EVALUATION OF HERBICIDE-BASED COTTON REGROWTH CONTROL USING REMOTE SENSING

C. Yang, S. M. Greenberg, J. H. Everitt

ABSTRACT. Post-harvest destruction of cotton (Gossypium hirsutum L.) stalks is an important cultural practice for managing overwintering boll weevils (Anthonomus grandis Boheman) and other insect pests such as the silverleaf whitefly (Bemisia argentifolii Bellows and Perring) and the pink bollworm (Pectinophora gossypiella). A field experiment was conducted to examine the usefulness of remote sensing technology for evaluating herbicide-based regrowth control for cotton stalk destruction. Ten treatments (one control and nine combinations of three herbicide mixtures and three application timings) were assigned to 30 shredded cotton plots according to a randomized complete block design in a south Texas cotton field in 2002. Ground reflectance spectra were collected on randomly selected sites from each plot. Meanwhile, airborne multispectral digital imagery was obtained from the field, and plant regrowth was visually rated at five different levels ranging from no live plants to mostly healthy plants based on ground observations. The reflectance spectra were able to visually separate regrowth differences among the treatments. Although the airborne imagery did not provide sufficient visual differentiation among the treatments, the spectral information extracted from the imagery allowed quantitative separations among the treatments. Seven spectral variables, including the green, red, and near-infrared bands of the multispectral imagery and four vegetation indices derived from the three bands, were used to compare the differences among the treatments. Multiple comparisons showed that the red band and the four vegetation indices detected significant differences among the treatments as detected by the visual rating method. These results indicate that remote sensing can be a useful tool for evaluating herbicide-based regrowth control strategies for cotton stalk destruction.

Keywords. Cotton regrowth control, Cotton stalk destruction, Herbicide, Multispectral imagery, Reflectance spectrum, Remote sensing.

Destruction of cotton (Gossypium hirsutum L.) stalks soon after harvest has long been recognized as a useful practice for reducing the number of overwintering boll weevils (Anthonomus grandis Boheman) (Sterling et al., 1989). This practice has been used as a prime tool for managing boll weevil, silverleaf whitefly (Bemisia argentifolii Bellows and Perring), and pink bollworm (Pectinophora gossypiella) populations in the Lower Rio Grande Valley of south Texas (Norman et al., 2003). Without thorough area-wide stalk destruction, these insects can feed and reproduce on the host plants and survive over the winter to increase the pest pressure for the following growing season. The Cotton Pest Control Law in Texas requires that producers in each regulated county plant and destroy cotton within an authorized period (Texas Department of Agriculture, 2005). For example, in the Lower Rio Grande Valley of Texas, cotton can be planted between 1 February and 1 March and must be destroyed by 1 September each year. Although boll weevil eradication programs are to be implemented in the Rio Grande Valley and other Texas counties, cotton stalk destruction remains an important part of the eradication programs and is still enforced by the Texas law. Even if boll weevils are eliminated in the future, stalk destruction will still be a preventive measure to keep this insect from coming back. More importantly, stalk destruction can help curb other cotton insect pests such as the silverleaf whitefly and the pink bollworm. Currently, the commonly used stalk destruction method is shredding followed by plowing. Although this method is effective, recent increases in minimum tillage and no tillage systems have made it challenging. Therefore, other alternative cotton stalk destruction methods, such as herbicide applications, have been tested and practiced. 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.

Currently, only limited research has been conducted to identify effective herbicides as well as their application methods for cotton stalk destruction. Moreover, there is no standard procedure 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 is useful, but visual observations are subjective and...
ground measurements can be time consuming. From the perspective of remote sensing, regrowth from shredded cotton stalks treated with different herbicides would have different spectral responses. Therefore, spectral characteristics of the regrowth may be used to differentiate the effectiveness among various herbicide treatments.

