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ASSESSING COTTON REGROWTH AFTER HERBICIDE TREATMENTS USING REMOTE SENSING

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Abstract

Cotton (*Gossypium hirsutum* L.) regrowth control with herbicides provides an alternative method for post-harvest destruction of cotton stalks. Field experiments were conducted in 2002 and 2003 to assess the effectiveness of different herbicide treatments for cotton regrowth control using remote sensing technology. Eight treatments (combinations of herbicides and application timings) and six treatments were evaluated in 2002 and 2003, respectively, with each experiment arranged in a randomized complete block design. Airborne multispectral imagery was acquired from the test plots in both years shortly before the state-mandated date for cotton stalk destruction. Ground reflectance spectra and plant visual ratings were also obtained from each experimental plot simultaneously. The reflectance spectra were able to detect differences in regrowth among some of the treatments. The airborne imagery permitted visual differentiation among some of the treatments. For quantitative analysis, the green, red, and near-infrared bands of the multispectral imagery and four vegetation indices derived from the three bands were used as spectral variables to compare the differences among the treatments for each experiment. Statistical analysis showed that the seven spectral variables were able to identify the differences among the treatments as detected by the ground observations. Results also indicated that the herbicide, 2,4-D (Savage), applied to shredded stalks at 1.12 kg formulation per hectare (1 lb/ac) twice within a one-month period provided excellent regrowth control.

Introduction

Under ideal environmental conditions, cotton (*Gossypium hirsutum* L.) plants can regrow following harvest and generate hostable fruit in three to four weeks for boll weevil (*Anthonomous grandis* Boheman) feeding and reproduction (Bremer, 1999; Lemon et al., 2003). Therefore, cotton stalk destruction following harvest is an important cultural practice for managing overwintering boll weevils and other insects such as the silverleaf whitefly (*Bemisia argentifolii* Bellows and Perring) and the pink bollworm (*Pectinophora gossypiella*). Stalk destruction is more important in the southern and eastern portions of Texas, especially in the Rio Grande Valley, where warmer temperatures and rainfall favor cotton regrowth. The Cotton Pest Control Law in Texas requires that producers in each regulated zone plant and destroy cotton within an authorized period (Texas Department of Agriculture, 2002). For example, in the Lower Rio Grande Valley of Texas, cotton can be planted after 1 February and must be destroyed by 1 September each year. To meet the state regulations, many producers choose to plow cotton stalks to eliminate unwanted regrowth, while others choose to shred the stalks and then disk or plow them. These mechanical methods are generally successful. However, recent increases in conservation tillage practices permit alternative methods, such as herbicides, for cotton stalk destruction.

Sparks et al. (2002) evaluated the efficacy of Savage® (2,4-D) and Harmony Extra® for post harvest cotton stalk destruction. Both herbicides performed better when applied to shredded stalks than to standing stalks. Savage applied to shredded cotton appeared to provide excellent regrowth control, while Harmony Extra delayed but did not prevent regrowth. Norman et al. (2003) conducted greenhouse and field experiments to evaluate 2,4-D and other herbicides under different application timings for cotton regrowth control. Results indicated that 2,4-D applied to shredded stalks twice during a 30-day period was 100% effective in terminating stalks.

Although a few studies have been conducted to identify effective herbicides as well as their application rates and timings for cotton stalk destruction, continued research is necessary to determine the best approaches and their reliability under different environmental conditions. To evaluate the effectiveness of various regrowth control methods, Sparks et al. (2002) used visual ratings and plant physical measurements to quantify the differences among several stalk destruction treatments. This approach seems to be simple and workable, but it is subjective and has not been standardized among investigators. Moreover, it can be time-consuming if a large number of treatments over an extensive area are involved. From the perspective of remote sensing, different levels of cotton regrowth from shredded cotton stalks can be characterized by the spectral response of the regrowth. Therefore, spectral characteristics of the regrowth may be used to quantify the amount of regrowth, thus differentiating the effectiveness among various herbicide treatments. Yang et al. (2003b) successfully evaluated the effectiveness of different cotton defoliation methods using airborne multispectral imagery. Yang et al. (2003a) conducted a preliminary field experiment to evaluate different cotton regrowth control treatments using remote sensing. The objectives of this study were: 1) to further examine ground reflectance spectra and airborne multispectral imagery for quantifying cotton regrowth as compared with traditional visual observations; and 2) to evaluate the effectiveness of different herbicide treatments for regrowth control.

