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EVALUATION OF COTTON DEFOLIATION TREATMENTS WITH AIRBORNE DIGITAL IMAGERY

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Abstract

Visual observations and ground measurements are commonly used to evaluate cotton (*Gossypium hirsutum* L.) harvest aids for defoliation, boll opening, and regrowth control. This paper presents a remote sensing-based method for evaluating the effectiveness of different defoliation treatments. Field experiments were conducted on two cotton fields in south Texas in 2001, in conjunction with a study on the effects of defoliants alone and in combination with insecticides on boll weevil mortality. Eight treatments (one control and seven combinations of defoliants and insecticides) with three replications were assigned across 24 experimental plots in a randomized complete block design in each of the two fields. Airborne color-infrared (CIR) digital images were obtained from the first field six days after chemical application and from the second field on the day of application and three more times afterwards. Ground reflectance spectra and plant physical data such as number of leaves were collected on selected sites within each plot. The reflectance spectra effectively separated different levels of defoliation, but a large number of spectra were required to obtain reliable results. The airborne images permitted visual differentiation among the treatments as early as 3 days after the chemical application, though the images collected 6 days after the application revealed the most significant differences among the treatments. For quantitative analysis, the green, red, and near-infrared (NIR) bands of the CIR images and the normalized difference vegetation index (NDVI) derived from the NIR and red bands were used as spectral variables to compare the differences among the treatments. Multiple comparisons showed that spectral variables differed significantly among some of the defoliation treatments. These results indicate that remote sensing can be a useful tool for evaluating the effectiveness of cotton defoliation strategies.

Introduction

Use of harvest aids to terminate and prepare the cotton crop for machine harvest has been an accepted practice for expediting crop maturity, increasing harvest efficiency, and improving lint yield and quality. Many materials have been registered and recommended for use as harvest aids in the US. Def/Folex, Dropp, Harvade, Ginstar, ethephon, Finish, and CottonQuik are some of the most popular products, and newer products such as Leafless, Aim, and Action are being evaluated as harvest aids. Proper use of these products is important to ensure the quality of defoliation, boll opening, and regrowth control. However, variability of growing conditions during the season, different varieties and cultural systems used, and environmental factors during the harvest all combine to result in no standard method for harvest aid timing or choice of materials (Patterson and Smith, 2001). Although not exact, timing of harvest aid application is generally guided by such techniques as percent open bolls, the cut boll technique, and nodes above cracked boll (Banks, 2001). Choice of harvest aids varies with production region, type of harvest, and physical and environmental factors. Nevertheless, most growers use mixtures popular in their area to accomplish some or all of the following actions: defoliation, boll opening, regrowth control, and desiccation in the case of stripper cotton. Obviously, the evaluation of a harvest aid alone or in combination with others is extremely important for identifying the optimal rate for the product and/or combinations of products.

Picker cotton is usually treated with a hormonal or herbicidal defoliant to remove the leaves, while stripper cotton is treated with a defoliant followed by a desiccant or simply with a once-over desiccant in low yielding fields (Cothren and Witten, 2001; Keeling, 2001). Both hormonal and herbicidal defoliants injure the leaf by increasing ethylene production that causes the leaf to fall from the plant, while desiccants are more harsh than defoliants and cause injury that leads to rapid moisture loss and drying of the leaves. From the perspective of remote sensing, plants treated with either a defoliant or desiccant will have a different spectral response from normally growing plants. Furthermore, plants treated with different defoliants or desiccants will have different spectral responses over time. The spectral behavior or characteristics of the plants in response to different chemical treatments will facilitate separation of these defoliation treatments about their defoliation speeds and effectiveness.

Remote sensing observations in the visible and near-infrared (NIR) regions of the electromagnetic spectrum and the vegetation indices calculated from these observations can be used to measure the amount of photosynthetically active tissue in plant canopies (Wiegand and Richardson, 1984). Therefore, remote sensing may have the potential for evaluating the effectiveness of various defoliation treatments. Traditional approaches for this type of evaluation are based on visual observations and ground measurements (Warrick, 2001). This study was designed to examine the potential of remote sensing as a tool for evaluating the effectiveness of different defoliation treatments. Field experiments were conducted on two cotton fields in south Texas in 2001, in conjunction with another research project to study the effects of defoliants alone and in combination with insecticides on boll weevil mortality (Greenberg et al., 2002). The specific objectives of this study were to: 1) examine the feasibility of airborne digital imagery for evaluating the effectiveness of different defoliation treatments; and 2) develop procedures for differentiating among various defoliation treatments using airborne digital imagery.

