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USE OF REMOTELY SENSED IMAGERY FOR VARIABLE RATE APPLICATION OF COTTON DEFOLIANTS

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Abstract

Application of chemical harvest aids is necessary to improve harvestability and lint quality of the cotton crop. When applied properly to the crop, these chemicals stimulate leaf loss and promote boll opening. Traditionally, harvest aids have been applied at a constant rate across a field, resulting in over-application to areas that may have matured faster than others due to soil type, insect pressure, or disease.

In 2002, a field-scale experiment was designed to test the appropriateness of using remotely sensed imagery for variable rate application of cotton harvest aids. The experiment was conducted in the Delta Region of northwestern Mississippi. Variable rate applications were compared with traditional blanket applications for effectiveness, net profits, and fiber quality. When compared to traditional blanket applications, variable rate applications reduced chemical use by 17-18% while effectiveness, yield, and fiber quality were maintained. With additional research, variable rate applications of cotton harvest aids have the potential to reduce chemical use and increase net returns to growers.

Introduction

Cotton (*Gossypium hirsutum* L.) is a perennial plant grown as an annual crop. Because of the indeterminate growth habit of the crop, fruit and leaves do not mature uniformly (Supak et al., 2001). Leaves remaining on the plant at harvest reduce lint quality as well as picker efficiency (Williford, 1992).

Adoption of mechanical harvesting in the United States had a significant impact on the need for cotton defoliation. Fortenberry (1956) reported that in 1947, only two percent of the U.S. cotton crop was mechanically harvested. By 1970, 98% of the crop was harvested mechanically (Ghetti and Looney, 1972). When cotton was harvested by hand, very little plant and leaf matter found its way into the lint. However, when harvested mechanically, the presence of heavy foliage may cause an increase in trash content and discolor (stain) lint (Crawford et al., 2001). Thus, the need for defoliation became very prominent in the years following World War II.

Chemical harvest aids may be used to control physiological processes such as leaf drop, plant growth, and boll opening. The use of chemical defoliation methods provides a more timely leaf removal process compared to the natural process of senesce and abscission in cotton (Cothren et al., 2001). Defoliants are chemicals that induce leaf loss in plants through plant injury (herbicidal) and/or growth hormones (hormonal) (Cothren and Witten, 2001). Herbicidal defoliants, such as tribufos and endothall, produce ethylene, which impede the movement of auxin to the abscission zone causing the leaf to drop. Hormonal defoliants, such as thidiazuron and ethephon, also enhance ethylene production, thus giving similar responses to herbicidal defoliants (Cothern et al., 2001). Desiccants, such as paraquat, lead to rapid water loss and drying of leaves. The physiological processes in the plant are disrupted so rapidly that the leaf abscission process has not had adequate time to occur, thus the leaves typically remain attached to the plant (Crawford et al., 2001). Boll openers are ethephon-based products that breakdown to produce ethylene which leads to the splitting of the boll walls causing the bolls to open (Cothern and Witten, 2001).

The effectiveness of such chemical harvest aids depends largely on application timing and the chemicals used. Plant conditions and environmental conditions at the time of application, as well as the tank mixes, increase the likelihood of a favorable response and reduced costs (Gwathmey and Hayes, 1997). Several studies have reported the influence of plant and environmental conditions on harvest-aid activities (Snipes and Wills, 1994; Gwathmey and Hayes, 1997) while another study concentrated on effectiveness of using various chemical harvest-aids in combination (tank mixing) with each other (Snipes and Cathey, 1992 and Gwathmey and Hayes, 1997).

Proper timing of chemical harvest aid applications is important to attain maximum yield and lint quality. Traditionally, timing of defoliant application has been determined by quantifiable measurements such as percent open bolls, the cut boll technique, and/or nodes above cracked boll (NACB) (Brecke et al., 2001). In the Delta region of Mississippi, defoliation is generally recommended when 60% of the bolls are open (Whitwell et al., 1987). Defoliant applications based on the percentage of open bolls (20, 40, 60, and 80%) was investigated by Snipes and Baskin (1994). They concluded that defoliant applications made at 60% open bolls or greater did not decrease yield or fiber quality. Research conducted by Benson et al. (2000) used heat units accumulated after cutout as an indicator of crop maturity. Heat unit accumulations were calculated starting at the date of cutout (five nodes above white flower) and defoliation treatments were applied at approximately 650, 750, 850, and 950 heat units past cutout. Yields were not affected when defoliation was initiated at 763 or more heat units past cutout.

It is often difficult to determine optimum plant conditions or predict plant response under varying plant conditions. Spectral vegetation indices (e.g., Huete et al., 1985; Qi et al., 1994; Tucker, 1979) are often used to quantify plant canopy characteristics. Significant correlations between spectral data and green leaf area and/or green leaf biomass in soybean were described by Holben et al. (1980). Wiegand et al. (1991) reported a good relationship between the canopy coverage of cotton and vegetation indices derived from SPOT imagery (Coefficient of determination, R-square, of 0.66 or greater). Additionally, digital imagery may be used for the evaluation of defoliation measurements (Stewart et al., 1997).

In 2000, approximately 5.4 million kg (12 million lb) of chemical harvest aids were applied to the 5.8 million hectares (14.4 million acres) of cotton grown in the United States (National Agriculture Statistics Service, 2001). Cotton producers in the Delta region of Mississippi spend an average of \$42.60 ha^{-1} (\$17.25 $acre^{-1}$) on harvest-aids (i.e., boll openers, defoliants) accounting for roughly four percent of direct input costs (MSU Extension, 2000). Site-specific applications of chemical harvest aids compensate for the uneven distribution of plant biomass and unopened bolls that typically occur in a given field (Bader et al., 2001). In addition, remotely sensed data may be useful for timing defoliant applications (Sanders et al., 2001; D.B. Reynolds, personal communication, 2002).