Remote sensing technology has long been used to assess crop growth conditions. 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 variables such as leaf area index, biomass, and yield (Tucker et al., 1980; Wiegand and Richardson, 1984; Yang and Anderson, 1999; Plant et al., 2000; Yang et al., 2000) and to detect crop stresses such as nutrient deficiency and pests (Moran et al., 1997; Johannsen et al., 2000). Remote sensing applications in agriculture have been steadily increasing in recent years due to improvements in spatial and spectral resolutions of both satellite and airborne remote sensing systems. More recently, ground-based multispectral imaging systems have been tested for real-time crop nitrogen status assessment (Kim et al., 2000; Noh et al., 2005).

Use of harvest aids for cotton defoliation and regrowth control has been an accepted practice. Yang et al. (2003) successfully evaluated the effectiveness of different cotton defoliation treatments using airborne multispectral imagery. However, no research has been conducted to evaluate herbicide-based cotton regrowth control using remote sensing technology. The objective of this study was to examine the feasibility of ground reflectance measurements and airborne multispectral imagery for evaluating the effectiveness of various regrowth control treatments as compared with traditional visual observations and ground measurements.

**METHODS AND MATERIALS**

**EXPERIMENTAL DESIGN**

A 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, in 2002. The field was planted with cotton (cultivar Deltapine 50) in early March, and normal production practices were used in the field during the growing season. A randomized complete block design was established within the field at the time of cotton harvest. Ten treatments, including one control and nine combinations of three herbicide mixtures and three application timings, were randomly assigned to 30 shredded experimental plots in three blocks (fig. 1). Immediately after harvest, cotton stalks within all the plots were shredded at 8 to 10 cm from the soil line with a two-row rotary shredder. The shredded plots were two rows (2.0 m) wide and 112 m long and separated by two rows of standing (non-shredded) cotton stalks as a buffer. The herbicides used included Amine 4 2,4-D Weed Killer (dimethylamine salt of 2,4-dichlorophenoxyacetic acid, Platte Chemical Company, Fremont, Neb.), Clarity (diglycolamine salt of 3,6-dichloro-o-anisic acid, BASF Corp., Research Triangle Park, N.C.), Valor WP (Flumioxazin, Valent USA Corp., Walnut Creek, Cal.), and Roundup UltraMAX [Glyphosate, B(phosphonomethyl)glycine, Montsanto Company, St. Louis, Mo.]. Amine (2,4-D) and Clarity were each used alone, while Valor and Roundup were used together as one herbicide mixture. A Spider Spray Trac sprayer (West Texas Lee Company, Inc., Idalou, Texas) was used to apply the herbicides to the designated plots on three dates: 26 July (immediately after shredding), 2 August (7 days after shredding), and 9 August (14 days after shredding). The sprayer was equipped with multiple booms, and three of the booms were used to apply Amine (2,4-D), Clarity, and the mixture of Valor and Roundup, respectively. The sprayer covered two rows (the width of the individual plots) at a time with one nozzle spraying a 25 cm band over each row. Application rates for the herbicides were 2.34 L/ha (1 qt/ac) of Amine (2,4-D), 1.17 L/ha (1 pt/ac) of Clarity, 73 mL/ha (1 oz/ac) of Valor, and 2.34 L/ha (1 qt/ac) of Roundup. These application rates conformed to label recommendations. The volume of spray solution (water) used was 126 L/ha (13.5 GPA) for Amine (2,4-D), Clarity, and the mixture of Valor and Roundup. The applications were made early in the morning when the wind was calm so that drift between plots was minimized.

**COLLECTION OF GROUND REFLECTANCE, AIRBORNE IMAGERY, AND PLANT PHYSICAL DATA**

Ground reflectance spectra were collected from each plot with a FieldSpec handheld spectroradiometer (Analytical Spectral Devices, Inc., Boulder, Colo.) on 27 August (32 days after shredding). The spectroradiometer was sensitive in the visible to near-infrared (NIR) portion of the spectrum (350-1050 nm) with a nominal spectral resolution 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

