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Evaluating Techniques for Determining Tillage Regime in the Southeastern Coastal Plain and Piedmont

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ABSTRACT

Reduced tillage and residue management can have significant impacts on soil and water quality, primarily through the accumulation of soil organic C. Yet, methods of tillage and residue cover assessment are time and resource intensive, and often do not yield spatially representative results. A major goal of this study was to compare new remote sensing (RS) indices with the current line-transect approach for differentiating between conventional (CT) and conservation tillage systems. Experimental plots were located in two physiographic regions in Georgia: the Southern Piedmont and Southern Coastal Plain. Treatments consisted of no tillage (NT) or CT at the Piedmont site, and strip-tillage (ST) or CT at the Coastal Plain site. Remotely sensed data were acquired three times prior to canopy closure, using a handheld multispectral radiometer (485–1650 nm) and thermal imager (7000–14 000 nm). Soil texture and soil water content were measured to assess the impact of changes in soil background reflectance on crop residue assessments. Results showed that differences in spectral response between CT and conservation tillage systems were best observed using a normalized difference ratio of near infrared (NIR) (1650 ± 100 nm) and blue (485 ± 45 nm) spectra under dry conditions and low canopy cover (<25%). Differences in soil texture and color were the primary limiting factors in differentiating between tillage treatments. However, using readily available soil survey data, our data indicate that visible and NIR spectra can be used to rapidly differentiate between CT and conservation tillage systems in the Georgia Southeastern Coastal Plain and Piedmont physiographic regions.

The literature is replete with references to the benefits of reduced tillage and residue management as a sustainable agricultural best management practice. Conservation tillage has been shown to increase C accretion, reduce runoff and erosion, and increase soil water-holding capacity (McMurtrey et al., 1993; Lal and Kimble, 1997; Truman et al., 2003). These changes in soil quality and hydrology impact the accuracy of soil and water quality models currently being used to evaluate the effects of conservation practices, determine eligibility for federal conservation program resources, and assess changes in watershed hydrology. However, current methods of estimating crop residue cover are time and resource intensive, and often do not yield spatially representative cover assessments (Morrison et al., 1993). Thus, a rapid method of monitoring field-scale distributions of crop residue cover is necessary to reduce model uncertainties and better establish the benefits of conservation tillage to soil and water quality.

Estimates of residue cover are typically made via roadside surveys (Conservation Technology Information Center, 2004) or in-field line-transect measurements (Shelton et al., 1993). Thoma et al. (2004) compared three methods of residue classification including the roadside survey, in-field line transect, and satellite-derived estimates of residue coverage via Landsat Thematic Mapper (TM) data. In their study, the roadside survey failed to identify residue coverages between 25 and 35% cover nearly 58% of the time compared to in-field line-transect estimates. Limited accuracy of the roadside survey was attributed to difficulties in observing crop residue at oblique viewing angles, and generally resulted in an overestimation of percent residue cover. Thoma et al. (2004) reported that Landsat TM data were more efficient, providing rapid, unbiased estimates of residue cover into two classes (<30% and >30% crop residue cover).

Laboratory and field-scale RS of crop residues have yielded mixed results (McMurtrey et al., 1993; Chen and McKyes, 1993; Sullivan et al., 2004; Daughtry et al., 2005). Unlike growing vegetation, crop residue lacks a unique spectral signature in much of the visible (VIS) and NIR spectrum (McMurtrey et al., 1993; Streck et al., 2002). Instead, crop residues have spectral response features similar to soil spectra, increasing without inflection throughout the VIS and NIR, and differing only in magnitude of spectral response (Baumgardner et al., 1985; Aase and Tanaka, 1991; Daughtry et al., 1995; Sullivan et al., 2004). Difficulties in estimating crop residue cover are a function of soil physical properties, soil water content, crop residue type, crop residue water content, and surrounding green vegetation (Chen and McKyes, 1993; Daughtry et al., 1995; Nagler et al., 2000). In particular, soil background reflectance may be greater or less than crop residue reflectance depending on soil color and water content (Aase and Tanaka, 1991). This manifests a significant challenge in remote residue cover determinations based on differences in the magnitude of spectral response alone.