The objectives of this study were: (1) evaluate the use of remotely sensed imagery for timing defoliant applications, and (2) test the effectiveness of remotely sensed imagery for site-specific applications of defoliants in cotton. Site-specific applications of cotton defoliants have the potential to reduce chemical usage and increase net returns to growers. Analyzing the reduction in defoliant use, as well as the impact on cotton yield and fiber quality will test both goals.

The long-term goal of the project is to develop techniques useful at a commercial scale for timing defoliant applications and the development of site-specific defoliant prescription maps.

Materials and Methods

The study field was located in the Delta region of Mississippi near Gunnison in Bolivar County. The soils of the area are primarily of the Robinsonville (coarse-loamy, mixed, superactive, nonacid, thermic Typic Udifluvents), Sharkey (very-fine, smectitic, thermic Chromic Epiaquerts), and Commerce (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Epiaquepts) soil associations.

The cotton cultivar Paymaster 1218 BG/RR (Delta and Pine Land Company, Scott, Mississippi) was planted on 20 Apr. 2002 using a 12-row planter with 102 cm (40 inch) row spacing. However, due to the cool and wet conditions that plagued the early growing season, the study field was completely replanted on 22 May 2002. Favorable growing conditions in June and July resulted in rapid crop development.

The experiment employed a randomized complete block design. By utilizing a block design, the existing field variability should be minimized within the blocks and maximized between blocks (Little and Hills, 1978). Each block consisted of three strips (Figure 1): (1) a blanket application applied when the crop has approximately 60% open bolls, (2) a variable rate treatment applied when the crop has approximately 60% open bolls, and (3) a variable rate treatment applied based on timing information derived from imagery. Each strip was 24 rows wide (24 m) and extended across the length of the field (approximately 535 m).

Apparent soil electrical conductivity (soil EC_a) data were obtained on the study field using the Veris 3100 sensor cart (Veris Technologies, Salina, Kansas). This mobile system uses six rolling coulters for electrodes and simultaneously generates shallow (0-30 cm) and deep (0-100 cm) measurements of soil EC_a (Lund et al., 1998). The sensor was operated at a speed of 3.58 $m\ s^{-1}$ on transects 12 m apart and data was logged at 1-s intervals. Soil EC_a measurements have found to be related to a several soil properties, including soil water content (Sheets and Hendrickx, 1995) and clay content (Williams and Hoey, 1987).

Field data were collected on a 0.5-acre (0.2-ha) rectangular grid for a total of 90 samples. All measurements were collected at the same grid point prior to and following the defoliant application. Prior to the application, plant height, LAI, nodes above cracked boll (NACB), and the percentage of open bolls were recorded at each sample point. Leaf area index measurements were collected only under diffuse light conditions (i.e., early evening or early morning). Collection of LAI data in direct sunlight usually results in underestimation of canopy LAI (Welles and Norman, 1991). At each sample point, one above canopy measurement and four below canopy measurements were replicated three times to determine LAI.

In order to compare the effectiveness of the variable rate and blanket defoliant applications, additional data was collected at seven and 14 days after treatment (DAT). Again, each point was visited and a visual rating of the percent defoliation and percent desiccation was performed. Additionally, each sample point was evaluated to determine the percentage of open bolls, percentage of basal regrowth, and percentage of terminal regrowth.

To determine the percentage of open bolls, a 1-m row segment was identified at the sample point and the total number of bolls as well as the number of open bolls were counted. The percentage of open bolls was calculated as the number of open bolls divided by the total number of bolls.

Using the same 1-m segment of row, the percentage of basal regrowth and the percentage of terminal regrowth were determined. First, the number of plants in the 1-m segment of row was determined. Next, the numbers of plants exhibiting basal regrowth and/or terminal regrowth were counted. A plant was considered as having regrowth (either basal or terminal) if new leaves were greater than 10-mm in size. The percentage of basal regrowth was calculated by dividing the number of plants exhibiting basal regrowth by the total number of plants. The percentage of terminal regrowth was determined in the same manner.

To determine if the variable rate applications of defoliant had any effect on lint quality, lint samples were also collected at 14 DAT. Initially, lint samples were to be collected on the same scale as the field measurements. Due to threatening weather, however, the harvest schedule was greatly accelerated and time only permitted the collection of one composite sample from each of the treatment strips. The USDA-Southern Regional Research Center (SRRC) in New Orleans, LA, conducted the analysis of fiber properties. Samples were ginned using a 10-saw laboratory gin. From the ginned cotton, 4-g and 50-g subsamples were removed for analysis with the Advanced Fiber Information System (AFIS) and High Volume Instrument (HVI) equipment, respectively.

The AFIS utilizes a small sample (10,000 fibers) and provides extensive information on fiber length and diameter distribution, fineness, and maturity measurements (Calhoun et al., 1997). Analysis conducted via HVI provides information on fiber length, uniformity, strength, micronaire, and color (USDA-AMS, 2001).

Image Data

The RDACS/Model II (Mao and Kettler, 1995) airborne camera system was used to collect multispectral imagery that consisted of three bands (840 nm, 695 nm, 540 nm, ±5 nm) with a 1-m spatial resolution. In order to monitor the crop throughout the growing season and determine the appropriate time to defoliate, imagery was collected every seven to 10 days.

