The *Journal of Cotton Science 10:136–145 (2006)*
http://journal.cotton.org, © The Cotton Foundation 2006

WEED SCIENCE

Assessing Cotton Stalk Destruction with Herbicides Using Remote Sensing Technology

Chenghai Yang*, Shoil M. Greenberg, James H. Everitt, and John W. Norman, Jr.

ABSTRACT

Control of cotton stalk regrowth with herbicides on standing or shredded cotton provides an alternative method for post-harvest destruction of cotton stalks. Field experiments were conducted in 2002 and 2003 in the Rio Grande Valley of south Texas to assess the effectiveness of different herbicide treatments for cotton regrowth control using remote sensing technology. Eight treatments (combinations of herbicides and application timings) in 2002 and six treatments in 2004 arranged in a randomized complete block were evaluated on shredded cotton plots. Airborne color-infrared (CIR) imagery was acquired from the test plots in both years shortly before the state-mandated date for cotton destruction. Ground reflectance spectra and visual ratings ranging from no live plants to mostly healthy plants were also obtained from each plot. The reflectance spectra showed differences in regrowth among the treatments. The airborne CIR imagery provided limited visual differentiation among the treatments because of the small amount of regrowth. For quantitative analysis, the green, red, and near-infrared bands of the CIR 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 spectral variables were able to identify the differences among the treatments as detected by the ground observations.

Under ideal environmental conditions, cotton (*Gossypium hirsutum* L.) plants can regrow following harvest and generate fruit suitable for boll weevil (*Anthonomus grandis grandis* Boheman) feeding and reproduction in three to four weeks (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* (Saunders)] (Normal et al., 2003). Stalk destruction is important in the southern and eastern portions of Texas, especially in the Rio Grande Valley of south Texas, where warmer temperatures and rainfall favor cotton regrowth. The Cotton Pest Control Law in Texas requires producers to plant and destroy cotton within an authorized period in each regulated zone (Texas Department of Agriculture, 2006). In the Rio Grande Valley of Texas, cotton can be planted after 1 February and must be destroyed by 1 September each year.

The boll weevil eradication programs recently implemented in the Rio Grande Valley and other Texas counties may help eliminate the boll weevil in the future, but cotton stalk destruction remains an important part of the eradication programs and is still enforced by the Texas law. Even after boll weevils are eliminated, stalk destruction will still be a preventive measure to keep this insect from reinfesting. To meet state regulations, many producers choose to plow cotton stalks to eliminate unwanted regrowth, while others choose to shred stalks and then disk or plow them. These mechanical methods are generally successful, but recent increases in conservation tillage practices require alternative methods, such as herbicide application, for cotton stalk destruction.

Sparks et al. (2002) evaluated the efficacy of 2,4-D and thifensulfuron plus tribenuron for post-harvest cotton stalk destruction. Both herbicides performed more effectively when applied to shredded stalks than to standing stalks. Application of 2,4-D to shredded cotton provided excellent regrowth control, while thifensulfuron plus tribenuron delayed but did not prevent regrowth. Norman et al. (2003) conducted greenhouse and field experiments to evaluate 2,4-D

C. Yang, S. M. Greenberg, and J.H. Everitt, USDA-ARS Kika de la Garza Subtropical Agricultural Research Center, 2413 East Highway 83, Weslaco, TX 78596; J. W. Norman, Jr.. Texas A&M University, Texas Agricultural Research and Extension Center, 2415 East Highway 83, Weslaco, TX 78596
* Corresponding author: cyang@weslaco.ars.usda.gov

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-d period was 100% effective in terminating stalks.

Although a few studies have been conducted to identify effective herbicides and their application rates and timings for cotton stalk destruction, continued research is necessary to determine optimal 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. The ratings were defined 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. This approach is simple and workable, but it is subjective and has not been standardized among investigators, and it can be time-consuming if a large number of treatments over an large area are involved. Spectral reflectance and vegetation indices derived from remote sensing data, such as the normalized difference vegetation index (NDVI), have been widely used to quantify crop growth conditions (Tucker et al., 1980; Wiegand and Richardson, 1984; Yang and Anderson, 1999). Therefore, spectral characteristics of cotton regrowth may be used to quantify the amount of regrowth and to differentiate 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) also conducted a preliminary field experiment to evaluate different herbicide-based cotton regrowth control treatments using remote sensing. The objective of this study was to further examine remote sensing techniques, including ground reflectance spectra and airborne color-infrared (CIR) digital imagery, for assessing the effectiveness of different herbicide treatments for cotton regrowth control.