Materials and Methods

Experimental Design

One field experiment was conducted in 2002 and another in 2003 for this study. The 2002 experiment was conducted on an irrigated cotton field located at “Hiler” Annex Farm of the Texas Agricultural Research and Extension Center at Weslaco, Texas. Cotton (cultivar Stoneville 4892 BR) was planted to the field on 20 February. Eight treatments (combinations of two herbicides and four application timings) were assigned to four blocks in a randomized complete block design (Figure 1). Cotton plants within each plot and the control area were shredded at 8-10 cm from the soil surface with a two-row rotary shredder immediately after harvest on 22 July. The plots within each block were 4 rows (4.1 m) wide and 15 m long and separated by two rows of standing (non-shredded) cotton as a buffer, while the blocks were separated by approximately 4 m wide alleys of standing cotton. The herbicides used were 2,4-D (Savage brand) (Dimethylamine salt of 2,4-dichlorophenoxyacetic acid, Platte Chemical Company, Greeley, Colorado) and dicamba (Clarity brand) (Diglycolamine salt of 3,6-dichloro-o-anisic acid, BASF Corporation, Research Triangle Park, North Carolina). Application rates for the herbicides were 1.12 kg formulation per hectare (1 lb/ac) of 2,4-D and 1.17 L formulation per hectare (1 pt./ac) of dicamba. Each herbicide was mixed with water to form a spray solution of 93.5 L/ha (10 gal/ac). There were four application timings for each herbicide: less than 24 hours after shredding (D0), 3 days after shredding (D3), 1 week (D7) and 2 weeks (D14) after shredding. The herbicide application dates were 23 July (approximately 14 hours after shredding), 25, 29 July, and 5 August. A second application with 1.12 kg/ha of 2,4-D was made to all plots on 20 August (D29). A two-row Spider Spray Trac sprayer (West Texas Lee Company, Inc., Idalou, Texas) was used to apply the herbicides to the plots on the designated dates.

The 2003 field experiment was conducted on an irrigated cotton field located at the South Research Farm of the USDA-ARS Kika de la Garza Subtropical Agricultural Research Center at Weslaco, Texas. Cotton (cultivar Deltapine 50) was planted to the field on 17 March. Six treatments were assigned to four blocks in a randomized complete block design (Figure 2). Cotton plants within each plot and the control area were shredded at 8-10 cm from the soil surface immediately after harvest on 23 July. The plots were 4 rows (4.1 m) wide and 38 m long and separated by two rows of standing (non-shredded) cotton as a buffer. The herbicides used were 2,4-D (Savage brand) and AIM (Carfentrazone-ethyl, FMC Corporation, Philadelphia, Pennsylvania). Application rates for the herbicides were 1.12 kg formulation per hectare (1 lb/ac) of 2,4-D and 0.84 kg formulation per hectare (0.75 lb/ac) of AIM. Each herbicide was mixed with water to form a spray solution of 93.5 L/ha (10 gal/ac). There were four application timings: less than 24 hours after shredding (D0), 1 week (D7), 2 weeks (D14), and 4 weeks (D28) after shredding. Treatments 1 and 2 had one 2,4-D application on D0 and D7, respectively, while treatments 3 and 4 had a second 2,4-D application on D14 and D28, respectively, in addition to the first 2,4-D application on D0. Treatments 5 and 6 included a combination of 2,4-D and AIM applied at two different times. After receiving a combination of both herbicides on D0, treatments 5 and 6 had a second application of both herbicides on D7 and D14, respectively. The herbicide application dates were 24, 31 July, 7 and 21 August.

Collection of Ground Reflectance Spectra, Airborne Imagery and Visual Ratings

Ground reflectance spectra were collected using a FieldSpec HandHeld spectroradiometer (Analytical Spectral Devices, Inc., Boulder, Colorado) on 27 August 2002 (36 days after shredding) for experiment 1 and on 27 August 2003 (35 days after shredding) for experiment 2. The spectroradiometer was sensitive in the visible to near-infrared (NIR) portion of the spectrum (350-1050 nm) with a spectral sampling interval of 1.4 nm. Spectra were taken on five randomly selected canopies from each plot and each spectrum was an average of 10 sample spectra over each canopy. The spectroradiometer had a field of view angle of 25°and was held at 1 m above the canopy during data collection, resulting in a circular target area of 44 cm in diameter.

Airborne color-infrared (CIR) digital imagery was acquired using a digital imaging system described by Escobar et al. (1997) from the two cotton fields on the same dates ground reflectance data were taken for both years. The imaging system consisted of three Kodak MegaPlus digital charge coupled device (CCD) cameras. The imaging system was upgraded from its original configuration to enhance acquisition speed and take advantage of the full resolution of the cameras. The enhanced system had the capability of obtaining images with 1280×1024 pixels as compared with the 1024×1024 pixels the old system had. The cameras were sensitive in the visible to NIR regions (400-1000 nm) and had a built-in analog-to-digital (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. A Cessna 206 aircraft was used to acquire imagery at an altitude of approximately 460 m between 1200 and 1400h local time under sunny conditions. The ground pixel size achieved was approximately 0.2 m. For radiometric calibration of the imagery, four 8 m by 8 m tarpaulins with nominal reflectance values of 4, 16, 32 and 48%, respectively, were placed near the fields during image acquisition. The actual reflectance values from the tarpaulins were measured using the FieldSpec spectroradiometer.

Plant regrowth in each plot was visually rated on a 1-to-5 scale based on ground observations. The ratings are as follows: 1-no live plants; 2-some plants alive, but exhibit herbicide damage; 3-most plants alive, but exhibit herbicide damage; 4-some plants appear healthy; and 5-most plants appear healthy.