![Figure 1. Layout of ten cotton regrowth control treatments across three blocks in a randomized complete block design for a cotton field in 2002.](image-url)
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) imagery was acquired using a digital imaging system described by Escobar et al. (1997) on the cotton field on the same date that ground reflectance data were taken. The imaging system consisted of three Kodak MegaPlus digital charge-coupled device (CCD) cameras. The original acquisition computer in the imaging system was replaced in 2002 by a faster computer equipped with three more advanced Bitflow RUN-PCI 11 image grabbing boards (Bitflow, Woburn, Mass.) and custom software 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 pixel images of the old system. 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 1200h 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 × 8 m tarpaulins with nominal reflectance values of 4%, 16%, 32%, and 48%, respectively, were placed at the north edge of the field during image acquisition. The actual reflectance values from the tarpaulins were measured using the FieldSpec handheld spectroradiometer. Based on the reflectance measurements of the plants and soil background in the field, the reflectance values in the green and red bands for the study area were less than 25%, while the reflectance values in the NIR band were less than 55%. In order to increase the contrast of the regrowth control treatments in the green and red band images, the apertures for the cameras equipped with the green and red filters were adjusted so that the 32% reflectance tarpaulin was nearly, but not quite, saturated on the images. Thus, the 48% reflectance tarpaulin was saturated and had the maximum digital count value (255) on both the green and red band images. Since the NIR reflectance of the plants was more than 48%, the aperture for the NIR camera was adjusted so that the study area in the NIR image was not saturated during image acquisition.

Plant regrowth in each plot was visually rated on a 1-to-5 scale based on the ratings used by Sparks et al. (2002). The ratings were as follows; 1 = no live plants; 2 = some plants alive, but appear sick; 3 = most plants alive, but appear sick; 4 = some plants appear healthy; and 5 = most plants appear healthy. Visual assessments of the plots were performed by a crew of three people. The three members rated the regrowth as a group and agreed on the rating for each plot.

Airborne Imagery Processing

The NIR, red, and green band images in the CIR composite image were registered to one another to correct the misalignments among the bands. The digital count values of the registered band images were then converted to reflectance based on three calibration equations (one for each band) relating reflectance values to the digital count values on the four tarpaulins. Because of the saturation of the 48% tarpaulin on the red and green band images, the digital count values extracted from the tarpaulin were not used for the calibration of the two band images. Image registration and calibration were performed using ERDAS IMAGINE (ERDAS, Inc., Atlanta, Ga.). To determine the reflectance values in the three band images for each plot, a rectangular area with a width of two pixels (0.4 m) was overlaid on each of the two rows within the plot to cover all possible regrowth, and average reflectance values were extracted 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. Two of the vegetation indices were band ratios defined as:

\[
NR = \frac{\text{NIR}}{\text{Red}} \\
NG = \frac{\text{NIR}}{\text{Green}}
\]

And the other two were normalized differences (ND) defined as:

\[
\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \\
\text{GNDVI} = \frac{\text{NIR} - \text{Green}}{\text{NIR} + \text{Green}}
\]

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 regrowth rating. Multiple comparisons of means were made using Fisher’s protected least significant difference (LSD) procedure. Regression equations relating regrowth rating to the vegetation indices were determined. All the statistical analyses were performed using SAS software (SAS Institute, Inc., Cary, N.C.).

Results and Discussion

Reflectance Spectra of Cotton Plants

Figure 2 presents representative reflectance spectra for normal cotton plants, regrowth after shredding, and bare soil in the visible to NIR region of the spectrum. In the visible portion of the spectrum, reflectance for normal plants is higher in the green region than in the blue and red regions. Toward the red end of the visible spectrum, 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 gradually in the visible to NIR region of the spectrum. The reflectance curve for plant regrowth falls somewhere between the reflectance curves for the normal plants and bare soil. Although the general shape of the reflectance spectrum for regrowth is similar to the reflectance spectrum for normal plants, the reflectance is much higher in the visible region and much lower in the NIR region than the reflectance for normal plants. Moreover, the difference between the green and red bands becomes minimal for regrowth. These deviations in reflectance are mainly attributed to relatively small regrowth and large soil exposure within the field of view of the spectroradiometer. These spectral behaviors are the basis for the separation of different regrowth control treatments.