MATERIALS AND METHODS

Experimental design. One field experiment was conducted in 2002 and another in 2003. 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, TX. Stoneville 4892 BR (STV 4892 BR; Stoneville Pedigreed Seed Co.; Memphis, TN) cotton was planted on 20 February. The field was defoliated on 12 July and harvested on 22 July. Eight treatments (combinations of two herbicides and four application timings) were assigned to four blocks in a randomized complete block design. Cotton plants within each plot and the reference area were shredded at 8-10 cm above the soil surface with a two-row rotary shredder immediately after harvest. The plots within each block were four rows (4.1 m) wide with 1.02 m between rows and 15 m long. Plots were separated by two rows of standing (non-shredded) cotton as a buffer. The blocks were separated by approximately 4-m wide alleys of standing cotton. Herbicides used were 2,4-D (Savage; Platte Chemical Company; Greeley, CO) and dicamba (Clarity; BASF Corporation; Research Triangle Park, NC). Application rates for the herbicides were 1.06 kg ai/ha of 2,4-D and 0.82 kg ai/ha of dicamba. Each herbicide was mixed with water to yield a spray solution of 93.5 L/ha. There were four application timings for each herbicide as follows: less than 24 h (D1), 3 d (D3), 7 d (D7), and 14 d (D14) after shredding. Herbicide application dates were 23, 25, and 29 July and 5 August. A second application of 1.06 kg ai/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, TX) was used to apply all treatments.

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, TX. Deltapine 50 (DPL 50; Delta Pine and Land Co.; Scott, MS) cotton was planted on 17 March. Due to late planting, the field was not ready for harvest approximately 6 wk before the state-mandated date for cotton destruction. In order to have enough time for the experiment, cotton plants in the field were shredded without defoliation or harvest. Six treatments were assigned to four blocks in a randomized complete block design. Plants within each plot and the reference area were shredded at 8-10 cm above the soil surface on 23 July. The plots were four rows (4.1 m) wide and 38 m long and separated by two rows of standing (non-shredded) cotton as a buffer. Herbicides used were 2,4-D (Savage; Platte Chemical Company; Greeley, CO) and carfentrazone (Aim; FMC Corporation; Philadelphia, PA). Application rates for the herbicides were 1.06 kg ai/ha of 2,4-D and 0.34 kg ai/ha of carfentrazone. Each herbicide was mixed with water to yield a spray solution of 93.5 L/ha. There were four application timings as follows: 14 h (D1), 7 d (D7), 14 d (D14), and 28 d (D28) after shredding. Treatments 1 and 2 had one 2,4-D application at D1 and D7, respectively. Treatments 3 and 4 had a second 2,4-D application on D14 and D28, respectively, in addition to the first application on D1. Treatments 5 and 6 had an initial application of 2,4-D plus carfentrazone on D1, followed by a second application of both herbicides on D7 and D14, respectively. Herbicide application dates were 24 and 31 July and 7 and 21 August.

Collection of ground reflectance spectra, airborne imagery, and visual rating data. Ground reflectance spectra were collected using a FieldSpec HandHeld spectroradiometer (Analytical Spectral Devices, Inc.; Boulder, CO) on 27 Aug. 2002 (36 d after shredding) for experiment 1 and on 27 Aug. 2003 (35 d 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 nominal 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 row during data collection, resulting in a circular target area 44 cm in diameter. Reflectance measurements were made between 1230 h and 1430 h local time under sunny conditions.

Airborne CIR digital imagery was acquired from the two cotton fields on the same dates ground reflectance data were taken using an imaging system described by Escobar et al. (1997). The imaging system consisted of three Kodak MegaPlus digital charge coupled device (CCD) cameras (Rochester, NY). 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. 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 h and 1400 h local time under sunny conditions. The ground pixel size achieved was approximately 0.2 m. For radiometric calibration of the imagery, four tarpaulins (8 m x 8 m) 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 spectroradiometer. For ground verification, cotton regrowth in each plot was visually rated on a 1 to 5 scale defined by Sparks et al. (2002) 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.

Image 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 of the four tarpaulins. Image registration and calibration were performed using ERDAS IMAGINE 8.6 software (ERDAS, Inc.; Atlanta, GA). To extract reflectance values from the imagery, a rectangular area covering the most abundant regrowth along a row among all the treatments was first defined. The rectangle was then overlaid on each row within a plot and reflectance values for each of the three bands were extracted. The average of the extracted reflectance values from the four rows within each plot was considered as the reflectance value for the plot. Three mean reflectance values were derived from each plot, one for each of the three bands. Four vegetation indices were calculated from the reflectance values for the three bands to measure vegetation vigor and abundance (Yang and Everitt, 2002). Two of the vegetation indices were band ratios defined as NR = NIR/Red and NG = NIR/Green. The other two were the NDVI and the green NDVI (GNDVI) defined as NDVI = (NIR-Red)/(NIR+Red) and GNDVI = (NIR-Green)/(NIR+Green).