Additionally, imagery from satellite data sources was acquired to evaluate its potential use for defoliant applications. Satellite imagery was obtained from Space Imaging's IKONOS and DigitalGlobe's QuickBird platforms, as well as SPOT Image Corporation's SPOT satellite.

After acquisition, the raw RDACS data was processed using the following steps:

1. The data was extracted from the 8-mm tape and prepared for processing.
2. Bands were band-to-band registered. The RDACS sensor has three separate Kodak cameras, each equipped with a filter to allow the specified wavelength to reach the CCD array. Because the sensor has three separate cameras, the image bands are not co-registered. The band-to-band registration process was performed to spatially register the image bands to each other.
3. Radiometric calibration was performed on the imagery. The calibration procedure relied on pseudo-invariant features that were located near the study area as reference for the calibration process. These features included asphalt roads, gravel roads, and concrete bridges. Spectroradiometer reflectance measurements of the pseudo-invariant features were collected and used to transform the raw 8-bit Digital Numbers (DNs) to percent reflectance. A linear regression was performed between the digital numbers of the pseudo invariant features retrieved from the imagery and the true percent reflectance measurement for each pseudo invariant feature. The linear regression equation was then applied to the imagery to convert the data to percent reflectance.
4. Imagery was georeferenced using a combination of Digital Ortho Quarter Quads (1:12,000 National Mapping Accuracy Standard) and GPS reference points. Nearest-neighbor resampling was used and was output in the Universal Transverse Mercator (UTM) coordinate system (WGS-84 datum, zone 15 north).
5. All non-field areas, including field edges and roads among the fields, were masked out of the image scene, leaving only pixels within the experiment field.

6. Vegetation indices were calculated from the imagery. For this project, the vegetation indices used were the NDVI (Tucker, 1979) and the green NDVI (GNDVI) (Gitelson et al., 1996). Calculation of the NDVI and GNDVI was accomplished using Equations 1 and 2, respectively.

$$\mathrm{NDVI} = (\mathrm{Band}\ 3_{840nm} - \mathrm{Band}\ 2_{695nm}) / (\mathrm{Band}\ 3_{840nm} + \mathrm{Band}\ 2_{695nm}) \qquad [1]$$

$$\mathrm{GNDVI} = (\mathrm{Band}\ 3_{840nm} - \mathrm{Band}\ 1_{540nm}) / (\mathrm{Band}\ 3_{840nm} + \mathrm{Band}\ 1_{540nm}) \qquad [2]$$

Yield Data

Cotton yield measurements were obtained using Case-IH six row cotton pickers equipped with an Ag Leader PF3000 Pro (Ag Leader Technology, Ames, IA) commercial yield sensing system and DGPS receiver. Data were collected at 2-s intervals and written to a PCMCIA card located on the yield monitor.

Yield monitor calibration was accomplished using a boll buggy equipped with an electronic scale. Randomly selected loads were weighed and compared with the yield monitor load weight. If necessary, correction factors were then applied to the yield monitor.

After harvest, the yield data files were downloaded from the PCMCIA cards and exported to comma-delimited ASCII files for further processing. Each data file was converted to an ESRI shapefile and edited to remove points logged when the picker had stopped and/or momentarily reversed its direction of travel (i.e., due to plugging). After editing was complete, the shapefile was saved and exported as a comma-delimited ASCII file.

Next, the yield data was processed with Microsoft Visual Basic (Microsoft Corporation, Redmond, Washington) using algorithms similar to those described by Birrell et al. (1996). Observations with yields below 25 lbs/acre and above 12000 lbs/acre were removed as well as observations collected when the picker was traveling at speeds less than 0.5 miles/hour. At the same time, geographic coordinates (longitude, latitude) were converted to Universal Transverse Mercator (UTM) coordinates.

Although each treatment strip was 24 rows wide, only the center 12 rows were used to determine yield, thus creating a buffer between the treatment strips. The mean yield for each sample point was calculated by extracting all of the data points from an 80-m segment (40-m before and after the sample point) of the two center picker passes. Finally, the mean yield values were merged with their respective treatment designation and exported to a comma-delimited ASCII file.

Economic Analysis

The net impacts of variable rate defoliant on lint yields and fiber quality were evaluated by the calculation of net revenues for each treatment. An approach similar to that used by Larson et al. (2002) was used to evaluate net revenues as a function of yield and fiber quality. Lint price differences for fiber quality as influenced by harvest aid treatments may be expressed as

$$P_d = P_{cls} + P_m + P_{str} + P_u, \qquad [3]$$

where P_d is the total price difference for each treatment from the base price of cotton (¢ lb^{-1}); P_{cls} is the price difference for the combination of color grade, leaf grade and staple (¢ lb^{-1}); P_m is the price difference for micronaire (¢ lb^{-1}); P_{str} is the price difference for strength (¢ lb^{-1}); and P_u is the difference in price for length uniformity (¢ lb^{-1}).

Thus, net revenues (*NR*) for each treatment can be expressed with the following partial budgeting equation:

$$NR = (P_b + P_d) \times Y - DC_j \qquad [4]$$

where P_b is the North Delta base quality lint price (¢ lb^{-1}); P_d is the total price difference (¢ lb^{-1}) for each treatment as defined in Equation 4; Y is the lint yield measured for each treatment (lb ac^{-1}); and *DC* is the defoliation material and application cost for treatment *j* (\$ ac^{-1}).