Since the spectra from some of the ten treatments are similar and difficult to visually differentiate, they are shown in three separate figures by application timing. The spectra for the control and bare soil are also shown in the figures for
Figure 2. Representative reflectance spectra for normal cotton plants, plant regrowth, and bare soil in the visible (400-700 nm) to NIR (700-900 nm) region of the spectrum.

comparison. Figure 3 presents representative reflectance spectra of cotton plant regrowth when the three herbicide treatments were applied immediately after shredding. The spectra for the control and the plots treated with the mixture of Valor and Roundup are almost identical, indicating that applying this herbicide mixture immediately after shredding had little effect on regrowth control. The spectra from the plots treated with Amine (2,4-D) and Clarity deviate apparently from the spectrum for the control, indicating that these two herbicides applied immediately after shredding effectively curbed cotton regrowth. However, the difference between the two treatments was very small.

Figures 4 and 5 show representative reflectance spectra of cotton regrowth when the herbicide treatments were applied 7 days and 14 days after shredding, respectively. The spectra for all three herbicide treatments differed from the spectrum for the control, indicating that applying these herbicides 7 days or 14 days after shredding had an apparent effect on regrowth control. However, it was difficult to reliably determine which treatment had the best regrowth control effect because of the subtle differences among the three herbicide treatments on both application timings. Generally, a minimum amount of time should be given after shredding.
to allow sufficient regrowth tissue to receive the herbicide treatments. This seemed to be especially important for the mixture of Valor and Roundup, but Amine (2,4-D) and Clarity did not seem to be very sensitive to application timing.

Since plots receiving effective regrowth control tended to have less plant regrowth, the reflectance from these plots was higher in the visible region and lower in the NIR region than the reflectance from the control. Moreover, the reflectance from these plots tended to have lower reflectance in the visible region and lower or higher reflectance in the NIR region than the reflectance for bare soil, depending on the amount of regrowth. Based on the spectral behaviors of different treatments relative to the spectra of the control and bare soil, the effectiveness of the treatments can be evaluated.

As indicated in figures 3 through 5, spectra can be a useful tool for differentiating the effectiveness of various herbicide treatments. However, because of spatial variability within the treatments, limited amounts of regrowth, and variations within the field of view of the spectroradiometer, great care has to be taken to obtain accurate spectra. For example, regrowth after shredding in this experimental field was very small due to the effects of the herbicides and dry weather. The average width of plant regrowth varied from 0 (no regrowth) to approximately 25 cm (control) 32 days after shredding. Since the diameter of the target area of the spectra was 44 cm, each sample spectrum was based on a circular area much wider than the width of the regrowth. Clearly, the resulting spectra taken from such a small area were affected by inaccurate positioning of the instrument and the variability in plant regrowth and soil conditions within each plot. Therefore, to obtain accurate and reliable spectra, the instrument should be positioned at a predetermined height and right above the canopy during the data collection, and a large number of representative spectra should be collected.

**Visual Comparisons of Herbicide Treatments with Digital Imagery**

Figure 6 shows a black-and-white red band digital image acquired from the cotton field on 27 August, 32 days after cotton stalks were shredded. The relation between reflectance and digital count values for the red band based on the 4%, 16%, and 32% reflectance tarpaulins is also shown in the figure. The shredded rows in each experimental plot have a light gray color, while the unshredded rows have a dark gray tone. The calibration tarpaulins placed at the north edge of the field show the relative reflectance levels, except that the 48% reflectance tarpaulin was saturated. Because of the limited amount of regrowth, it is extremely difficult to visualize the differences among the treatments in the airborne image. Although minor differences could be seen among some of the treatments when the image was enlarged, it was difficult to obtain reliable visual separations from the image. As stated previously, the pixel size of the image was about 0.2 m and the width of the regrowth was less than 0.25 m, so the regrowth on the image was less than one or two pixels wide, which was not sufficient to produce an apparent visual effect. Therefore, to use airborne imagery for visual evaluation of the differences among various herbicide treatments, high spatial resolution imagery may be required. Although the spatial resolution of the image was not fine enough for visual evaluation, it contained quantitative spectral information concerning plant regrowth for each of the plots in the field. This quantitative spectral information can be used to statistically determine the differences among the treatments.