Materials and Methods

Experimental Design

Field experiments were conducted on two irrigated cotton fields located at the South Research Farm of the USDA-ARS Kika de la Garza Subtropical Agricultural Research Center in Weslaco, Texas in 2001. Cotton cultivar Deltapine 50 was planted in early March and rows were spaced 1.02 m (40") apart. Both fields were fertilized and furrow irrigated according to the normal cotton production recommendations in the area. They also received pesticide applications as needed. Eight treatments, one control and seven combinations of defoliants and insecticides, with three replications were assigned across 24 experimental plots in a randomized complete block design for each of the two fields (Figure 1). The plots were 6 rows (6.1 m) wide for both fields, 112 m long for field 1, and 85 m long for the west part of field 2 and 113 m long for the east part of the field 2 (Figure 1). The defoliants used were Def 6 (Bayer Corporation, Kansas City, MO) and Dropp 50WP (Aventis Crop Sciences, Wilmington, DE). The insecticides used were Guthion 2L (Bayer Corporation, Kansas City, MO) and Karate 2.08Z (Syngenta Crop Protection, Inc., Greensboro, NC). The combinations of the defoliants and insecticides and their rates are listed in Table 1. The seven combinations of defoliants and insecticides were applied with a self-propelled John Deere sprayer on July 24 for field 1 and on August 14 for Field 2. The sprayer covered six rows (the width of the individual plots) at a time with one nozzle on each side and one over the top of each row. Each treatment was applied at 25 GPA or 234 L/ha across the three blocks. Leaf counts were taken from 10 randomly selected plants within each plot for both fields six days after the application. Percent defoliation was calculated from the mean number of leaves per plant within each plot and the mean number of leaves per plant in the control.

Ground Plant Reflectance and Airborne Imagery Acquisition

Figure 2 shows typical reflectance curves for cotton plants and bare soil in the visible (400-700 nm) to NIR region (700-900) of the spectrum. In the visible portion of the spectrum, chlorophyll controls much of the spectral response of the plants. Chlorophyll molecules absorb blue and red light for use in photosynthesis. Much less of the green light is absorbed and more is reflected. Therefore, reflectance is higher in the green region than in the blue and red regions. In the NIR portion of the spectrum, spectral response of the plant canopy is controlled not by plant pigments, but by the structure of the spongy mesophyll tissue in the plant leaves. Much of the radiation in the NIR portion is reflected by the spongy issue. Toward the red end of the visible spectrum, as the absorption of red light by chlorophyll pigments begins to decline, reflectance rises sharply and gradually flattens out in the NIR portion. The reflectance curve for bare soil is close to a straight line and soil reflectance increases with wavelengths in the visible to NIR region of the spectrum. These behaviors of cotton plants and bare soil are the basis for the separation of defoliated from healthy plants. The actual spectra for cotton plants and bare soil vary with cotton variety and soil type, though they are similar to the curves shown in Figure 2, which were obtained from one of the two fields used in this study. For the particular cotton and soil in the field, the soil was more reflective in the visible (blue, green and red) portion of the spectrum, while cotton plants were more reflective in the NIR portion of the spectrum. Field plant canopy reflectance was measured on five randomly selected canopies from each plot with a hand-held spectroradiometer on July 27 and 31 for field 1 and on August 17, 20, and 23 for field 2. The spectroradiometer was sensitive in the visible to NIR portion of the spectrum (350-1050 nm).

Airborne CIR images were taken from the two cotton fields using a digital imaging system described by Escobar et al. (1997). The system was composed of three Kodak Megaplus digital charge coupled device (CCD) cameras and a computer equipped with three image digitizing boards that had the capability of obtaining images with 1024 × 1024 pixels. The cameras were sensitive in the visible to NIR regions (400-1000 nm) and had a built-in A/D converter that produced a digital output signal with 256 gray levels. The three cameras were filtered for spectral observations in the green (555-565 nm), red (625-635 nm), and NIR (845-857 nm) wavelength intervals, respectively. Digital imagery was acquired on July 30 (six days after the chemical application) for field 1 and on August 14 (the day of chemical application), August 17, 20, and 23 for field 2. A Cessna 206 aircraft was used to acquire the imagery at an altitude of 762 m between 1200 and 1400h local time under sunny conditions. The imagery had a ground pixel size of approximately 0.35 m.

The raw digital count values of the images were not converted to reflectance values in this study. Although digital count values depend on the ambient illumination conditions and the characteristics of the imaging systems being used, these values are linearly related to the calibrated reflectance values and are useful for many applications where reflectance is not available or necessary. Since this study was to examine CIR imagery and its individual band components for differentiating among defoliation treatments, raw digital count values were sufficient for this purpose.