Imagery Processing and Calculation of Vegetation Indices
The NIR and green band images in each CIR composite were registered to the red band image to correct the misalignments among the three bands. The registered band images were converted to reflectance based on three calibration equations (one for each band) relating reflectance values to the digital count values on the four tarpaulins. Image registration and calibration were performed using ERDAS IMAGINE 8.6 (ERDAS, Inc., Atlanta, Georgia). Reflectance values of the regrowth within each plot were extracted from hundreds of pixels on each band image along the cotton rows, and the average of the pixel values was considered as the reflectance for the band within the plot. Four vegetation indices were calculated from the three bands to measure vegetation vigor and abundance. Two of the vegetation indices were band ratios defined as

$$NR = NIR/Red \quad (1)$$
$$NG = NIR/Green \quad (2)$$

The other two were normalized differences (ND) defined as:

$$NDNR = (NIR-Red)/(NIR+Red) \quad (3)$$
$$NDNG = (NIR-Green)/(NIR+Green) \quad (4)$$

NDNR is commonly referred to as the normalized difference vegetation index (NDVI).

Statistical Analysis
The five ground reflectance spectra collected from each plot were averaged to produce a mean reflectance spectrum for the plot. Analyses of variance were performed on the seven spectral variables and the visual rating index. Multiple comparisons on means were made using Fisher's protected least significant difference (LSD) procedure. Correlation coefficients between the visual rating and each of the seven spectral variables were determined. All statistical analyses were performed using SAS (SAS Institute Inc., Cary, North Carolina).

Results and Discussion

Reflectance Spectra of Cotton Regrowth
Figure 3 presents the reflectance spectra of cotton regrowth, measured 36 days after stalk shredding, for the eight herbicide treatments in the 2002 experiment. For clarity, the spectra are shown in four separate graphs by initial application timing. The spectra for the control and bare soil are also shown in each graph for comparison. The spectrum for the control had the shape of a typical spectral curve for normal healthy plants and the spectrum for bare soil was close to a straight line. If the regrowth is lush and abundant, the spectrum for the regrowth will be close to that for the control; otherwise, the spectrum will be close to the soil spectrum. This spectral behavior is the basis for the separation of different levels of cotton regrowth. The spectra for all treatments in 2002 were closer to the soil spectrum than to the control spectrum (Figure 3), indicating that all herbicide treatments significantly limited cotton regrowth. In fact, the regrowth in the control plots was healthy and had a width of approximately one half of the row spacing at the time of reflectance data collection, while the regrowth in all plots treated with herbicides exhibited obvious injury and had a width ranging from zero (no regrowth) to less than a quarter of the row spacing. As mentioned early, the spectroradiometer covered a circular area with a diameter of 44 cm, which was about 43% of the row spacing and much larger than the width of the regrowth in all treatment plots. Therefore, the spectra for all treatments were mainly the spectral response from the soil background. Nevertheless, the regrowth in all treatments caused the spectra to deviate slightly from the soil spectrum. Based on the levels of deviation, the four treatments with two 2,4-D applications were more effective than the other four treatments with an initial dicamba application followed by a 2,4-D application (Figure 3). Moreover, the four treatments with the initial 2,4-D applications at the four different timings were almost equally effective, while the treatments with the initial dicamba applications 3 days and 7 days after shredding were slightly more effective than those with the initial dicamba applications immediately and 14 days after shredding.

Figure 4 presents the reflectance spectra of cotton regrowth, measured 35 days after stalk shredding, for the six treatments in the 2003 experiment. Similarly, the spectra are shown in three graphs and the spectra for the control and bare soil are also shown in each graph. Unlike 2002, the 2003 reflectance spectra for the six treatments deviate significantly from the soil spectrum. This apparent deviation was due to the heavy residue cover present in the experimental plots in 2003. In the 2002 experiment cotton plants were defoliated and harvested before being shredded, but in the 2003 experiment the plants were neither defoliated nor harvested before being shredded. Much of the ground was covered with shredded cotton stalks. Since the cotton residues had lower spectral reflectance than bare soil in the visible to NIR region, the spectra taken from the plots were below the soil spectrum. Nevertheless, the spectra for all six treatments resembled the soil spectrum more than the control spectrum (Figure 4), indicating that all treatments had a significant effect on regrowth control. However, the spectra for the two treatments with only one 2,4-D application (Figure 4a) had an obvious concaved shape deviating from that of the soil spectrum, indicating the two treatments had more regrowth and were not as effective as the other four treatments (Figures 4b and 4c). Besides, there were no apparent differences between the two treatments with two applications of 2,4-D (Figure 4b) or between the two treatments with two applications of 2,4D and AIM (Figure 4c). Ground reflectance spectra can be a useful tool for differentiating the effectiveness of various herbicide treatments. However, it is not always easy to obtain reliable spectra because of spatial variability within the treatments, limited amounts of regrowth, and variations in the field of view of the spectroradiometer. To minimize the effects of these factors, many spectral samples are needed to obtain accurate and reliable spectra.