Statistical analysis. Analysis of variance was performed on the seven spectral variables (three bands and four vegetation indices) and visual rating for each experiment. Multiple comparisons on means were made using Fisher's protected least significant difference (LSD) procedure. Correlation coefficients between visual rating and each of the seven spectral variables were determined. All statistical analyses were performed using SAS (SAS Institute Inc.; Cary, NC).

RESULTS AND DISCUSSION

Reflectance spectra of cotton regrowth. Reflectance spectra of regrowth for the eight herbicide treatments in the 2002 experiment are shown in Figure 1. For dicamba, the spectra are shown in four separate graphs. The spectra for normal regrowth (without herbicide treatment) and bare soil are also shown in each graph for comparison. The spectrum for normal regrowth had the shape of a typical spectral curve for healthy plants (Campbell, 1987), and the spectrum for bare soil was essentially a straight line. If regrowth for a treatment is lush and abundant, the spectrum for the regrowth will be similar to that for normal regrowth; otherwise, the spectrum will be similar to that of the soil. 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 spectrum of normal growth (Fig. 1), indicating that all herbicide treatments significantly limited cotton regrowth. Based on field observations, normal regrowth in the

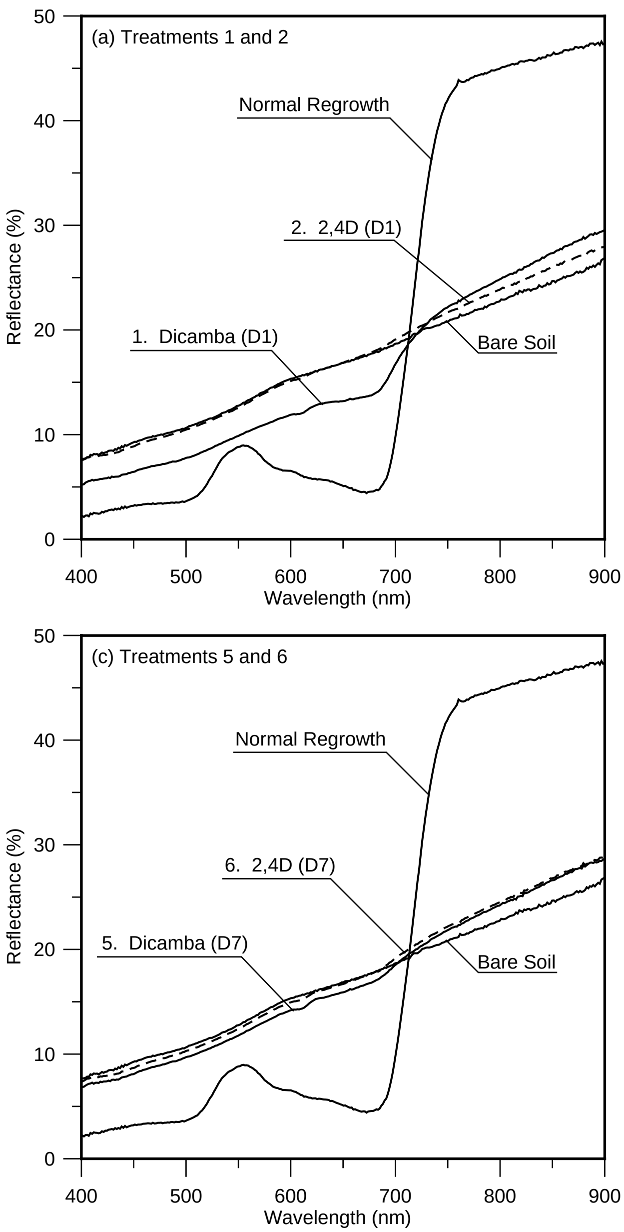
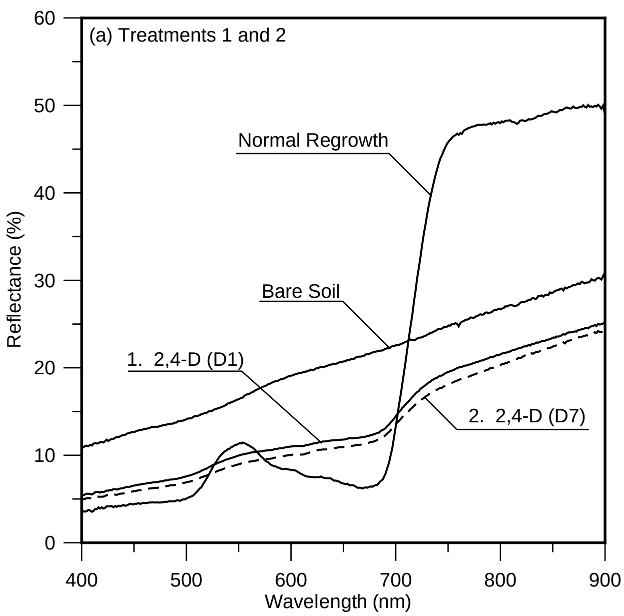