![Figure 6. Black-and-white red band image of a cotton field acquired 32 days after cotton stalks were shredded. The relation between reflectance and digital count values for the red band based on the first three tarpaulins placed on the field is also presented. Treatment numbers are defined in figure 1. Each experimental plot consisted of two shredded rows (light gray color) and was separated by two rows of standing stalks (dark gray color).](image-url)
Table 1. Comparisons of means for seven spectral variables among ten cotton regrowth control treatments based on airborne image data obtained 32 days after cotton stalks were shredded in a field at Weslaco, Texas, in 2002.

<table>
<thead>
<tr>
<th>Treatment[a]</th>
<th>NIR (%)</th>
<th>Red (%)</th>
<th>Green (%)</th>
<th>NR</th>
<th>NG</th>
<th>NDVI</th>
<th>GNDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Control</td>
<td>22.1</td>
<td>14.4 a</td>
<td>12.5</td>
<td>1.534 a</td>
<td>1.763 a</td>
<td>0.211 a</td>
<td>0.276 a</td>
</tr>
<tr>
<td>2. Amine (2,4-D) (D0)</td>
<td>21.4</td>
<td>15.3 bc</td>
<td>12.9</td>
<td>1.400 cd</td>
<td>1.662 bcd</td>
<td>0.166 cd</td>
<td>0.248 bcd</td>
</tr>
<tr>
<td>3. Clarity (D0)</td>
<td>21.0</td>
<td>15.3 bc</td>
<td>12.8</td>
<td>1.367 d</td>
<td>1.639 cd</td>
<td>0.155 d</td>
<td>0.242 cd</td>
</tr>
<tr>
<td>4. Valor + Roundup (D0)</td>
<td>22.1</td>
<td>14.3 a</td>
<td>12.3</td>
<td>1.551 a</td>
<td>1.792 a</td>
<td>0.216 a</td>
<td>0.283 a</td>
</tr>
<tr>
<td>5. Amine (2,4-D) (D7)</td>
<td>21.4</td>
<td>15.7 c</td>
<td>12.9</td>
<td>1.366 d</td>
<td>1.639 cd</td>
<td>0.155 d</td>
<td>0.242 cd</td>
</tr>
<tr>
<td>6. Clarity (D7)</td>
<td>21.4</td>
<td>15.0 b</td>
<td>12.8</td>
<td>1.426 bc</td>
<td>1.680 bc</td>
<td>0.175 bc</td>
<td>0.254 bc</td>
</tr>
<tr>
<td>7. Valor + Roundup (D7)</td>
<td>21.4</td>
<td>15.1 bc</td>
<td>12.3</td>
<td>1.416 bcd</td>
<td>1.677 bcd</td>
<td>0.172 bcd</td>
<td>0.252 bcd</td>
</tr>
<tr>
<td>8. Amine (2,4-D) (D14)</td>
<td>21.1</td>
<td>15.3 bc</td>
<td>12.9</td>
<td>1.377 cd</td>
<td>1.635 d</td>
<td>0.159 cd</td>
<td>0.241 d</td>
</tr>
<tr>
<td>9. Clarity (D14)</td>
<td>21.6</td>
<td>14.8 ab</td>
<td>12.8</td>
<td>1.458 b</td>
<td>1.694 b</td>
<td>0.186 b</td>
<td>0.257 b</td>
</tr>
<tr>
<td>10. Valor + Roundup (D14)</td>
<td>21.3</td>
<td>15.2 bc</td>
<td>12.3</td>
<td>1.396 cd</td>
<td>1.680 bc</td>
<td>0.165 cd</td>
<td>0.254 bc</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Treatment[a]</th>
<th>Rating[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Control</td>
<td>5.0 a</td>
</tr>
<tr>
<td>2. Amine (2,4-D) (D0)</td>
<td>2.7 cd</td>
</tr>
<tr>
<td>3. Clarity (D0)</td>
<td>2.3 d</td>
</tr>
<tr>
<td>4. Valor + Roundup (D0)</td>
<td>4.2 b</td>
</tr>
<tr>
<td>5. Amine (2,4-D) (D7)</td>
<td>2.8 cd</td>
</tr>
<tr>
<td>6. Clarity (D7)</td>
<td>2.7 cd</td>
</tr>
<tr>
<td>7. Valor + Roundup (D7)</td>
<td>2.5 d</td>
</tr>
<tr>
<td>8. Amine (2,4-D) (D14)</td>
<td>2.8 cd</td>
</tr>
<tr>
<td>9. Clarity (D14)</td>
<td>3.3 c</td>
</tr>
<tr>
<td>10. Valor + Roundup (D14)</td>
<td>3.0 cd</td>
</tr>
</tbody>
</table>

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.