Visual Comparisons of Herbicide Treatments with Digital Imagery

Figure 5 shows a CIR image acquired from the experimental plots on 27 August 2002, 36 days after cotton stalks were shredded. The eight rows of plant stalks at the bottom of the image (the south side of the field) were not shredded after harvest and new leaves regrew on the original stalks. The plants in the control were the regrowth from shredded stalks without any herbicide treatment, though some of the rows in the control were sprayed during equipment adjustment. The regrowth from the eight non-shredded rows and the control area was healthy and vegetative and appeared bright red on the CIR image. The buffers separating the plots were not as vegetative because of the drift from the herbicide applications, but they had a reddish tone and could be easily identified on the image. Because of the limited amount of regrowth in the treatment plots, most of the plots had a grayish and light bluish color. The only regrowth that could be seen on the image was from the plots treated with 2,4-D following an initial application of dicamba, respectively, 14 hours and 14 days after shredding (treatments 1 and 7). The regrowth in these plots was small compared with the control, but it was large enough to show a reddish tone along the rows in the image. The regrowth in the plots for the other six treatments was so small and unhealthy that it was extremely difficult to visualize the differences among these treatments.

Figure 6 shows a CIR image acquired from the experimental plots on 27 August 2003, 35 days after cotton stalks were shredded. The non-shredded plants (buffers) between the plots, which were very healthy and vegetative, had a very bright red color on the image. The regrowth from shredded stalks in the control area appeared red, while the regrowth from the treatment plots had a dark brownish color, which was mainly due to the cotton residues on the soil surface. Since the regrowth in all plots was very small, the differences among the treatments can hardly be visualized from the image. Nevertheless, the images from both the 2002 and 2003 experimental plots contained digital spectral data concerning the cotton regrowth for each treatment. This quantitative spectral information can be used to statistically determine the differences among the treatments for each of the two experiments.

Comparisons of Herbicide Treatments Using Spectral Indices

Table 1 shows the comparisons of means for the seven spectral variables (three bands and four vegetation indices) among the eight herbicides treatments based on the CIR image taken 36 days after cotton stalks were shredded in the 2002 experiment. The means for visual ratings are also shown in the table. Although the NIR band did not identify any significant difference among the treatments, the red and green bands and the four vegetation indices detected two significantly different groups among the eight treatments. The regrowth from treatments 1 and 7, which had an initial dicamba application, respectively, 14 hours and 14 days after shredding, had lower reflectance values in the red and green bands and higher values for the four vegetation indices than the regrowth from the other six treatments. As indicated by the spectra in Figures 3 and 4, more cotton regrowth would have lower reflectance in the red and green bands and higher reflectance in the NIR band. Thus, treatments 1 and 7 had more cotton regrowth than the other treatments based on the reflectance values from the red and green bands. Also from equations 1-4, when there was more cotton regrowth, all four vegetation indices would have higher values because more regrowth would result in higher NIR reflectance and lower red and green reflectance. Based on the four vegetation indices, the same result was obtained, indicating treatments 1 and 7 were not as effective as the other six treatments. However, no statistical differences were detected between treatments 1 and 7, nor were significant differences found among treatments 2, 3, 4, 5, 6 and 8. These results generally agreed with those from the visual analysis of the spectra and the airborne CIR imagery.

Three statistically distinct groups were identified based on the visual rating. As detected by the image data, treatments 1 and 7 had a significantly higher visual rating than the other six treatments. However, the visual rating further separated the six treatments into two groups with treatments 3 and 5 as one and treatments 2, 4, 6, and 8 as the other. Treatments 3 and 5, which had an initial dicamba application, respectively, 3 days and 7 days after shredding, had slightly higher rating values than treatments 2, 4, 6, and 8, which had an initial 2,4-D application, respectively, 14 hours, 3 days, 7 days, and 14 days after shredding. Although the image data separated the treatments into only two groups statistically, the general trend of the spectral values agreed very well with the ground visual rating values. In fact, the correlation coefficients between the visual rating and each of the six spectral variables were -0.972 for the red band, -0.966 for the green band, 0.974 for NR, 0.967 for NG, 0.976 for NDVI, and 0.968 for NDNG. Based on the results of the 2002 experiment, 2,4-D applied to shredded cotton stalks at 1.12 kg formulation per hectare twice within a one-month period provided excellent regrowth control, while dicamba applied at 1.17 L formulation per hectare followed by a 2,4-D application was not as effective.

Table 2 shows the comparisons of means for the seven spectral variables among the six herbicides treatments based on the CIR image taken 35 days after cotton stalks were shredded in the 2003 experiment. The visual rating values are also shown in the table. All seven spectral variables were able to detect significant differences among the six treatments. However, there were no such clearly defined groups in the 2003 experiment as seen in 2002. Among the seven spectral variables, only the band ratio, NR, and the normalized difference vegetation index, NDVI, gave the identical separation results. Nevertheless, the comparison results from all the spectral variables revealed that treatments 1 and 2 had the most regrowth, followed by treatments 4 and 5, and treatments 3 and 6 had the least regrowth. No significant difference was found between treatment 3 (two applications of 2,4-D 14 hours and 14 days after shredding) and treatment 6 (two applications of 2,4-D and AIM 14 hours and 14 days after shredding). These results generally agreed well with the ground observations. A correlation analysis indicated that the visual rating was highly related to each of the seven spectral variables, and the correlation coefficients were 0.922 for the NIR band, -0.975 for the red band, -0.976 for the green band, 0.971 for NR, 0.998 for NG, 0.966 for NDVI, and 1.000 for NDNG. Both treatments 3 and 6 offered excellent regrowth control, but treatment 3 including only 2,4-D was less expensive, and therefore a better choice, than treatment 6, which included both 2,4-D and AIM.

