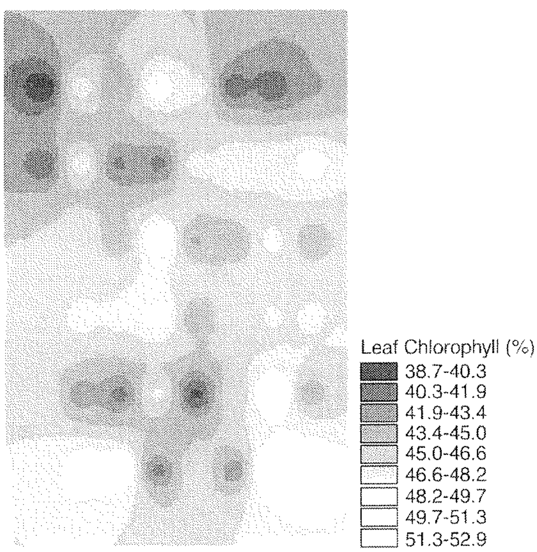
hyperspectral reflectance data and low correlation between these data and leaf chlorophyll content (Campbell, 1996). Another factor that contributes to the low accuracy of hyperspectral reflectance data and low correlation among the two parameters mentioned above is that vegetation canopies are composed of many layers with leaves that vary in size, shape, orientation to the sensor, and vigor. In addition, the upper leaves create shadows that mask the lower leaves, decreasing their reflectance characteristics. The overall spectral reflectance recorded by the hyperspectral instrument is ultimately a combination of these factors, which may result in an average reflectance value that may not be representative of any individual leaf of a single plant. To minimize the effect of these factors, a large number of leaves from different layers of the plant should be sampled for determining leaf chlorophyll.

FIGURE 1. Spatial distribution (images are 100 × 150 m) of (a) hyperspectral reflectance data (band 807.6 nm), (b) cotton leaf chlorophyll content, (c) soil nitrate-nitrogen concentrations, and (d) cotton yield.

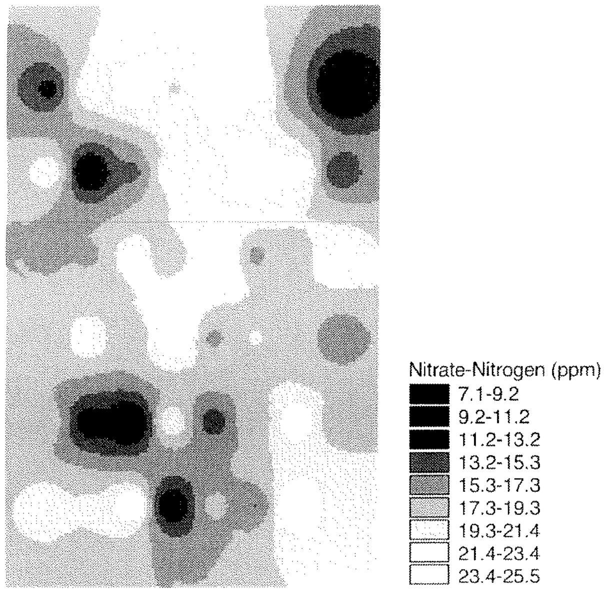
a.



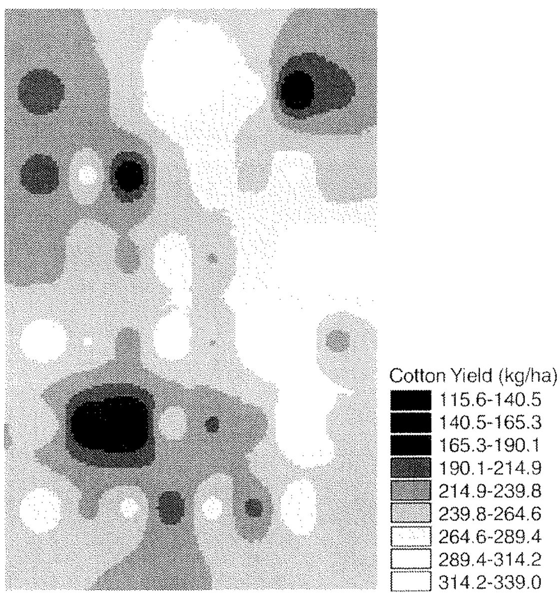
b.



c.