Comparisons of Herbicide Treatments Using Spectral Indices

Table 1 shows the mean values of the NIR, red, and green bands and the four vegetative indices by treatment based on the field image taken on 27 August. The red band and the four vegetation indices detected significant differences among the treatments, while the NIR and green bands did not reveal any statistical difference. Compared with the three bands, the four vegetation indices were more effective and consistent in differentiating among the treatments. As can be seen from the spectra shown in figures 3 through 5, more plant regrowth would have higher reflectance in the NIR band and lower reflectance in the red and green bands than less regrowth. Similar to the NIR band, the four vegetation indices tend to have higher values when the amount of plant regrowth is more abundant. In other words, more effective herbicide treatments, which result in less plant regrowth, should have higher reflectance in the red and green bands and lower reflectance in the NIR band as well as lower values for the four vegetation indices.

The data in table 1 clearly indicate that the herbicide treatments had varying degrees of effectiveness for cotton regrowth control. There was no statistical difference between the control and treatment 4, indicating that application of the Valor and Roundup mixture immediately after shredding had little effect on regrowth control. However, this herbicide mixture was more effective in curbing regrowth if being applied one or two weeks after shredding, although no significant difference existed between the two application timings. Treatments with Amine (2,4-D) were very effective, and there were no significant differences among the three application timings, indicating that application timing might not be sensitive for this herbicide within the first two weeks after shredding. Clarity applied immediately after shredding was as good as Amine (2,4-D), but its effectiveness decreased when applied one or two weeks later. In fact, Clarity applied two weeks after shredding was the second least effective treatment, only better than the mixture of Valor and Roundup applied immediately after shredding.

Table 2 presents plant regrowth ratings among the ten treatments based on ground observations made 31 days after shredding, one day before the reflectance and image data were collected. The ground observation results generally agreed well with those from the airborne imagery for the experiment field. However, a statistical difference was detected between the control and treatment 4 by ground rating, while no significant difference was found between the two by the spectral data. This may be partly due to the coarse rating scale. The airborne imagery considered every regrowth area within each plot, while the visual rating was based on ground observations over a few areas within the plot. Therefore, airborne imagery should provide more detailed and more objective information about cotton plant regrowth.

[1] D0, D7, and D14 represent applying herbicides immediately, 7 days, and 14 days after shredding, respectively.

[2] Rating scale: 1 = no live plants; 2 = some plants alive, but appear sick; 3 = most plants alive, but appear sick; 4 = some plants appear healthy; and 5 = most plants appear healthy. 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.

1. Control
2. Amine (2,4-D) (D0)
3. Clarity (D0)
4. Valor + Roundup (D0)
5. Amine (2,4-D) (D7)
6. Clarity (D7)
7. Valor + Roundup (D7)
8. Amine (2,4-D) (D14)
9. Clarity (D14)
10. Valor + Roundup (D14)
Table 3. Regression results for linear models relating regrowth rating to vegetation indices based on airborne image data and ground observations from a shredded cotton field with ten regrowth control treatments at Weslaco, Texas, in 2002.