Summary and Conclusions

This study demonstrates that remotely sensed data, including ground reflectance spectra and airborne multispectral imagery, can be used to assess the effectiveness of different herbicide treatments for cotton stalk destruction. Ground spectra offer spectral observations over continuous wavelengths at selected sites, and they can differentiate among the treatments when a sufficient number of spectra are captured to represent the ground conditions. Airborne multispectral digital imagery provides a continuous view of the imaging area at selected wavelength bands and has the potential for quick visual comparisons among the treatments. Moreover, airborne imagery contains spectral information for every area of the field and allows quantitative separations of the treatments using the reflectance values in the individual bands and/or the vegetation indices derived from these bands. Although both ground spectra and airborne imagery provide useful information concerning cotton regrowth, limited ground measurements and observations are necessary to validate the remote sensing results. Compared with traditional methods, the remote sensing-based approach is more objective and efficient, especially if many treatments are to be evaluated over large areas.

Results from the two field experiments also indicate that both herbicide type and application timing will affect the effectiveness of cotton regrowth control. An initial application of either 2,4-D or dicamba followed by a second application of 2,4-D significantly reduced cotton regrowth, but 2,4-D applied twice within a one-month period provided excellent regrowth control for cotton stalk destruction.

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Table 1. Comparisons of means for seven spectral variables and one visual rating variable among eight herbicide treatments based on airborne color-infrared image and ground rating data obtained 36 days after cotton stalks were shredded in a field in 2002.

Treatment	NIR (%)	Red (%)	Green (%)	NR	NG	NDVI	NDNG	Visual Rating
1. Dicamba (D0) + 2,4-D (D29)	22.7a	15.6a	11.4a	1.456a	2.002a	0.185a	0.333a	3.00a
2. 2,4-D (D0) + 2,4-D (D29)	22.7a	18.0b	13.1b	1.265b	1.737b	0.117b	0.269b	1.38c
3. Dicamba (D3) + 2,4-D (D29)	22.7a	17.3b	12.6b	1.321b	1.807b	0.136b	0.285b	2.13b
4. 2,4-D (D3) + 2,4-D (D29)	22.9a	18.1b	13.2b	1.267b	1.740b	0.117b	0.269b	1.50c
5. Dicamba (D7) + 2,4-D (D29)	22.7a	17.6b	12.7b	1.289b	1.786b	0.126b	0.282b	2.00b
6. 2,4-D (D7) + 2,4-D (D29)	22.6a	17.7b	12.8b	1.279b	1.774b	0.121b	0.278b	1.50c
7. Dicamba (D14) + 2,4-D (D29)	22.7a	15.9a	11.5a	1.436a	1.983a	0.178a	0.329a	3.00a
8. 2,4-D (D14) + 2,4-D (D29)	22.6a	17.8b	12.8b	1.271b	1.775b	0.119b	0.278b	1.50c

[1] D0, D3, D7, D14, and D29 represent applying herbicides 14 hours, 3 days, 7 days, 14 days, and 29 days, respectively, after cotton stalks were shredded.
[2] NR = NIR/Red, NG = NIR/Green, NDVI = (NIR-Red)/(NIR+Red), and NDNG = (NIR-Green)/(NIR+Green).
[3] Rating scale: 1-no live plants; 2-some plants alive, but exhibit herbicide damage; 3-most plants alive, but exhibit herbicide damage; 4-some plants appear healthy; and 5-most plants appear healthy.
[4] Means within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.

Table 2. Comparisons of means for seven spectral variables and one visual rating variable among six herbicide treatments based on airborne color-infrared image and ground rating data obtained 35 days after cotton stalks were shredded in a field in 2003.

Treatment	NIR (%)	Red (%)	Green (%)	NR	NG	NDVI	NDNG	Visual Rating
1. 2,4-D (D0)	21.1a	9.4a	7.6ab	2.253a	2.784ab	0.385a	0.471ab	2.40ab
2. 2,4-D (D7)	21.2a	9.3a	7.4a	2.272a	2.871a	0.388a	0.482a	2.58a
3. 2,4-D (D0+D14)	20.1b	9.8ab	8.3cd	2.051c	2.430cd	0.344c	0.416cd	1.40cd
4. 2,4-D (D0+D28)	21.3a	9.5ab	8.0bc	2.237ab	2.670b	0.382ab	0.454b	2.10abc
5. 2,4-D+AIM (D0+D7)	20.7ab	9.6ab	8.2cd	2.161b	2.532c	0.367b	0.434c	1.75bcd
6. 2,4-D+AIM (D0+D14)	20.1b	10.0b	8.5d	2.008c	2.369d	0.335c	0.405d	1.25d