Figure 1. Reflectance spectra of cotton regrowth measured 36 d after stalk shredding for the eight herbicide treatments in the 2002 experiment. The spectra for normal regrowth and bare soil are also shown for comparison. D1, D3, D7, and D14 represent applying herbicides initially 14 h, 3 d, 7 d, and 14 d after cotton stalks were shredded, respectively. A second application of 2,4-D was made to all treatments 29 d after cotton stalks were shredded.

untreated reference area was healthy and had a width of approximately one half of the row spacing at the time of reflectance data collection, while regrowth in all plots treated with herbicides exhibited obvious injury and had a width ranging from zero (no regrowth) to slightly more than a quarter of the row spacing. As mentioned previously, 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 the treatment plots. The spectra for all the treatments were mainly the spectral response from the soil background. Nevertheless, 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 (treatments 2, 4, 6 and 8) were more effective than the four treatments with an initial dicamba application followed by a 2,4-D application (Fig. 1). 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 d and 7 d after shredding seemed to be slightly more effective than those with the initial dicamba applications immediately and 14 d after shredding.

Reflectance spectra of regrowth for the six treatments in the 2003 experiment are shown in Figure 2. The spectra are shown in three graphs and the spectra for normal regrowth and bare soil are also presented in each graph. Unlike in the 2002 experiment, the spectra for the six treatments in 2003 deviate significantly from the soil spectrum. This apparent deviation was due to 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 plants were neither defoliated nor harvested before being shredded. Much of the ground was covered with shredded cotton stalks. Since cotton residues had lower spectral reflectance than bare soil in the visible



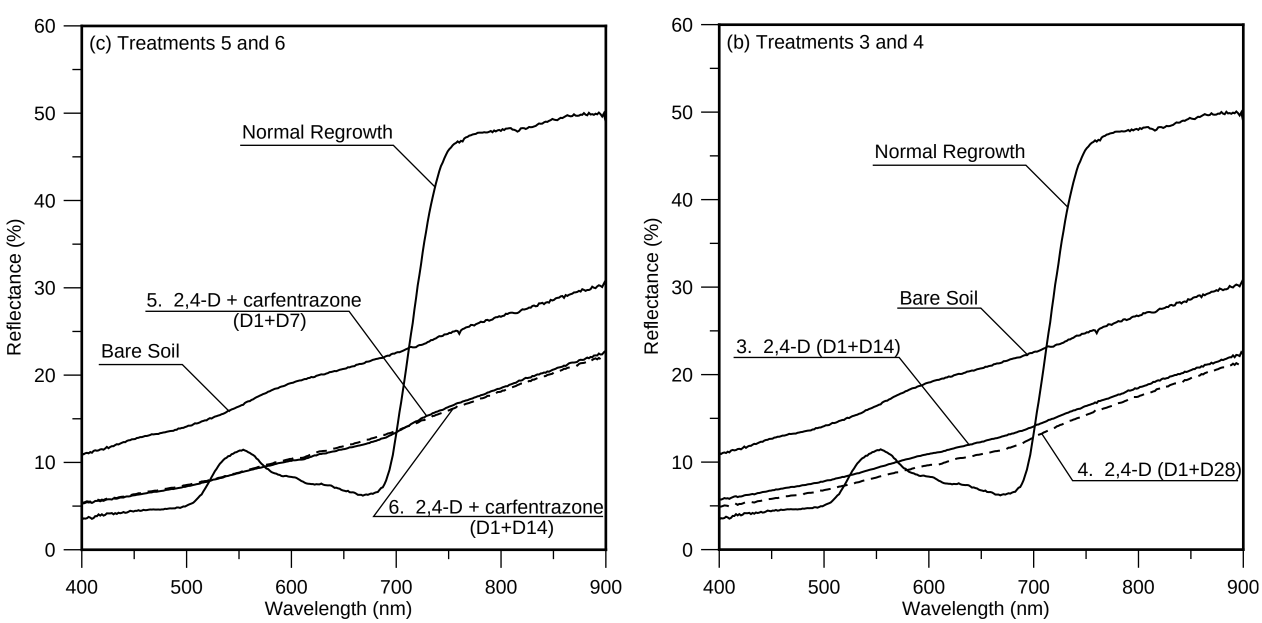


Figure 2. Reflectance spectra of cotton regrowth measured 35 d after stalk shredding for the six herbicide treatments for the 2003 experiment. The spectra for normal regrowth and bare soil are also shown for comparison. D1, D7, D14, and D28 represent applying herbicides 14 h, 7 d, 14 d, and 28 d after cotton stalks were shredded, respectively.