Imagery Processing and Analysis

The NIR, red and green band images in each CIR composite image were registered to correct the misalignments among them. The registered images were then georeferenced or rectified to the Universal Transverse Mercator (UTM), World Geodetic Survey 1984 (WGS-84), Zone 14, coordinate system based on ground control points around each field located with a submeter-accuracy global positioning system (GPS) receiver. Image registration and rectification were performed using ERDAS IMAGINE (ERDAS, Inc., 1997).

In addition to the NIR, red and green bands, one of the most widely used vegetation indices, known as the normalized difference vegetation index (NDVI), was also used to quantify the differences among the defoliation treatments. NDVI is defined as

$$\text{NDVI} = (\text{NIR}-\text{Red})/(\text{NIR}+\text{Red}) \tag{1}$$

The band images were exported from ERDAS IMAGINE into another geographic information system (GIS), Arc/Info (ESRI, Inc., 2000), as grids for analysis. The raw digital values in the NIR and red bands were used to calculate NDVI. Thus, there were four spectral images or grids (three bands and one vegetation index) for each date. To determine the spectral response from each of the experimental plots, the polygon coverages defining the plots for each field as shown in Figure 1 were overlaid on each of the four grids. Pixel values within each plot were extracted and averaged as the spectral response for the plot on a particular date. The five ground reflectance spectra collected from each plot on each date were averaged to provide the representative spectra for the plot on that date. The image data for the four spectral variables and the percent defoliation data were first analyzed using analysis of variance techniques and then multiple comparisons were performed among the means using Fisher's protected least significant difference (LSD) procedure (SAS Institute Inc., 1988).

Results and Discussion

Reflectance Spectra of Cotton Plants

Figure 3 presents the reflectance spectra of cotton plants obtained on August 20, six days after the treatment of field 2. For comparison, the spectrum for bare soil in the field is also shown. Since spectra from some of the eight treatments are similar and difficult to differentiate, only the spectra from treatments 1, 2, and 6 are presented. As shown in Table 1, treatment 1 was the control, treatment 2 received two defoliants (Def and Dropp) and one insecticide (Guthion) all at half rate, and treatment 6 received Def at full rate and another insecticide (Karate) at half rate. The spectra for treatments 2 and 6 are different from that of the control. The reflectance of the defoliated plants was higher in the visible portion and lower in the NIR portion of the spectrum than the reflectance of healthy plants. Since defoliated plants had fewer leaves than healthy plants, the reflectance taken from the defoliated plants represented a combination of reflectance values from both the plants and bare soil. Therefore, the spectra for defoliated plants fell between the spectra for healthy plants and bare soil. The higher the defoliation, the closer the spectrum should be to that of bare soil. However, even completely defoliated plants won't have the same reflectance curve as the bare soil because soil exposure is reduced as leaves fall from the plants. Based on the spectra of different treatments relative to the spectra of healthy plants and bare soil, the effectiveness of defoliation can be evaluated. For example, treatment 2 had better defoliation than treatment 6 in this particular experiment because the spectrum for treatment 2 was closer to that of bare soil.

Although spectra can be useful for determining the effectiveness of different defoliation treatments, it is not always easy to obtain reliable spectra from the field because of spatial variability within the treatments and the small field of view of the spectroradiometer. For example, the spectroradiometer used in this experiment had a field of view angle of 15°, which at a height of 1 m above the canopy only covered a circular area of 26 cm in diameter. The row spacing in this experiment was 1.02 m, thus each sample spectrum was based on a circular area about a quarter of the width of the row. Clearly, the resultant spectra taken from such a small area were affected by the variability in plant growth, position of the instrument, and amount of shadow and soil background within the field of view. To obtain reliable spectra, a large number of samples need to be taken and/or the instrument should be held at such a height that the area covered represents the actual conditions for the measured plants and background.

Visual Comparisons of Defoliation Treatments with Digital Imagery

Figure 4 shows the CIR composite image and its three band components acquired on July 30, six days after the chemical application, for field 1. Differences among the treatments can be clearly seen from the CIR image as well as from the red and green band images. However, the NIR band image revealed little difference among the treatments. On the CIR image, healthy plants showed a reddish-magenta tone, while defoliated plants had a light gray or pinkish color. On the red and green band images, plots with high defoliation tended to have a light gray color (high reflectance), while those with low or no defoliation had a dark gray tone (low reflectance). The NIR band image had a grayish color (high reflectance) for both low and high defoliation treatments. The brightness of the band images is attributed to the behavior of the spectra shown in Figure 3. The green, red and NIR band images represented the spectral observations in three narrow bands centered around 560, 630, and 851 nm, respectively. The data in Figure 3 suggest that better discrimination should be obtained from the red and NIR band than from the green band. However, the actual band images indicated that both the red and green bands were better than the NIR band. This is partly because the relative percent change in reflectance between healthy and defoliated plants was larger in the green and red bands than in the NIR band, even though the absolute change was smaller in the green band. Moreover, the NIR reflectance shown in Figure 3 was higher than that from the band image because the band image integrated the response of both vegetative canopies and bare soil within the plots, while the spectra measured with the spectroradiometer were mainly from vegetative canopies.