<table>
<thead>
<tr>
<th>Vegetation Index(^\text{[a]})</th>
<th>Regression Equation(^\text{[b]})</th>
<th>R(^2)</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>Regrowth rating = −13.11 + 11.36 × NR</td>
<td>0.799</td>
<td>0.40</td>
</tr>
<tr>
<td>NG</td>
<td>Regrowth rating = −20.46 + 13.99 × NG</td>
<td>0.769</td>
<td>0.43</td>
</tr>
<tr>
<td>NDVI</td>
<td>Regrowth rating = −2.90 + 34.29 × NDVI</td>
<td>0.801</td>
<td>0.40</td>
</tr>
<tr>
<td>GNDVI</td>
<td>Regrowth rating = −10.12 + 51.97 × GNDVI</td>
<td>0.774</td>
<td>0.42</td>
</tr>
</tbody>
</table>

\(^a\) NR = NIR / Red, NG = NIR / Green, NDVI = (NIR − Red) / (NIR + Red), and GNDVI = (NIR − Green) / (NIR + Green).

\(^b\) The best fitting regression models were significant at the 0.001 level. The number of samples for each model was 10.

Table 3 shows the regression results for linear models relating regrowth rating to each of the four vegetation indices based on the means for the ten treatments. The coefficients of determination for the four vegetation indices were very similar, ranging from 0.77 for NG and GNDVI to 0.80 for NR and NDVI. There were essentially no differences in predictability between NG and GNDVI or between NR and NDVI. These results agreed with those shown in table 1. These regression equations can be used to estimate the regrowth rating for any area within the field based on a vegetation index. However, these relations are field-specific and may not be valid for other fields because spectral data vary with field conditions and with the time the treatments are applied and imagery is collected. Nevertheless, these vegetation indices can be used to estimate the relative effectiveness of different herbicide treatments. The smaller the vegetation index values, the more effective the treatments are for curbing cotton regrowth. If the absolute effectiveness of the treatments is necessary, limited ground observations are required to determine the relations between the regrowth rating and the vegetation indices.

Figure 7 shows a gray scale image of regrowth rating generated from the NDVI regression equation presented in table 3. In contrast with the red band image, the shredded rows on the NDVI-derived regrowth rating image have a darker gray color, while the unshredded rows on the image have a light gray tone. Although NDVI was better than the red band for quantitatively separating the treatments, it is still very difficult to visualize the differences among the treatments on the NDVI-derived regrowth rating image. Therefore, quantitative analysis of the spectral information extracted from the image was a more reliable method for differentiating the effectiveness among the treatments.

Compared with traditional ground observations, airborne imagery covers every area of a field and provides more detailed and objective information about cotton plant regrowth. However, because of limited amounts of regrowth and relatively coarse spatial resolution of airborne digital imagery, care has to be taken in extracting the data from the imagery and interpreting the remote sensing results. Moreover, it is always necessary to make limited ground measurements and observations so that the remote sensing results can be validated. As expected, higher spatial resolution imaging systems may allow quicker and better visual evaluation of herbicide treatments and provide more detailed plant regrowth information for accurate quantitative evaluation. However, more research is needed to determine the optimum spatial resolution for both visual and quantitative differentiation of cotton regrowth control methods.

Figure 7. Gray scale image of regrowth rating generated from the NDVI regression equation shown in table 3 for a cotton field. Treatment numbers are defined in figure 1. Each experimental plot consisted of two shredded rows (dark gray color) and was separated by two rows of standing stalks (light gray color).
CONCLUSIONS
This study illustrates how reflectance spectra and airborne multispectral imagery can be used to evaluate the effectiveness of different herbicide-based cotton regrowth control treatments. Ground reflectance spectra can be used to differentiate among treatments if they are properly taken from a sufficient number of canopies representing the regrowth conditions. Airborne multispectral digital imagery provides a continuous view of the imaging area and has the potential for quick visual comparisons among treatments. However, because of the limited amount of cotton plant regrowth and relatively coarse spatial resolution of the digital imaging system used in this study, it was very difficult to visually separate the differences among the treatments from the imagery. Nevertheless, the imagery contained digital spectral information for every area of the regrowth plots and allowed quantitative separations of these treatments. The two band ratios and the two normalized difference vegetation indices used in this study were effective for separating the treatments. Although ground observations and measurements are always necessary to validate remote sensing results, it is clear that remote sensing techniques can be a useful tool for evaluating the effectiveness of cotton regrowth control methods, especially if a large number of treatments are to be evaluated over large fields.

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