Nitrate-Nitrogen (ppm)
7.1-9.2
9.2-11.2
11.2-13.2
13.2-15.3
15.3-17.3
17.3-19.3
19.3-21.4
21.4-23.4
23.4-25.5

d.


Cotton Yield (kg/ha)
115.6-140.5
140.5-165.3
165.3-190.1
190.1-214.9
214.9-239.8
239.8-264.6
264.6-289.4
289.4-314.2
314.2-339.0

The treatment design of this experiment was done to create variability that is seen in arable fields. However, after 40 kg of nitrogen addition, there was little variability in the mean values of soil nitrate-nitrogen, leaf chlorophyll, and cotton yield (Table 3). This could be due in part to excess nitrogen accumulation over time in the treated plots. Accordingly, the nitrogen inhibitor did not cause significant reductions in soil nitrate-nitrogen, leaf chlorophyll content, and cotton yield. Furthermore, the control plots were the only plots with a nitrogen sufficiency index of < 90%. Peterson et al. (1993) suggest that in corn a nitrogen sufficiency index of less than 95% indicates nitrogen deficiency. No data was available for cotton. However, these results suggest that the optimum amount of nitrogen needed in this experiment to maximize cotton yield and reduce the potential of nitrate leaching is 40 kg N ha^{-1} using any of the three forms.

TABLE 3. Soil nitrate-nitrogen, cotton leaf chlorophyll, and cotton yield as influenced by source and rate of nitrogen applied, Belle Mina, AL, 1997.

Treatments	Soil nitrate-nitrogen (ppm)	Leaf chlorophyll content (%)	Cotton yield (kg ha^{-1})
Control	8.6^{f}	0.43^{cd}	760^{d}
Control + CMP	8.8^{f}	0.42^{d}	870^{cd}
40 kg N ha^{-1} Urea	16.5^{e}	0.46^{abcd}	1210^{abc}
40 kg N ha^{-1} Urea +CMP	15.8^{e}	0.45^{abcd}	1210^{abc}
40 kg N ha^{-1} FPL	19.3^{abcde}	0.45^{abcd}	1250^{ab}
40 kg N ha^{-1} FPL + CMP	18.3^{cde}	0.45^{abcd}	1255^{ab}
40 kg N ha^{-1} CPL	16.3^{e}	0.44^{bcd}	1110^{bcd}
40 kg N ha^{-1} CPL + CMP	16.3^{e}	0.45^{abcd}	1215^{abc}
80 kg N ha^{-1} Urea	22.8^{ab}	0.48^{ab}	1340^{ab}
80 kg N ha^{-1} Urea + CMP	21.5^{abcd}	0.47^{abcd}	1435^{ab}
80 kg N ha^{-1} FPL	23.4^{a}	0.49^{a}	1525^{a}
80 kg N ha^{-1} FPL + CMP	19.8^{abcde}	0.46^{abcd}	1525^{a}
80 kg N ha^{-1} CPL	19.1^{de}	0.46^{abcd}	1335^{ab}
80 kg N ha^{-1} CPL + CMP	17.1^{e}	0.44^{abcd}	1265^{ab}
120 kg N ha^{-1} Urea	23.0^{ab}	0.47^{abcd}	1485^{a}
120 kg N ha^{-1} Urea + CMP	21.8^{abc}	0.46^{abcd}	1495^{a}
120 kg N ha^{-1} FPL	22.4^{abc}	0.48^{abc}	1550^{a}
120 kg N ha^{-1} FPL + CMP	21.4^{abcd}	0.47^{abcd}	1560^{a}
120 kg N ha^{-1} CPL	17.6^{de}	0.44^{abcd}	1335^{ab}
120 kg N ha^{-1} CPL + CMP	16.3^{e}	0.43^{cd}	1490^{a}

*Means with the same letter are not significantly different at $p < 0.05$.

CONCLUSION

The use of the relationship (i.e., best fit model) between hyperspectral reflectance data and leaf chlorophyll may allow farmers to assess crop leaf chlorophyll, an indicator of nitrogen deficiency. Additionally, GIS can be used to spatial display data collected from fields, thus allowing for some general visual interpretation of data. Overall, our results suggest that hyperspectral remote sensing technology has the potential to contribute toward improving the efficiency of applying nutrients to agricultural fields and consequently reducing environmental pollution.

Using hyperspectral remote sensing as a tool for precision agriculture is a new field of research and future work is needed to further explore the full potential of this technology.

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RECEIVED: 03/09/01
REVISED: 05/02/02
ACCEPTED: 05/20/02