Statistical Analysis

To analyze differences between treatments, analysis of variance (ANOVA) was conducted using the GLM procedure in SAS (SAS Institute, 1999). Data were analyzed to determine what, if any, influence variable rate applications exhibit on net profits, effectiveness, and fiber quality. For all statistical tests, a significance value of 0.10 was used.

Since all treatments were applied on the same date, the image-timed variable rate treatments were designated as conventional-timed variable rate treatments, and tests were conducted to compare the conventional application with the variable rate. To compare the means with this “unbalanced” design, the LSMEANS option was used with the GLM procedure, thus allowing estimation of marginal means over a balanced population (SAS Institute, 1999).

Results and Discussion

There were 13 remotely sensed data acquisitions over the study area. The imagery was processed as previously outlined and the NDVI and GNDVI values were calculated. The NDVI map was then masked to remove all non-crop areas and the mean NDVI value was calculated for the field. To monitor crop development, NDVI values were plotted versus time (Figure 2). As the cotton crop developed and accumulated biomass, the mean NDVI increased. On 24 Jul. 2002, the growth curve leveled-off, indicating the crop was no longer accumulating biomass, but rather redirecting photosynthate for boll development.

The anomalous decrease in NDVI that occurred on 20 Aug. 2002 was likely the result of dry conditions prevalent at that point in the growing season. Research conducted by Carter and Miller (1994) indicated that narrow band imagery (6- to 10-mn wavelengths) was more sensitive to plant stress than broader-band imagery. Since the remotely sensed data used for this project was acquired with a camera system having a 10-nm bandwidth, the moisture stress induced on the crop was detected by the imagery.

Due to a lack of equipment availability and other factors, all of the defoliant treatments were applied on the same date. However, the NDVI data indicated that defoliation should occur around 05 Sep. or later, as the slope of the NDVI growth curve was negative at that time. When additional data such as the percentage of open bolls was included with the NDVI plot (Figure 3), additional insight was obtained for the proper time to defoliate.

Prescription Generation and Application

During the last week of August and the first week in September, the pre-application field data was collected. Plant height, LAI, percent open bolls, and NACB data were obtained from each of the grid sample points. Data were entered into a database and then merged into a comma-delimited text file for further analysis.

Using imagery that was acquired on 05 Sep. 2002, NDVI and GNDVI maps were calculated using the Raster Calculator in ArcGIS 8.1 (ESRI, Redlands, CA). To obtain a NDVI or GNDVI value for each of the sample points, a polygon buffer having a 3-m radius was created around each sample point and overlaid on the vegetation index maps. All of the pixels that resided within the polygon were extracted and the mean value calculated for that sample point. The mean values of NDVI and GNDVI at each sample point were then appended to the data file containing plant height, LAI, percent open bolls, and nodes above cracked boll.

Both LAI and plant height were strongly correlated with the vegetation indices and moderately correlated with soil EC_a (Table 1). The percentage of open bolls was negatively correlated with both vegetation indices, as areas with larger amounts of vegetative matter tended to have fewer open bolls. Nodes above cracked boll were ancillary data collected to assist with timing the defoliant application. Studies have shown that defoliation of cotton at NACB of less than or equal four results in no reduction of fiber quality and yield losses less than one percent (Kerby et al., 1992). At the time data was collected on the study field, the mean NACB was 7.3.

After the initial analysis of the correlations between the plant measurements and the vegetation indices, additional analyses were conducted to develop the variable rate prescription that was applied to the field. It was decided by the Perthshire Farms staff that the chemicals to be used were thidiazuron (Dropp 50WP, Aventis CropScience, Research Triangle Park, NC) and a formulation of ethephon and cyclanilide (Finish 6, Aventis CropScience, Research Triangle Park, NC) (Table 2). Thidiazuron is a wetable powder that is used to remove leaf tissue, especially new, juvenile leaves and inhibit regrowth (Brecke et al., 2001). The formulation of ethephon and cyclanilide promotes boll opening and more complete defoliation (Brecke et al., 2001).

The use of a defoliant and a boll opener resulted in the need for two prescription maps: one for the quantity of vegetation (defoliant) and one for the percentage of open bolls (boll opener). To map the quantity of vegetation present, LAI values needed to be extrapolated from the grid sample points to the entire field.

Regression was used to derive the mathematical relationship between LAI and the vegetation indices. The REG procedure in SAS (SAS Institute, 1999) was used to perform stepwise regression to select which combination of variables best modeled the data. The independent variables included in the stepwise model included NDVI, GNDVI, shallow soil EC_a, and deep soil EC_a. The final regression model included NDVI and shallow soil EC_a (Equation 5). The R^2 and root mean square error (RMSE) of the selected model was 0.67 and 0.63, respectively. The use of a quadratic model was also considered, but this approach failed to increase the R^2 (0.67) or substantially decrease the RMSE (0.62).

$$\text{LAI} = (4.7481*\text{NDVI}) + (0.0738*\text{shallow soil } EC_a) - 0.3239 \qquad [5]$$

Although the NDVI map was a raster data set, the soil EC_a data was collected on intervals and stored as a point feature, thus some form of interpolation was required. Because of the spatial denseness of the soil EC_a data, a nearest neighbor interpolation was performed to create a raster surface of shallow soil EC_a using the Neighborhood Statistics function (McCoy and Johnston, 2001) in ArcGIS Spatial Analyst. Once the raster data set of shallow soil EC_a was created, the Raster Calculator was used to create a map of LAI (Figure 4).

The estimated LAI data was to classified into three classes to which the rates of defoliant would be applied. The experiment plan called for the low rate of defoliant to be applied to the lower one-third of the data, the moderate rate to the middle one-third of the data, and the high rate to the upper one third of the data. This technique was applied to the data, but appeared to not capture all the variation in the field. Therefore, the thresholds were adjusted slightly to the following: (1) 0% to 35%, (2) 35% to 60%, and (3) 60% to 100%.