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 spectrum for normal regrowth (Fig. 2), indicating that all treatments significantly limited regrowth. Based on ground measurements, regrowth in the untreated area had a width of approximately one half of the row spacing, while the regrowth in all treated plots exhibited severe injury and had a width ranging from zero (no regrowth) to less than a quarter of the row spacing. The spectra for the two treatments with only one 2,4-D application (Fig. 2a) appeared to have a 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 (Fig. 2b and 2c). There were no apparent differences between the two treatments with two applications of 2,4-D (Fig. 2b) or between the two treatments with two applications of 2,4D plus carfentrazone (Fig. 2c). Ground reflectance spectra can be a useful tool for differentiating the effectiveness of various herbicide treatments, but spectral measurements can be easily affected by spatial variability within treatments, limited amounts of regrowth, and variations in the field of view of the spectroradiometer. To minimize the effects of these factors, a large number of spectral samples are needed to obtain accurate and reliable spectra.

Visual comparisons of herbicide treatments using airborne CIR digital imagery. A CIR image acquired from the experimental plots on 27 Aug. 2002, 36 d after cotton stalks were shredded is shown in Figure 3. Eight rows of cotton plants 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. Plants in the untreated reference area were regrowth from shredded stalks without any herbicide treatment, although some of the rows in the area were sprayed during equipment adjustment (lower left). Vegetative regrowth from the eight non-shredded rows and the untreated area was healthy and appeared bright red on the CIR image. The buffers separating the plots were not as vegetative because of the drift from herbicide applications, but had a reddish tone and could be easily identified on the image. Regrowth in the treatment plots was generally small and had a blue-gray color, and regrowth for treatments 1 and 7 could be distinguished from the other treatments on the image. Regrowth in these plots was large enough to show a reddish tone along the rows in the image. Regrowth for the other six treatments was so small and unhealthy that it was extremely difficult to differentiate among them.

A CIR image acquired from the experimental plots on 27 Aug. 2003, 35 d after cotton stalks were

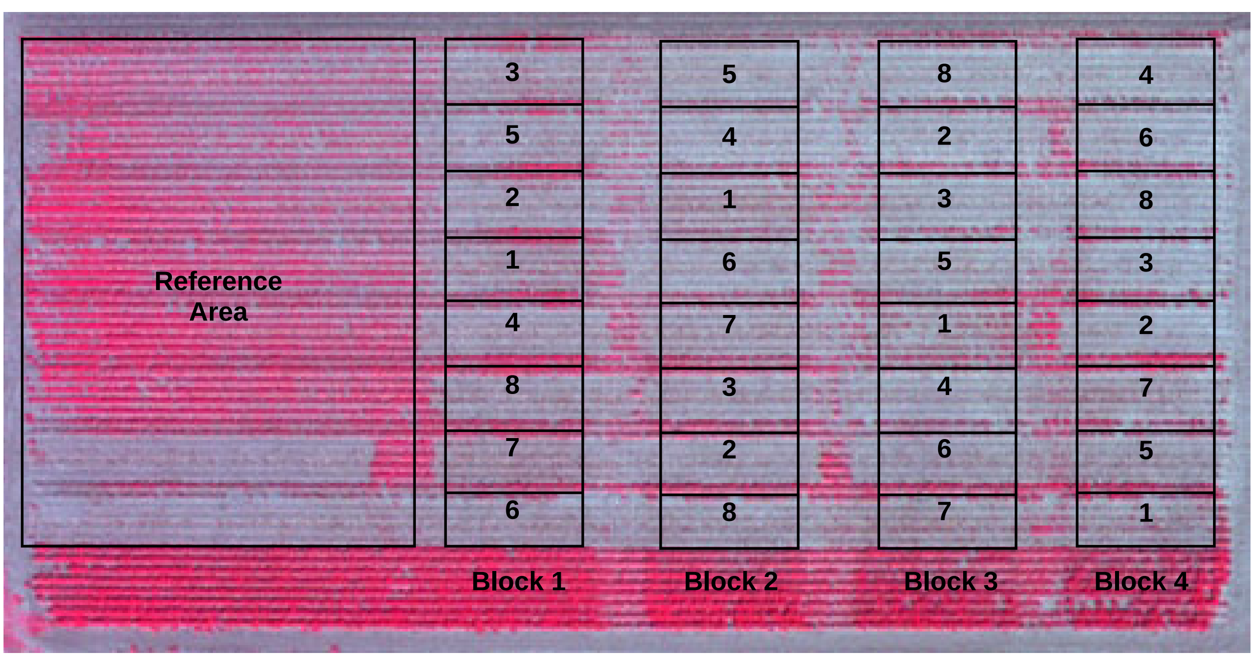


Figure 3. Color-infrared digital image of a cotton field acquired 36 d after cotton stalks were shredded in 2002. Application rates were 1.06 kg ai/ha of 2,4-D and 0.82 kg ai/ha of dicamba. D1, D3, D7, D14, and D29 represent applying herbicides 14 h, 3 d, 7 d, 14 d, and 29 d after cotton stalks were shredded, respectively. Each experiment plot consisted of four shredded rows (blue-gray) separated by two rows of standing stalks (red).