[1] D0, D7, D14, and D28 represent applying herbicides 14 hours, 7 days, 14 days, and 28 days, respectively, after cotton stalks were shredded.
[2] NR = NIR/Red, NG = NIR/Green, NDVI = (NIR-Red)/(NIR+Red), and NDNG = (NIR-Green)/ (NIR+Green).
[3] Rating scale: 1-no live plants; 2-some plants alive, but exhibit herbicide damage; 3-most plants alive, but exhibit herbicide damage; 4-some plants appear healthy; and 5-most plants appear healthy.
[4] Means within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected LSD procedure following an analysis of variance on a randomized complete block design.

Control	Block 1	Block 2	Block 3	Block 4
	1	5	8	4
	5	4	2	6
	2	1	3	8
	3	6	5	3
	4	7	1	2
	8	3	4	7
	7	2	6	5
	6	8	7	1

Treatment
1. Dicamba (D0) + 2,4-D (D29)
2. 2,4-D (D0) + 2,4-D (D29)
3. Dicamba (D3) + 2,4-D (D29)
4. 2,4-D (D3) + 2,4-D (D29)
5. Dicamba (D7) + 2,4-D (D29)
6. 2,4-D (D7) + 2,4-D (D29)
7. Dicamba (D14) + 2,4-D (D29)
8. 2,4-D (D14) + 2,4-D (D29)

Figure 1. Layout of eight herbicide treatments across four blocks in a randomized complete block design on a cotton field in 2002. Application rates were 1.12 kg formulation per hectare (1 lb/ac) of 2,4-D and 1.17 L formulation per hectare (1 pt./ac) of dicamba. D0, D3, D7, D14, and D29 represent applying herbicides 14 hours, 3 days, 7 days, 14 days, and 29 days, respectively, after cotton stalks were shredded.

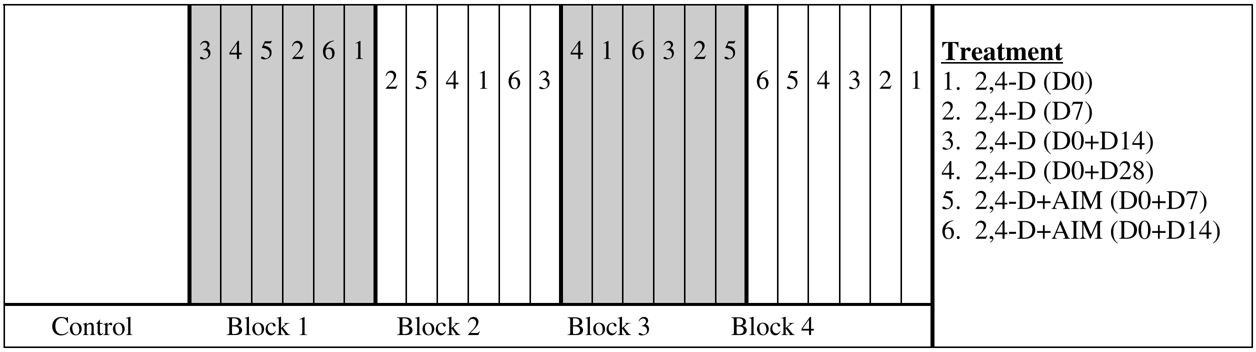

Figure 2. Layout of six herbicide treatments across four blocks in a randomized complete block design on a cotton field in 2003. Application rates were 1.12 kg formulation per hectare (1 lb/ac) of 2,4-D and 0.84 kg formulation per hectare (0.75 lb/ac) of AIM. D0, D7, D14, and D28 represent applying herbicides 14 hours, 7 days, 14 days, and 28 days, respectively, after cotton stalks were shredded.