A slightly different approach was used create a map of the percentage of open bolls. Regression techniques using the vegetation indices as the independent variables were relatively poor predictors of the percentage of open bolls ($R^2 = 0.38$, RMSE = 17.92). D.B. Reynolds (personal communication, 2002) recommended classifying the percentage of open bolls into three classes: (1) 0 to 50%, (2) 50 to 75%, and (3) 75 to 100% and then utilize discriminant analysis to develop a linear discriminant function using NDVI.

Discriminant analysis was performed using the DISCRIM procedure in SAS. To reduce bias in calculating the apparent classification error rate, the CROSSVALIDATE option was added to the DISCRIM procedure declaration. In this mode, *n*-1 out of *n* observations are used as the training set to classify the one observation left out of the analysis (SAS Institute, 1999). The discriminant function for the percentage of open bolls achieved a classification accuracy of 72% and the resulting equation is shown in Table 3. The discriminant function was then applied to the entire NDVI data set from 05 Sep. 2002 (Figure 5).

To create the actual prescription, a spray grid with a cell size of 24-m wide by 12-m deep was overlaid on the classified maps of LAI and the percentage of open bolls. To determine the rate for a given cell, the Zonal Statistics function in ArcGIS was used to determine what class (i.e., 1, 2, or 3) was the majority in that particular cell.

Since the two chemicals were going to be applied in a tank mix (the injection channels were not operational on the sprayer), it was necessary to merge the prescription for the defoliant with the prescription for the boll opener. Also, the prescription needed to be modified to include the conventional treatment strips (Figure 6). The prescription was converted to latitude/longitude coordinates and converted to the appropriate format for the A.I.M. Navigation System/Midtech Controller installed on the Case-IH Patriot.

The harvest aid application was performed on 17 Sep. 2002 using a Case-IH Patriot sprayer equipped with a 24-m (80 feet) boom. The as-applied data were recorded during application and the area treated (in acres) with each rate is shown in Figure 7. As previously mentioned, all treatments were applied on the same date.

Evaluation of Harvest Aid Performance

Harvest aid performance was evaluated at seven and 14 days after treatment. The percentage defoliation, desiccation, open bolls, basal regrowth, and terminal regrowth were determined at each of the grid sample points. Analysis of variance was conducted to determine if there was a difference between treatments (Table 4).

The performance of the variable rate application was not statistically different than that observed with the conventional application ($\alpha = 0.10$). The percentage of basal regrowth increased dramatically from seven to 14 days as considerable rainfall was received in the two weeks following the application.

Yield Data and Fiber Quality

Harvest of the study field was accomplished on 02 Oct. 2002. After post-processing the yield data, ANOVA was conducted to determine if variable rate applications had a significant impact on yield. Overall, there was only 20 lb ac^{-1} difference in seed cotton yield between the conventional and variable rate treatments (Figure 8). Results of the ANOVA revealed this difference was not statistically significant (*P*-value = 0.90).

Analysis of fiber quality was conducted with the AFIS and HVI equipment and the results analyzed with ANOVA (Table 5). The purpose of this analysis was to determine if variable rate applications significantly impacted fiber quality. Analysis of selected AFIS properties revealed no significant difference in most of the fiber properties, an exception being mean fiber diameter [denoted D(n)]. The difference in D(n) was thought to be more from environmental influences than from the actual defoliant application. Similarly, no significant differences were found in the HVI fiber properties.

Economic Analysis

Quotations from the USDA-Agricultural Marketing Service were used to estimate premiums and discounts from a base quality price for each treatment strip. The reported base price is for Strict Low Middling (color 41, leaf 4, staple 34 [fiber length between 26.67 and 27.18 mm], micronaire 35-36 and 43-49, strength 26.5-28.4 g tex^{-1}, and uniformity 81) cotton. On 21 Nov.

2002 the published base price for the North Delta was 47.58 ¢ lb^{-1} (USDA-AMS, 2002). A color grade of 41 and a leaf grade of 4 was assumed for the analysis of net revenues.

The costs associated with the conventional and variable rate applications are shown in Table 6. On a per acre basis, the variable rate method used in this study costs $1.40 more than the conventional blanket application. The increased cost of the application ($1.55 acre^{-1} vs. $1.31 acre^{-1}) reflects the additional expenses of the variable rate equipment (i.e., computer, controller, GPS). The variable rate method also includes remotely sensed imagery costs of $1.00 acre^{-1} as well as a $0.16 acre^{-1} charge for the use of a precision farming service consultant. For this experiment, the chemical costs used were: thidiazuron (Dropp 50WP), $110.54 lb^{-1} of active ingredient; and ethephon (Finish 6), $13.77 lb^{-1} of active ingredient.

Net revenues adjusted for fiber quality are shown in Table 7. Although the net revenues of the variable rate strips were $1.50 acre^{-1} more than those from the conventional strips, the difference was not statistically significant (= 0.10). This difference was attributed to the 18% reduction in the quantity of ethephon (Finish 6) and the 17% reduction in the amount of thidiazuron (Dropp 50WP) applied using the variable rate method. When compared with conventional applications, variable rate applications did not significantly impact the market value of the crop or price discounts due to fiber quality (Table 7).