Figure 5 shows the CIR composite images taken on four equally-spanned dates beginning on August 14, the day of chemical application, for field 2. The August 17 image revealed some differences among the treatments, even though it was taken only three days after the chemical application. The August 20 image, acquired six days after the application, showed distinct differences among the treatments. The August 23 image was very similar to the August 20 image, except that more leaves had fallen by August 23. Therefore, the CIR images were useful for visual comparisons of different defoliation treatments. Based on the black-and-white band images (not shown), the red and green bands were useful for differentiating the treatments, while the NIR was not. Since the spectral characteristics of cotton plants and bare soil vary with cotton variety and soil conditions, the images for a spectral band that are not effective for a particular situation may be useful for other cotton variety and soil combinations. However, CIR composite images are better than individual band images because they not only incorporate the effects of all the bands, but also present the results in a color format.

Comparisons of Defoliation Treatments Using Spectral Indices

Table 2 shows the mean digital values of the NIR, red and green bands and NDVI by treatment based on the July 30 image for field 1. The red and green bands and NDVI detected significant differences among the treatments, while the NIR did not reveal any difference. Since healthy plants had a lower spectral response in the red and green bands than defoliated plants with bare soil background, better defoliation treatments were expected to have higher spectral values in the red and green bands. On the contrary, healthy plants had higher NDVI values than defoliated plants with bare soil background; therefore, better defoliation corresponded to lower NDVI. The data in Table 2 clearly indicate three distinct groups among the eight treatments. Treatments 1, 7, and 8, which had the lowest spectral values in the red and green bands and the highest NDVI values, had the least defoliation. In fact, these three treatments did not receive any defoliants, though treatments 7 and 8 received Guthion and Karate at half rates, respectively. No defoliation effect from the two insecticides was detected. Treatments 2 and 3 had the highest spectral values in the red and green bands and lowest NDVI values, and therefore represented the best defoliation treatments. Both treatments 2 and 3 received Def and Dropp at half rates, though treatment 3 also received a half rate of Guthion. Again, Guthion did not have a detectable effect on defoliation. Treatments 4, 5 and 6, which received varying levels of defoliants and insecticides, were not as effective as treatments 2 and 3, but still caused significant defoliation.

Tables 3-5 show the mean digital values of the NIR, red and green bands, and NDVI by treatment based on the images of August 17, 20, and 23 for field 2. The red and green bands and NDVI detected significant differences among the treatments on August 17, three days after the application. Treatments 2, 3 and 6 produced better defoliation than the other treatments. On August 20, there were four distinct groups among the eight treatments. Similar to field 1, treatments 2 and 3, which had the highest spectral values in the red and green bands and lowest NDVI values, provided the best defoliation, followed by treatments 4, 5 and 6. Treatments 1, 7 and 8 provided no detectable defoliation. The only difference between the two fields was that treatment 4, which received both Dropp and Guthion at full rates, provide less defoliation than treatments 5 and 6 for field 2, whereas the three treatments were statistically indistinguishable for field 1. The results from August 23, nine days after the application, were similar to those from August 20, though the green band and NDVI detected that treatment 4 was only slightly less effective than treatment 6. Table 6 presents the mean numbers of leaves per plant and percent defoliation relative to the control (treatment 1) among the eight treatments based on ground observations within each plot six days after the application for fields 1 and 2. The ground observation results agreed well with those from the airborne imagery for both fields. However, the significant difference between treatments 1 and 8 in field 2 may be artifact because no defoliants were involved in either treatment. This difference was probably due to the small number of sample plants used for calculating the mean leaves per plant and the variability within the field. The airborne images considered every pixel across the entire plot, while the ground observations relied on only 10 plants per plot. Therefore, the remote sensing-based approach should offer more efficient and accurate evaluation of various defoliation strategies than commonly used ground observation and measurement approaches.