shredded is shown in Figure 4. Non-shredded plants (buffers) between the plots, which were healthy and vegetative, had a very bright red color on the image. Regrowth from shredded stalks in the untreated area appeared red, while regrowth from the treated plots had a green-gray color, mainly due to the cotton residues on the soil surface. Since regrowth in all plots was very small, the differences among the treatments could hardly be distinguished from the image. Nevertheless, the images from both the 2002 and 2003 experimental plots contained quantitative digital spectral data concerning regrowth for each treatment that was used to statistically determine the differences among the treatments for each of the two experiments.

Comparisons of herbicide treatments using spectral indices. Comparisons of means for the seven spectral variables (three bands and four vegetation indices) among the eight herbicide treatments based on the CIR image taken 36 d after cotton stalks were shredded in the 2002 experiment are shown in Table 1. Means for visual rating 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. Regrowth from treatments 1 and 7, which had an initial dicamba application 14 h and 14 d after shredding, respectively, had lower reflectance values in the red and green bands and higher values

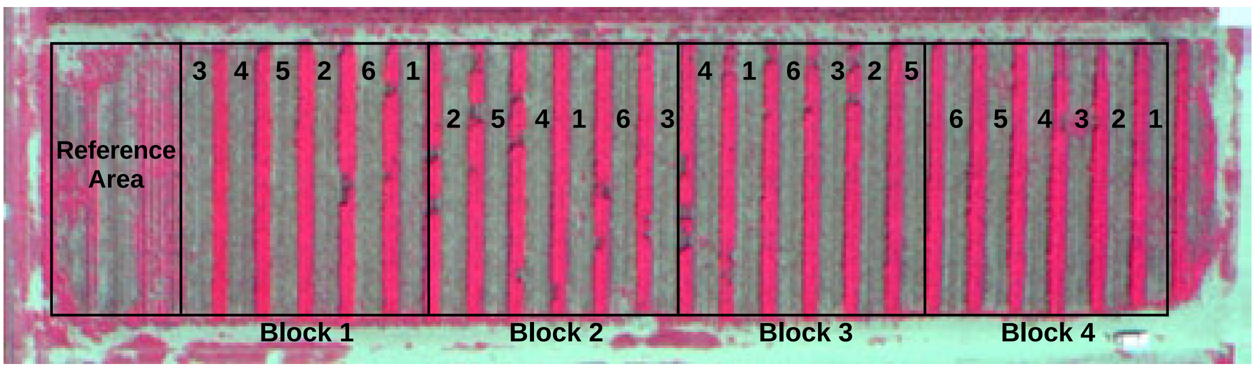


Figure 4. Color-infrared digital image of a cotton field acquired 35 d after cotton stalks were shredded in 2003. Application rates were 1.06 kg ai/ha of 2,4-D and 0.34 kg ai/ha of carfentrazone. D1, D7, D14, and D28 represent applying herbicides 14 h, 7 d, 14 d, and 28 d after cotton stalks were shredded, respectively. Each experiment plot consisted of four shredded rows (green-gray) separated by two rows of standing stalks (red).

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

Treatment[x]	Spectral variable[y]							Visual rating[z]
	NIR (%)	Red (%)	Green (%)	NR	NG	NDVI	GNDVI	
1. Dicamba (D1) + 2,4-D (D29)	22.7 a	15.6 a	11.4 a	1.456 a	2.002 a	0.185 a	0.333 a	3.0 a
2. 2,4-D (D1) + 2,4-D (D29)	22.7 a	18.0 b	13.1 b	1.265 b	1.737 b	0.117 b	0.269 b	1.4 c
3. Dicamba (D3) + 2,4-D (D29)	22.7 a	17.3 b	12.6 b	1.321 b	1.807 b	0.136 b	0.285 b	2.1 b
4. 2,4-D (D3) + 2,4-D (D29)	22.9 a	18.1 b	13.2 b	1.267 b	1.740 b	0.117 b	0.269 b	1.5 c
5. Dicamba (D7) + 2,4-D (D29)	22.7 a	17.6 b	12.7 b	1.289 b	1.786 b	0.126 b	0.282 b	2.0 b
6. 2,4-D (D7) + 2,4-D (D29)	22.6 a	17.7 b	12.8 b	1.279 b	1.774 b	0.121 b	0.278 b	1.5 c
7. Dicamba (D14) + 2,4-D (D29)	22.7 a	15.9 a	11.5 a	1.436 a	1.983 a	0.178 a	0.329 a	3.0 a
8. 2,4-D (D14) + 2,4-D (D29)	22.6 a	17.8 b	12.8 b	1.271 b	1.775 b	0.119 b	0.278 b	1.5 c

[x] D1, D3, D7, D14, and D29 represent applying herbicides 14 h, 3 d, 7 d, 14 d, and 29 d after cotton stalks were shredded, respectively. Application rates were 1.06 kg ai/ha of 2,4-D and 0.82 kg ai/ha of dicamba.