Conclusions

Measures of plant biomass (i.e., LAI) as well as the percentage of open bolls were collected and mapped using remotely sensed imagery and soil EC_a. Leaf area index and plant height were positively correlated with vegetation indices, specifically NDVI and GNDVI. The percentage of open bolls exhibited negative correlations with the NDVI and GNDVI as the bolls are slower to open when the crop was excessively tall.

Variable rate prescriptions for defoliation and the percentage of open bolls were derived from the remotely sensed data and applied to the study field. The effectiveness attained with variable rate defoliant applications was equal to that attained with the conventional blanket application. Although the variable rate application reduced the amount of chemical applied to the field and maintained effectiveness, the costs associated with the variable rate technology negate much of the savings when crop prices are so low. None-the-less, the environmental impacts of reduced chemical usage are definitely beneficial.

Very little research has been conducted on the use of variable rate applications for cotton defoliation. Additional work is needed to develop effective prescriptions and timing mechanisms and at the same time, reduce the amount of field data collected. In the future, decision support systems that integrate remotely sensed, climatological, and other data sources may provide an effective means for timing and variable rate application of cotton harvest aids.

Disclaimer

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the National Aeronautics and Space Administration (NASA), the Institute for Technology Development (ITD), or Mississippi State University.

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Table 1. Correlation coefficients between the vegetation indices and selected plant parameters.

Variable	**NDVI**	**GNDVI**
LAI	0.77	0.76
Plant Height	0.73	0.72
Open Bolls (%)	-0.59	-0.62
NACB[†]	0.51	0.51
Veris Shallow	0.41	0.40
Veris Deep	0.76	0.73

[†] Nodes above cracked boll

Table 2. Chemical application rates.

	Rate		
Chemical (active ingredient(s))	**Low**	**Moderate**	**High**
	———————	lb a.i. ac^{-1}	———————
Dropp 50 WP (thidiazuron)	0.04	0.05	0.06
Finish 6 (ethephon)	0.75	1.00	1.20

Table 3. Linear discriminant function for the percentage of open bolls.

	Class		
Variable	**1**	**2**	**3**
Constant	-9.95	-5.97	-3.48
NDVI	39.44	30.54	23.32

Table 4. Analysis of variance results for harvest aid effectiveness at seven and 14 DAT.

		Treatment		
Variable	**DAT**	**Conventional**	**Variable Rate**	**P-value**
		———————	%———————	
Defoliation	7	95.9 a	96.3 a	0.74
	14	98.6 a	98.7 a	0.82
Desiccation	7	0.6 a	0.4 a	0.36
	14	0.4 a	0.3 a	0.40
Open Bolls	7	94.1 a	93.9 a	0.87
	14	99.1 a	99.1 a	0.83
Basal Regrowth	7	2.6 a	2.5 a	0.96
	14	16.0 a	18.9 a	0.28
Terminal Regrowth	7	0.6 a	2.5 a	0.18
	14	0.8 a	3.5 a	0.11

[†] Within a row, means followed by the same letter are not significantly different (= 0.10).

Table 5. Results of AFIS and HVI analyses of selected fiber properties.

			Treatment	
Analysis	**Parameter**	**Units**	**Conventional**	**Variable rate**
AFIS	L(n)	in.	0.86 a[‡]	0.85 a
	SFC(n)	%	13.60 a	13.73 a
	UQL(n)	in.	1.08 a	1.07 a
	D(n)	µm	14.28 a	14.58 b
	Theta	[†]	0.47 a	0.48 a
	IFF	%	12.21 a	11.50 a
	A(n)	µm	114.01 a	117.56 a
	FFF	%	12.71 a	11.77 a
	MicronAFIS	[†]	4.27 a	4.47 a
HVI	UHM	in.	1.07 a	1.06 a
	UR	%	82.56 a	83.13 a
	SFC	%	7.64 a	7.34 a
	Strength	g tex^{-1}	27.86 a	27.51 a
	Elongation	%	10.88 a	10.79 a
	Micronaire	[†]	4.56 a	4.75 a

[†] Unitless

[‡] Within a row, means followed by the same letter are not significantly different (= 0.10).

Table 6. Costs associated with conventional and variable rate defoliant applications.

	Application Method	
Description	**Conventional**	**Variable rate**
	——————$ acre^{-1}——————	
Application	1.31	1.55
Imagery	0.00	1.00
Service Consultant	0.00	0.16

Table 7. Net revenues, market value, and quality discounts observed for conventional and variable rate harvest aid application methods.

	Application Method		
	Conventional	**Variable rate**	**Difference**
	——————————$ acre^{-1}——————————		
Net Revenue	348.00 a[†]	349.50 a	1.50
	——————————¢ lb^{-1}——————————		
Market Value	46.82 a	46.50 a	0.32
Total Discounts	-0.76 a	-1.08 a	0.32

[†] Within a row, means followed by the same letter are not significantly different (= 0.10).

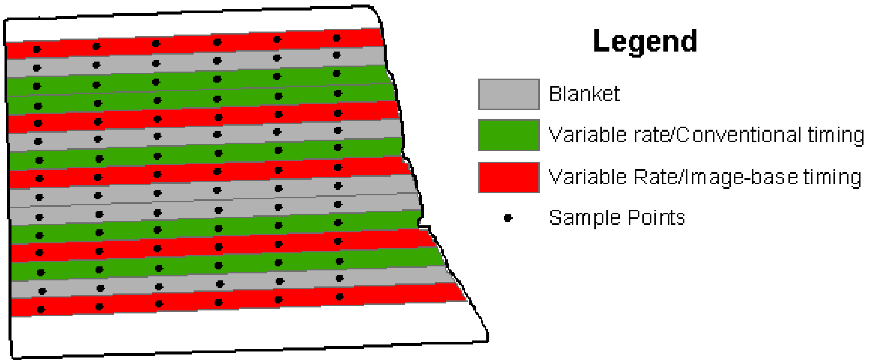

Figure 1. Randomized complete block design utilized in the experiment.