Summary and Conclusions

This study illustrated that remote sensing can be a useful tool for evaluating the effectiveness of different cotton defoliation treatments. Ground reflectance spectra can be used to differentiate among treatments if they are taken from a sufficient number of canopies representing the ground foliage and soil conditions. Airborne digital imagery is more effective and reliable than reflectance spectra for this application. Airborne imagery provides a continuous view of the imaging area and allows quick visual comparisons among treatments. Moreover, the imagery contains digital reflectance information for every area (pixel) of the field and allows quantitative separation of the treatments. Compared with traditional ground observation and measurement approaches, the remote sensing-based approach is more effective and efficient if a large number of treatments are to be evaluated over large fields. Depending on the imaging systems used, airborne imagery can have as few as one spectral band, as in the case of a single-band and single-camera system, or as many as hundreds of bands, as in a hyperspectral imaging system. The three-camera imaging system used in this study had two visible bands and one NIR band and was capable of obtaining CIR imagery. Not all the bands in a composite image are effective for differentiating among treatments. As shown in this study, the green and red bands were useful, while the NIR band was not. Vegetation indices derived from the individual bands can be more informative than the individual bands themselves. NDVI as used in this study was effective for separating the treatments. Although the optimal individual band images or combinations of band images may vary with cotton varieties, cultural systems, and soil and environmental conditions, it is clear that the remote sensing-based method illustrated in this study can be used to evaluate the effectiveness of different defoliation treatments under various conditions.

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Table 1. Defoliant and insecticide treatments for two cotton fields in 2001.

Treatment	Defoliant	Insecticide
1. Control		
2. Def+Dropp+Guthion	Def (half rate)+ Dropp (half rate)	Guthion (half rate)
3. Def+Dropp	Def (half rate)+ Dropp (half rate)	
4. Dropp+Guthion	Dropp (full rate)	Guthion (full rate)
5. Def+Guthion	Def (full rate)	Guthion (half rate)
6. Def+Karate	Def (full rate)	Karate (half rate)
7. Guthion		Guthion (full rate)
8. Karate		Karate (full rate)

[1] Full rate of Def = 2 pt/ac or 2.34 L/ha; full rate of Dropp = 0.2 lb/ac or 224 g/ha; full rate of Guthion = 0.25 lb AI/ac or 280 g AI/ha; and full rate of Karate = 0.033 lb AI/ac or 37 g AI/ha.

Table 2. Mean digital values of spectral variables among eight treatments based on airborne image data obtained on July 30, 2001, six days after chemical application, for field 1.

Treatment	NIR	Red	Green	NDVI
1. Control	156	83 c	115 c	0.310 a
2. Def+Dropp+Guthion	165	140 a	160 a	0.085 c
3. Def+Dropp	163	137 a	156 a	0.086 c
4. Dropp+Guthion	172	120 b	146 b	0.177 b
5. Def+Guthion	170	113 b	140 b	0.204 b
6. Def+Karate	167	114 b	140 b	0.188 b
7. Guthion	167	87 c	118 c	0.318 a
8. Karate	155	81 c	112 c	0.316 a

[1] Means within a column followed by the same letter are not significantly different at the 0.05 probability level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.
[2] NIR: df=7, F=2.12, p=0.1095, no LSD test.
[3] Red: df=7, F=44.22, p<0.0001, LSD=10.6.
[4] Green: df=7, F=35.33, p<0.0001, LSD=9.6.
[5] NDVI: df=7, F=24.18, p<0.0001, LSD=0.0597.

Table 3. Mean digital values of spectral variables among eight treatments based on airborne image data obtained on August 17, 2001, three days after chemical application, for field 2.

Treatment	NIR	Red	Green	NDVI
1. Control	173	68 bc	74 b	0.442 ab
2. Def+Dropp+Guthion	169	86 a	85 a	0.331 c
3. Def+Dropp	169	85 a	85 a	0.335 c
4. Dropp+Guthion	184	69 bc	75 b	0.458 ab
5. Def+Guthion	171	72 b	76 b	0.408 b
6. Def+Karate	166	81 a	82 a	0.345 c
7. Guthion	172	62 bc	69 c	0.469 a
8. Karate	170	68 c	73 bc	0.434 ab

[1] Means within a column followed by the same letter are not significantly different at the 0.05 probability level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.
[2] NIR: df =7, F=2.02, p=0.1250, no LSD test.
[3] Red: df =7, F=11.97, p<0.0001, LSD=7.8.
[4] Green: df =7, F=12.96, p<0.0001, LSD=5.0.
[5] NDVI: df=7, F=8.59, p=0.0004, LSD=0.0595.

Table 4. Mean digital values of spectral variables among eight treatments based on airborne image data obtained on August 20, 2001, six days after chemical application, for field 2.