In much the same way as vegetative indices are designed to reduce soil background effects, researchers have begun investigating tillage indices designed to capture the spectral response of crop residue (McNairn and

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Crop Residues
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Abbreviations: ATLAS, airborne terrestrial applications sensor; CAI, cellulose absorption index; CRC, crop residue cover; CT, conventional tillage; NIR, near infrared; NT, no tillage; RS, remote sensing; ST, strip tillage; TIR, thermal infrared; TM, Thematic Mapper; VIS, visible.

Protz, 1993; Daughtry et al., 1996; van Deventer et al., 1997; Gowda et al., 2001). Indices capitalize on differences in spectral response between residue and soil spectra within the NIR (Gausman and Allen, 1973; Aase and Tanaka, 1991). van Deventer et al. (1997) evaluated several Landsat 5 TM indices as a means to differentiate between CT and conservation tillage on 27 farms in Ohio. Results indicated the normalized difference tillage index using TM bands 5 (1550–1750 nm) and 7 (2080–2350 nm) best discriminated between CT and conservation tillage practices with 89% accuracy. Later, Gowda et al. (2001) applied logistic regression models developed by van Deventer et al. (1997) to Minnesota fields using 1997 Landsat TM imagery. Using logistic regression the percentage of conservation tillage fields classified correctly ranged from 42 to 77%, with indices containing TM band 5 having accuracies between 70 and 77%. Classification errors were attributed to field-scale variability in soil organic C, soil water content, and soil color.

More recently, Daughtry et al. (2005) evaluated RS indices, including the cellulose absorption index (CAI), to more specifically classify tillage practices by the extent of crop residue coverage. The CAI is designed to take advantage of absorption bands centered on 2100 nm, which are highly correlated with the presence of cellulose and lignin in organic materials (Elvidge, 1990; Daughtry et al., 1996). Results from Daughtry et al. (2005) indicated that Landsat TM vegetation and tillage indices were not well correlated with small changes in crop residue coverage. However, the CAI was linearly related to increasing amounts of crop residue coverage having an $r^2 = 0.88$ when the vegetative cover fraction was <0.30. In other studies, the CAI has been shown to be effective even in the presence of little crop residue coverage (Nagler et al., 2003). Earlier techniques used to estimate crop residue cover include fluorescence and the "soil-line" approach (Daughtry et al., 1995; Biard and Baret, 1997). However, data were collected in the laboratory or under artificial field conditions.

Thermal infrared (TIR) spectra also show promise as a new method for assessing field-scale variability in crop residue coverage. In an early study, Aase and Tanaka (1991) used infrared thermometer data to quantify varying degrees of residue cover under wet and dry conditions in the Great Plains. Results showed that under moist conditions, TIR data more accurately quantified residue cover compared to VIS and NIR spectra. Sullivan et al. (2004), evaluated the high spatial and spectral resolution airborne terrestrial applications sensor (ATLAS) to differentiate among wheat residue covers (0, 10, 20, 50, and 80%) in 15 by 15 m plots in Alabama. Results demonstrated that although red and NIR spectra could be used to assess crop residue coverage, TIR data more accurately differentiated between plots receiving 10, 20, 50, and 80% wheat residue cover. Moreover, spectral response curves indicate unique spectral signatures associated with increasing wheat residue cover were present in the 8200 to 9200 nm spectral regions. Authors attribute differences in TIR emittance to contrasting heat capacities of mineral vs. organic materials.

Few studies have evaluated the potential for RS data to depict residue cover in the southeastern USA, where conservation tillage practices are becoming increasingly common. Water quality, conservation effects assessment, and eligibility in federal conservation programs necessitates an accurate and rapid method to measure crop residue distributions. Our study was designed to (i) assess the impact of surface conditions on our ability to remotely discriminate between tillage regimes in two intensively row cropped physiographic regions, (ii) evaluate new RS indices to assess residue cover following cover crop kill and bed preparation in two distinct soils, and iii) compare line-transect crop residue cover estimates with RS residue cover estimates.