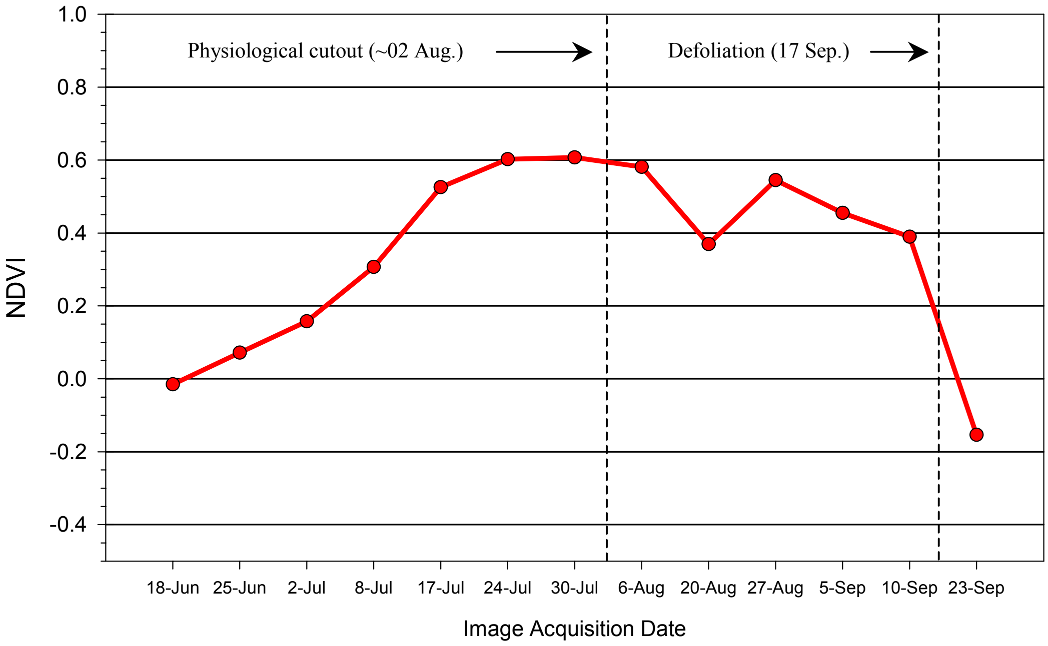

Figure 2. Plot of the field average NDVI versus the date of image acquisition.

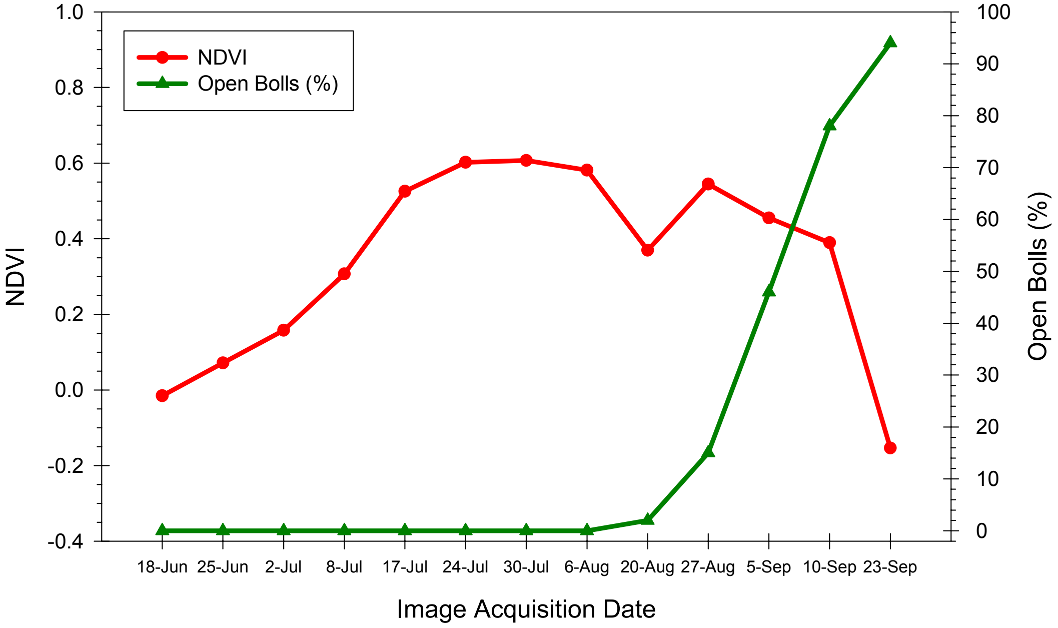

Figure 3. Plot of the field average NDVI and the percentage of open bolls versus the image acquisition date.

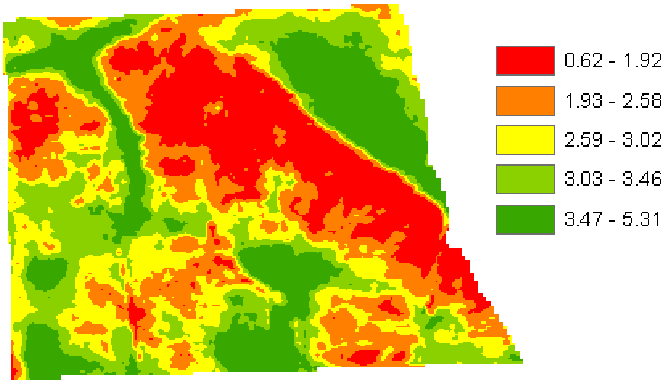

Figure 4. Estimated leaf area index created from Equation 5.