Treatment	NIR	Red	Green	NDVI
1. Control	130	45 d	65 d	0.487 a
2. Def+Dropp+Guthion	121	100 a	100 a	0.096 d
3. Def+Dropp	126	103 a	104 a	0.103 d
4. Dropp+Guthion	136	65 c	78 c	0.354 b
5. Def+Guthion	131	75 b	86 b	0.271 c
6. Def+Karate	121	77 b	87 b	0.222 c
7. Guthion	133	46 d	65 d	0.486 a
8. Karate	126	44 d	64 d	0.477 a

[1] Means within a column followed by the same letter are not significantly different at the 0.05 probability level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.
[2] NIR: df =7, F=2.05, p=0.1195, no LSD test.
[3] Red: df =7, F=170.13, p<0.0001, LSD=5.5.
[4] Green: df =7, F=120.11, p<0.0001, LSD=4.3.
[5] NDVI: df=7, F=58.74, p<0.0001, LSD=0.0652.

Table 5. Mean digital values of spectral variables among eight treatments based on airborne image data obtained on August 23, 2001, nine days after chemical application, for field 2.

Treatment	NIR	Red	Green	NDVI
1. Control	159	99 c	120 d	0.237 a
2. Def+Dropp+Guthion	153	158 a	153 a	-0.017 d
3. Def+Dropp	155	161 a	157 a	-0.019 d
4. Dropp+Guthion	170	127 b	135 c	0.148 b
5. Def+Guthion	164	133 b	140 bc	0.108 bc
6. Def+Karate	153	134 b	141 b	0.070 c
7. Guthion	163	101 c	118 d	0.241 a
8. Karate	156	101 c	119 d	0.219 a

[1] Means within a column followed by the same letter are not significantly different at the 0.05 probability level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.
[2] NIR: df =7, F=1.93, p=0.1405, no LSD test.
[3] Red: df =7, F=129.71, p<0.0001, LSD=6.6.
[4] Green: df =7, F=84.06, p<0.0001, LSD=5.1.
[5] NDVI: df=7, F=30.62, p<0.0001, LSD=0.0584.

Table 6. Mean numbers of leaves per plant and percent defoliation relative to the control among eight treatments based on ground observations from 10 plants within each plot six days after application in 2001 for fields 1 and 2.

	Field 1		Field 2	
Treatment	Percent per plant	Leaves defoliation	Leaves per plant	Percent defoliation
1. Control	38.6 a	0.0 c	53.2 a	0.0 a
2. Def+Dropp+Guthion	2.5 c	93.6 a	1.9 d	96.4 d
3. Def+Dropp	3.6 c	90.7 a	3.1 d	94.2 d
4. Dropp+Guthion	12.8 b	66.8 b	17.2 c	67.7 c
5. Def+Guthion	15.5 b	59.8 b	15.0 c	71.8 c
6. Def+Karate	10.7 b	72.3 b	18.5 c	65.2 c
7. Guthion	38.1 a	1.3 c	48.7 ab	8.5 ab
8. Karate	36.9 a	4.4 c	45.8 b	13.9 b

[1] Percent defoliation = [(leaves per plant for control - leaves per plant) / leaves per plant for control] * 100.
[2] Means within a column followed by the same letter are not significantly different at the 0.05 probability level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.
[3] Leaves per plant for field 1: df=7, F=95.39, p<0.0001, LSD=4.8.
[4] Leaves per plant for field 2: df=7, F=98.71, p<0.0001, LSD=6.3.