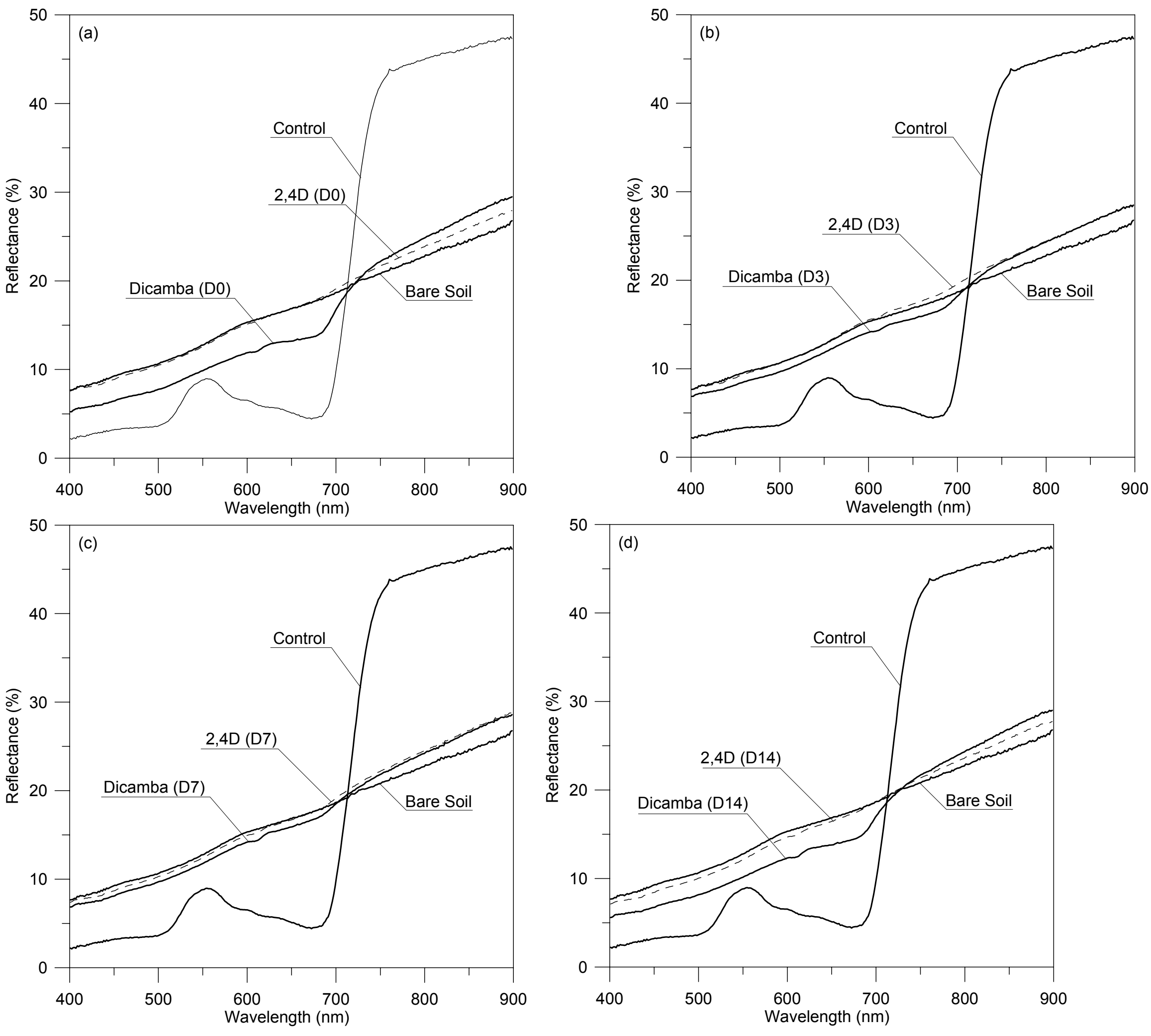

Figure 3. Reflectance spectra of cotton regrowth, measured 36 days after stalk shredding, for eight herbicide treatments for the 2002 experiment. The spectra for the control and bare soil are also shown for comparison. D0, D3, D7, and D14 represent the herbicides were initially applied, respectively, 14 hours, 3 days, 7 days, and 14 days after cotton stalks were shredded. A second application of 2,4-D was made to all treatments 29 days after cotton stalks were shredded.

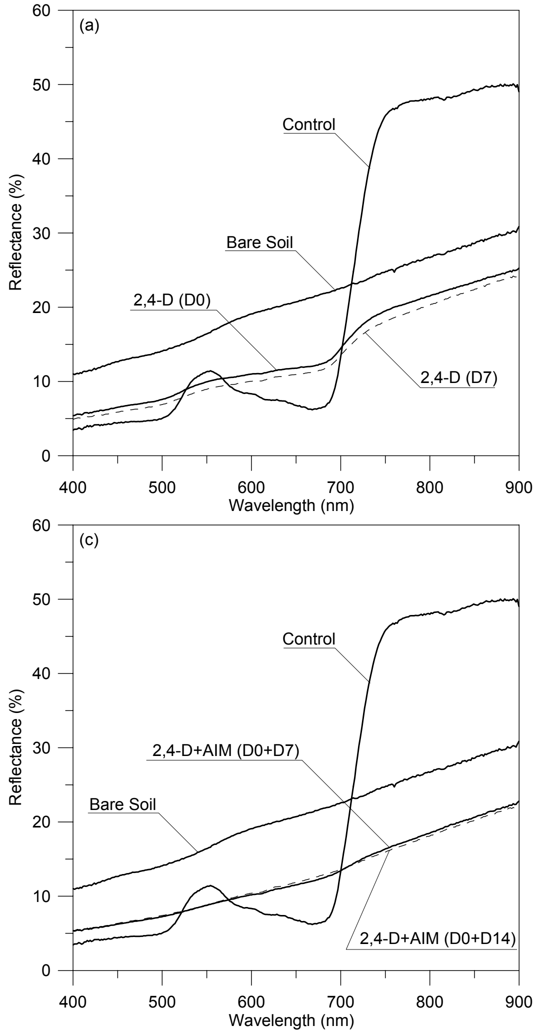

Figure 4. Reflectance spectra of cotton regrowth, measured 35 days after stalk shredding, for six herbicide treatments for the 2003 experiment. The spectra for the control and bare soil are also shown for comparison. D0, D7, D14, and D28 represent the herbicides were applied, respectively, 14 hours, 7 days, 14 days, and 28 days after cotton stalks were shredded.