[y] Spectral variables: NR = Near-infrared (NIR)/Red, NG = NIR/Green, NDVI = (NIR-Red)/(NIR+Red), and GNDVI = (NIR-Green)/(NIR+Green). Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD ($P = 0.05$).

[z] Visual rating on a scale of 1-5, where 1 = no live plants, 2 = some plants alive, but exhibiting herbicide damage, 3 = most plants alive, but exhibiting herbicide damage, 4 = some plants appear healthy, and 5 = most plants appear healthy.

for the four vegetation indices than regrowth from the other six treatments. As indicated by the spectra in Figures 1 and 2, more regrowth would have lower reflectance in the red and green bands and higher reflectance in the NIR band. Treatments 1 and 7 had more regrowth than the other treatments based on the reflectance values from the red and green bands. Also, from the formulas for the four vegetation indices, when there was more regrowth, all the vegetation indices would have higher values because more regrowth would result in higher NIR reflectance and lower red and green reflectance. The four vegetation indices provided the same differentiation among the treatments as the red and green bands, indicating treatments 1 and 7 were not as effective as the other treatments. Statistical differences were not detected between treatments 1 and 7 or 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 among the eight treatments based on visual rating. As detected by the image data, treatments 1 and 7 had a significantly higher visual rating than the other six treatments. The six treatments were further separated into two groups; treatments 3 and 5 in one group and treatments 2, 4, 6, and 8 in the other group. Treatments 3 and 5, which had an initial dicamba application 3 d and 7 d after shredding, respectively, had slightly higher visual rating values than treatments 2, 4, 6, and 8, which had an initial 2,4-D application 14 h, 3 d, 7 d, and 14 d after shredding, respectively. Although the image data did not separate treatments 3 and 5 from treatments 2, 4, 6, and 8 at the 0.05 probability level, the spectral values coincided with the ground visual rating values. In fact, the correlation coefficients between 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 GNDVI. Based on the results of the 2002 experiment, 2,4-D applied to shredded cotton stalks at 1.06 kg ai/ha twice within a one-month period provided excellent regrowth control, while dicamba applied at 0.82 kg ai/ha followed by a 2,4-D application was not as effective.

Comparisons of means for the seven spectral variables and visual rating among the six herbicide treatments based on the CIR image taken 35 d after cotton stalks were shredded in the 2003 experiment are shown in Table 2. All seven spectral variables detected significant differences among the six treatments, but there were no clearly defined groups as seen in 2002. Based on vegetation indices NR and NDVI, treatment 3 (two applications of 2,4-D 14 h and 14 d after shredding) and treatment 6 (two applications of 2,4-D plus carfentrazone 14 h and 14 d after shredding) had less regrowth and were more effective than the other four treatments, although no significant difference was found between treatments

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

Treatment[x]	Spectral variables[y]							Visual rating[z]
	NIR (%)	Red (%)	Green (%)	NR	NG	NDVI	GNDVI	
1. 2,4-D (D1)	21.1 a	9.4 a	7.6 ab	2.253 a	2.784 ab	0.385 a	0.471 ab	2.4 ab
2. 2,4-D (D7)	21.2 a	9.3 a	7.4 a	2.272 a	2.871 a	0.388 a	0.482 a	2.6 a
3. 2,4-D (D1+D14)	20.1 b	9.8 ab	8.3 cd	2.051 c	2.430 cd	0.344 c	0.416 cd	1.4 cd
4. 2,4-D (D1+D28)	21.3 a	9.5 ab	8.0 bc	2.237 ab	2.670 b	0.382 ab	0.454 b	2.1 abc
5. 2,4-D + carfentrazone (D1+D7)	20.7 ab	9.6 ab	8.2 cd	2.161 b	2.532 c	0.367 b	0.434 c	1.8 bcd
6. 2,4-D + carfentrazone (D1+D14)	20.1 b	10.0 b	8.5 d	2.008 c	2.369 d	0.335 c	0.405 d	1.3 d

[x] D1, D7, D14, and D28 represent applying herbicides 14 h, 7 d, 14 d, and 28 d after cotton stalks were shredded, respectively. Application rates were 1.06 kg ai/ha of 2,4-D and 0.34 kg ai/ha of carfentrazone.

[y] Spectral variables: NR = Near-infrared (NIR)/Red, NG = NIR/Green, NDVI = (NIR-Red)/(NIR+Red), and GNDVI = (NIR-Green)/(NIR+Green). Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD (P = 0.05).