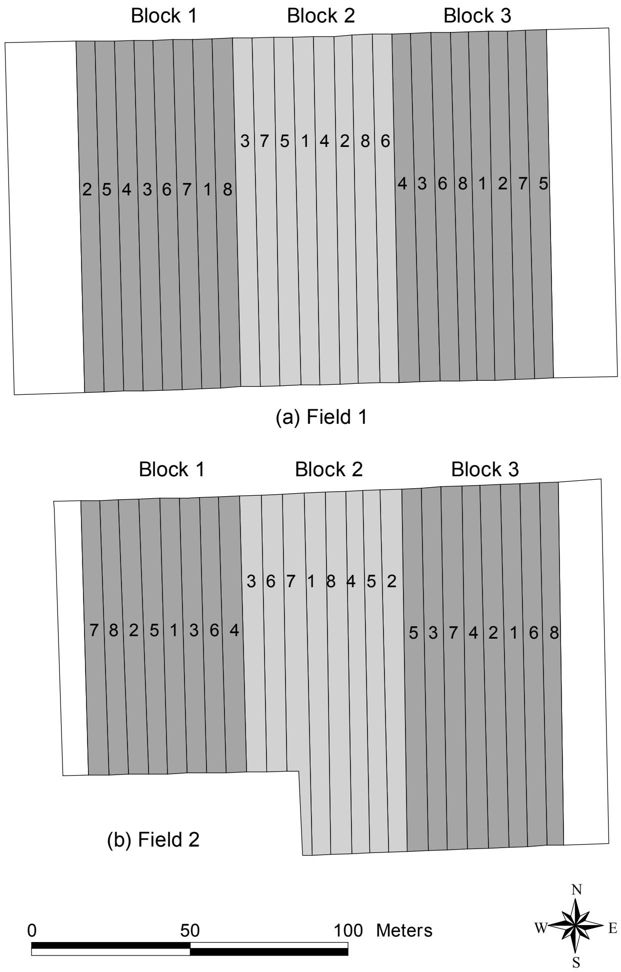

Figure 1. Layout of eight treatments (one control and seven combinations of defoliants and insecticides) in three blocks across 24 experimental plots in randomized complete block designs for two cotton fields in 2001.

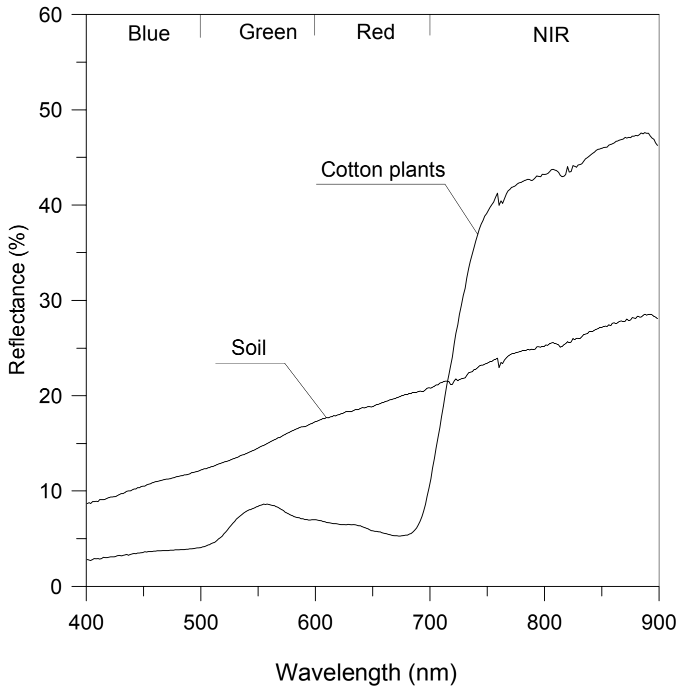

Figure 2. Typical reflectance curves for cotton plants and bare soil in the visible (400-700 nm) to NIR (700-900 nm) region of the spectrum.

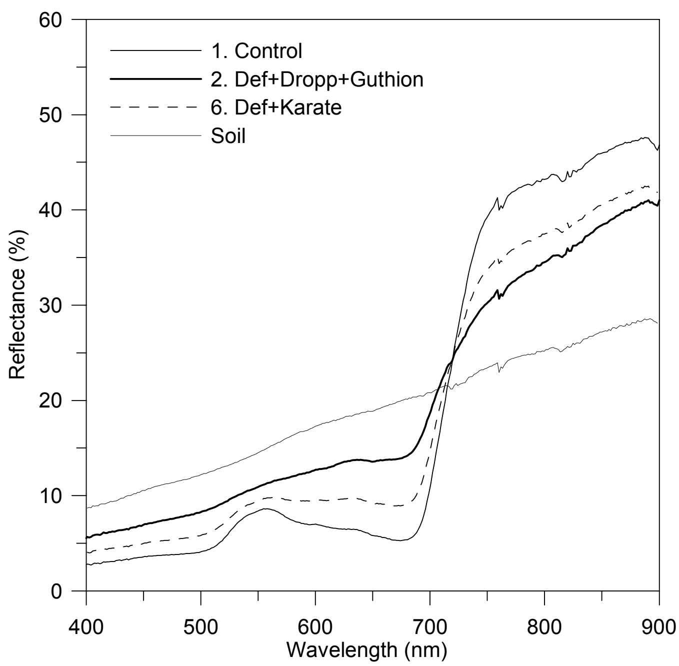

Figure 3. Reflectance spectra of cotton plants obtained on August 20, 2001, three days after chemical application, for three treatments in field 2. For comparison, the spectrum for bare soil in the field is also shown.