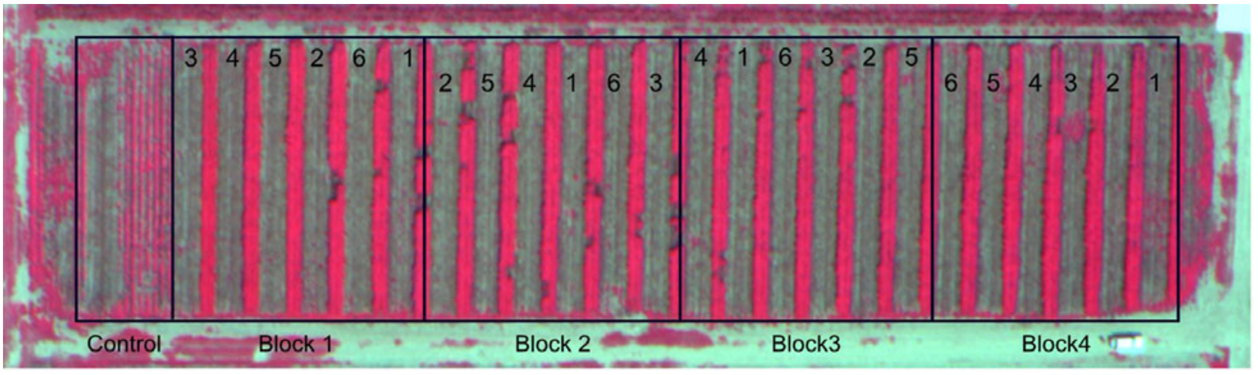

Figure 5. Color-infrared digital image of a cotton field acquired 36 days after cotton stalks were shredded in 2002. Treatment numbers are defined in Figure 1. Each experiment plot consisted of four shredded rows (grayish color) separated by two rows of standing stalks (reddish color).

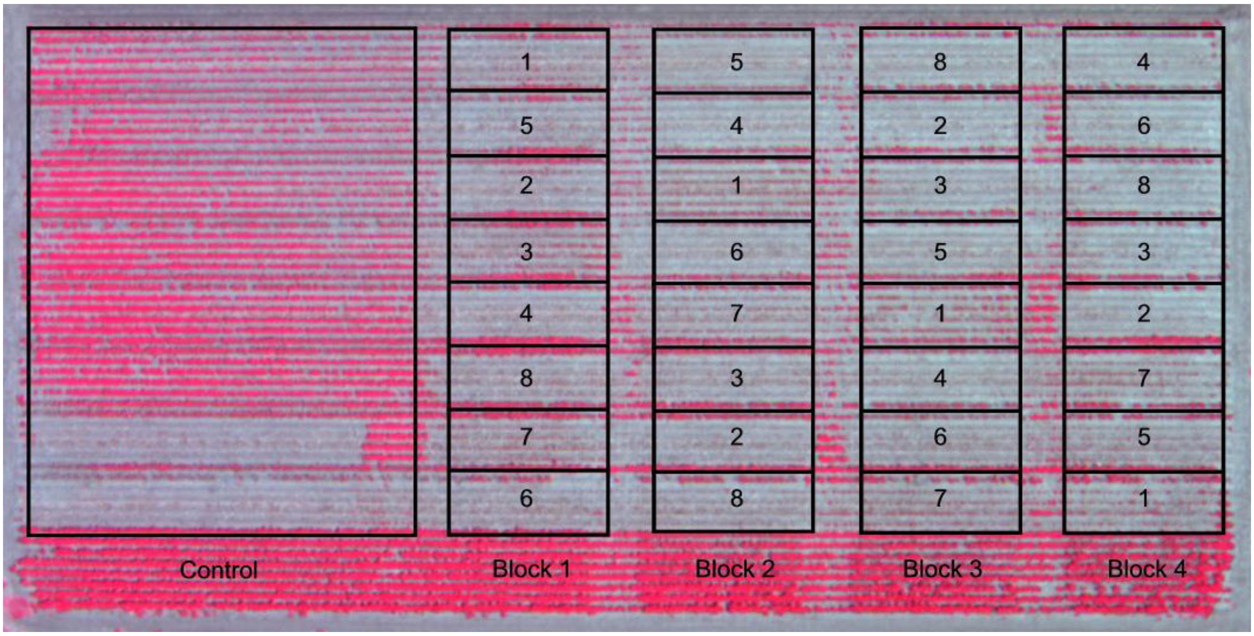

Figure 6. Color-infrared digital image of a cotton field acquired 35 days after cotton stalks were shredded in 2003. Treatment numbers are defined in Figure 2. Each experiment plot consisted of four shredded rows (brownish color) separated by two rows of standing stalks (bright red color).