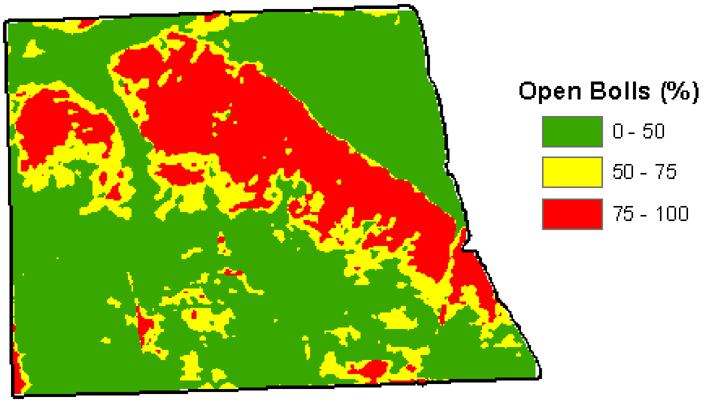

Figure 5. The percentage of open bolls mapped with discriminant analysis.

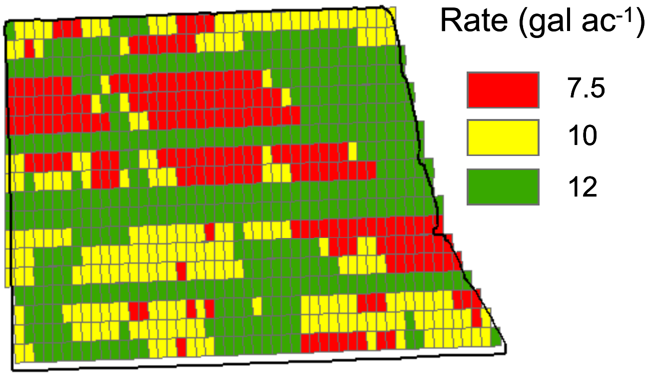

Figure 6. Intersected prescription for thidiazuron and ethephon with the conventional treatment strips.

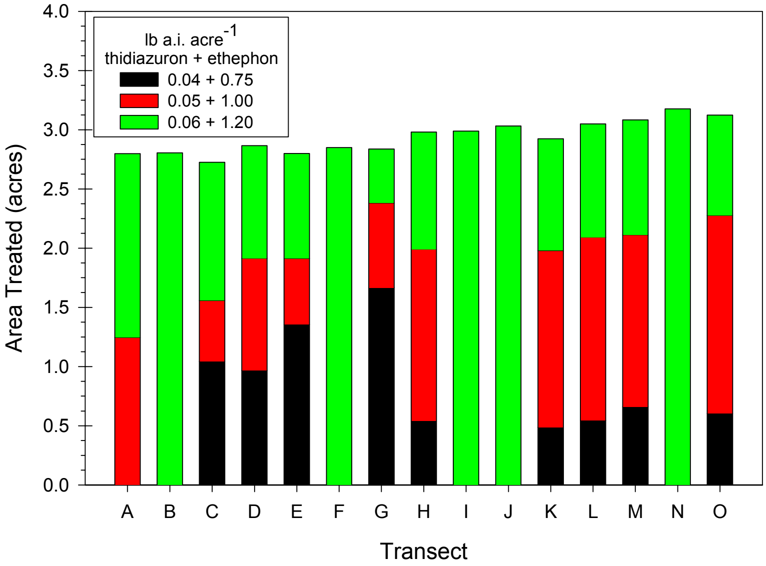

Figure 7. Area treated in each treatment strip with the low (black), moderate (red), and high (green) application rates of thidiazuron (Dropp 50WP) and ethephon (Finish 6).

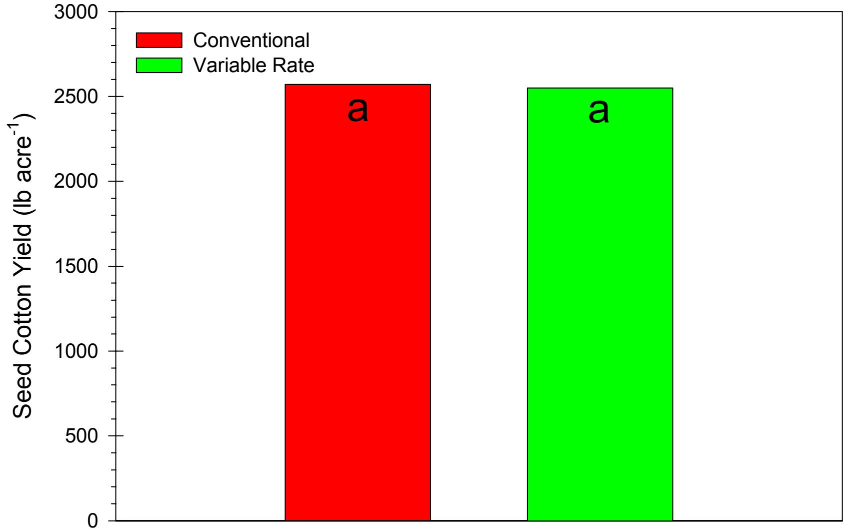

Figure 8. Seed cotton yields for the conventional and variable rate applications. Bars with the same letter are not significantly different (= 0.10).