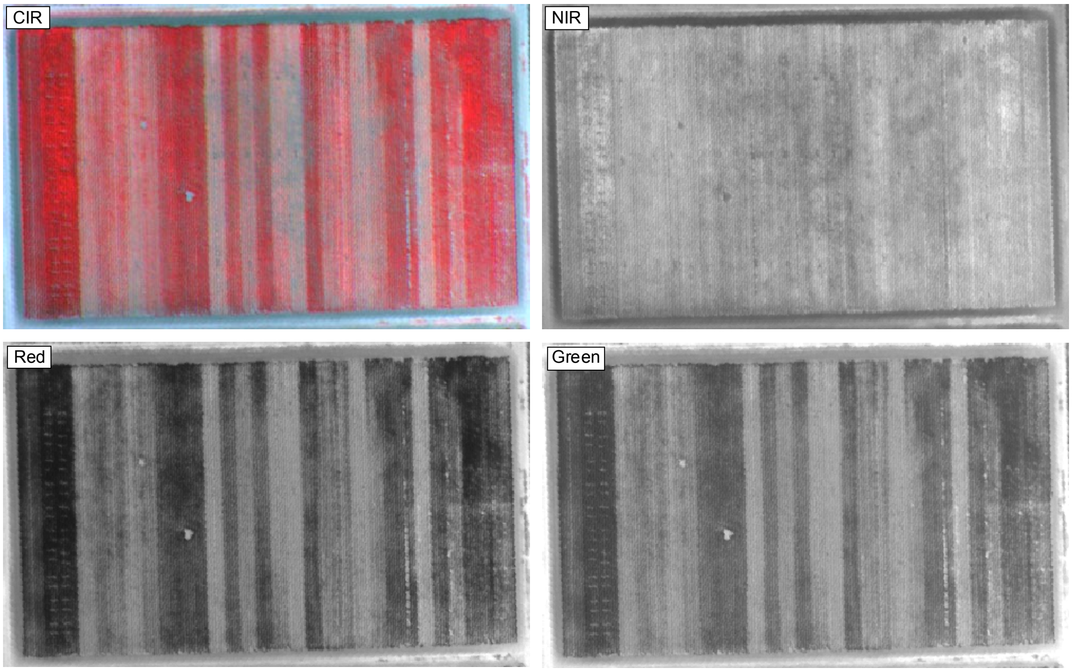

Figure 4. CIR composite image and its three band components acquired on July 30, 2001, six days after chemical application, for field 1.

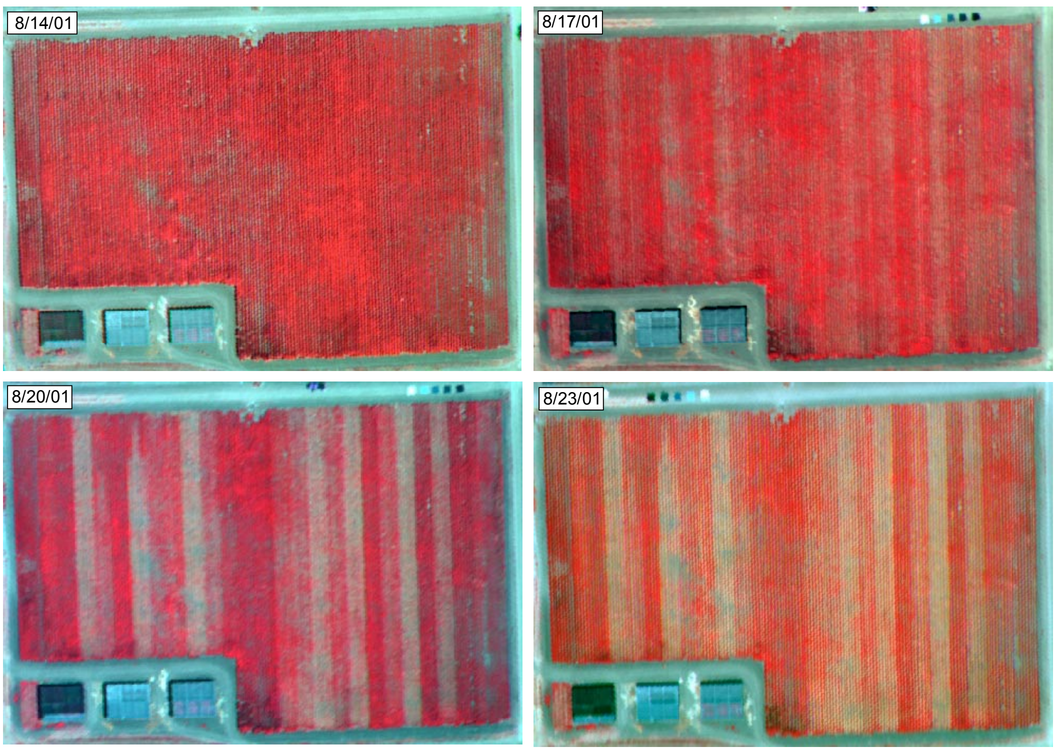

Figure 5. CIR composite images taken on four equally-spanned dates beginning on the day of chemical application for field 2.