[z] Visual rating on a scale of 1-5, where 1 = no live plants; 2 = some plants alive, but exhibiting herbicide damage; 3 = most plants alive, but exhibiting herbicide damage; 4 = some plants appear healthy; and 5 = most plants appear healthy.

3 and 6. The spectral values generally agreed with ground visual rating data. A correlation analysis indicated that 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 0.999 for GNDVI.

CONCLUSIONS

This study demonstrates that ground reflectance spectra and airborne CIR imagery can be used to assess the effectiveness of different herbicide treatments for cotton stalk destruction. Ground reflectance spectra offer spectral observations over continuous wavelengths at selected sites from each treatment and can be used to differentiate among the treatments. Airborne CIR digital imagery provides a continuous view of all of the treatment plots and has the potential for quick visual comparisons among the treatments. Airborne imagery contains spectral information for every area of the field and allows quantitative separations of the treatments using the spectral bands and vegetation indices derived from these bands. Although both ground reflectance 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 approaches are more objective and airborne imagery is more efficient and effective if a large number of treatments are to be evaluated over large areas.

ACKNOWLEDGEMENT

The authors thank Rene Davis and Fred Gomez (USDA-ARS, Weslaco, TX) for acquiring airborne imagery for the study, and Jim Forward (USDA-ARS, Weslaco, TX) for ground reflectance data collection and assistance in image processing.

DISCLAIMER

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

REFERENCES

Bremer, J. 1999. Suggestions for successful chemical cotton stalk termination. Pub. SCS-1999-24. Texas Cooperative Extension, Texas A&M University System, College Station, TX.

Campbell, J.B. 1987. Introduction to Remote Sensing. The Guilford Press, New York.

Escobar, D.E., J.H. Everitt, J.R. Noriega, M.R. Davis, and I. Cavazos. 1997. A true digital imaging system for remote sensing applications. p. 470-484. *In* Proc. Biennial Workshop on Color Photography and Videography in Resource Assessment, 16th, Weslaco, TX. 29 Apr. - 1 May 1997. Am. Soc. Photogrammetry and Remote Sensing, Bethesda, MD.

Lemon, R., C. Stichler, and J. Norman, Jr. 2003. Cotton stalk destruction with herbicides. Pub. SCS-2003-10. Texas Cooperative Extension, Texas A&M University System, College Station, TX.

Norman, J.W., Jr., S.M. Greenberg, A.N. Sparks, Jr., and C. Stichler. 2003. Termination of cotton stalks with herbicides in the Lower Rio Grande Valley of Texas. P. 1540-1544. *In* Proc. Beltwide Cotton Production Conf., Nashville, TN. 6-10 Jan. 2003. Natl. Cotton Counc. Am., Memphis, TN.

Sparks, A.N., Jr., J.W. Norman, Jr., C. Stichler, J. Bremer, and S. Greenberg. 2002. Cotton stalk destruction with selected herbicides and effects of application methodology. Unpaginated CDROM. *In* Proc. Beltwide Cotton Production Conf., Atlanta, GA. 8-13 Jan. 2002. Natl. Cotton Counc. Am., Memphis, TN.

Texas Department of Agriculture. 2006. The cotton stalk destruction program. Available online at http://www.agr.state.tx.us/license/regulatory/cotton/reg_cotton_stalk_destruction_program.htm (verified 19 Feb. 2006).

Tucker, C.J., B.N. Holben, and J.H. Elgin, Jr. 1980. Relationship of spectral data to grain yield variation. Photogrammetric Engineering and Remote Sensing 46(5): 657-666.

Wiegand, C.L., and A.J. Richardson. 1984. Leaf area, light interception, and yield estimates from spectral components analysis. Agron. J. 76(4): 543-548.

Yang, C., and G.L. Anderson. 1999. Airborne videography to identify spatial plant growth variability for grain sorghum. Precision Agric. 1(1): 67-79.

Yang, C., and J. H. Everitt. 2002. Relationships between yield monitor data and airborne multispectral multidate digital imagery for grain sorghum. Precision Agric. 3(4): 373-388.

Yang, C., S.M. Greenberg, J.H. Everitt, M.R. Davis, and J.W. Norman, Jr. 2003a. Evaluation of cotton regrowth control using remote sensing. p. 1588-1596. *In* Proc. Beltwide Cotton Production Conf., Nashville, TN. 6-10 Jan. 2003. Natl. Cotton Counc. Am., Memphis, TN.

Yang, C., S.M. Greenberg, J.H. Everitt, T.W. Sappington, and J.W. Norman, Jr. 2003b. Evaluation of cotton defoliation strategies using airborne multispectral imagery. Trans. ASAE 46(3): 869-876.