MATERIALS AND METHODS

Study Sites

Study sites were located in two physiographic provinces of Georgia to capitalize on the inherent variability between soils, tillage regime, and crop residue management systems at each site. At the Coastal Plain site, located at the University of Georgia Gibbs Farm Experiment Station near Tifton, GA (31°26′ N, 83°35′ W), the soil studied was a Tifton loamy sand (fine, loamy, siliceous, thermic Plinthic Kandiudult). Treatments consisted of CT and conservation tillage in the form of ST. Plots (25 by 55 m) were arranged in a completely randomized design and replicated three times. A winter rye (*Secale cereale* L.) cover crop was planted following cotton (*Gossypium hirsutum* L.) on 23 Nov. 2003 on all plots using a no-till drill. Strip tillage plots were not tilled before planting rye. Conventional tillage plots were disk harrowed on 3 Nov. 2003 in preparation for planting the rye cover. On 15 Apr. 2004 a contact herbicide was used to kill the winter rye before planting peanut (*Arachis hypogaea* L.) on 10 May 2004. All plots were planted using a 91-cm row spacing. In the ST treatment, 15- to 20-cm wide strips were prepared for planting. The remainder of the area between beds (row middles) was not tilled. Thus, between rows, the rye residue cover was distributed over 55 to 60 cm. The CT plots were completely disked each spring to turn rye cover and prepare beds.

The second site was located in the Piedmont region of Georgia, at the USDA, ARS, J. Phil Campbell, Sr., Natural Resource Conservation Center near Watkinsville, GA (33°54′ N, 83°24′ W). The soil was a Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult). Treatments consisted of CT and conservation tillage in the form of NT. Plots (10 by 30 m) were arranged in a completely randomized design and replicated three times. A winter rye cover crop was planted following corn harvest on 25 Oct. 2004. Corn stalks were mowed and CT plots were disk harrowed before planting rye. On 14 Mar. 2005, a contact herbicide was used to kill the winter rye before planting corn on 18 Apr. 2005. All plots were planted using a 76-cm row spacing. Corn was planted directly into the killed cover crop, thus rye residues were distributed evenly across each treatment. Conventional tillage plots were mowed and disked to turn rye and prepare beds for planting.

Ground Truth

Ground truth and RS data were collected three times at each site over a 4-wk period. This time frame corresponded to 24 May to 16 June 2004 at the Coastal Plain site, and 19 Apr. to 9 May 2005 at the Piedmont site. Sampling times were chosen to minimize crop canopy interferences based on planting dates and crop growth patterns. Ground truth consisted of digital images, soil water content (0–5 cm), and soil texture.

Two digital images were taken at nadir from random locations within each plot to quantify the extent of residue cover. Digital images were acquired without a flash, using a 5-mega pixel Olympus C-505 Zoom (Olympus, London, UK). Images were acquired from a height of 1.5 m, centered directly over the row, and represent an area of 1.4 m^2 on the ground. Images were classified into four classes: shadow, soil, residue and vegetation using ERDAS Imagine 8.4 (Leica Geosystems, Heerbrugg, Switzerland). Percent residue cover was calculated by dividing pixels classified as residue by the total pixel count in each image (5 million). To determine the validity of the classified images, an accuracy assessment was conducted in ERDAS Imagine using a random selection of four images (conservation tillage plots only) from each RS acquisition date. For each classified image, the assessment randomly chooses 40 points. Each point was then referenced as shadow, soil, crop residue, or vegetation based on a visual interpretation of the unclassified digital image. Results of the accuracy assessment were used to calculate the percentage of each class that was accurately identified. Based on these results, 80% of the classified points were accurately identified as shadow, soil, crop residue, or vegetation at each study site and RS acquisition. Average estimates of residue cover per RS acquisition were used in statistical analyses (Table 1).

Volumetric surface soil water content (θ_v, 0–5 cm) was obtained coincident with each RS acquisition using a Wet Sensor probe (Dynamax, Houston, TX). The Wet Sensor probe uses a measure of the dielectric constant of the soil matrix to estimate volumetric water content (Topp et al., 1980; Whalley, 1993). The general equation can be solved to estimate volumetric water content:

$$\sqrt{\varepsilon} = a_0 + a_1(\theta_v) \quad [1]$$

where $\sqrt{\varepsilon}$ is the square root of the dielectric constant, θ_v is volumetric soil water content, a_0 is the intercept, and a_1 is the slope. Using default calibration parameters for a mineral soil, the Wet Sensor has an accuracy of $\pm$3 to 5% volumetric water content. Because the probe was 7.6 cm in length, it was inserted at a 45° angle to ensure only the upper 5 cm of soil water content was measured. Wet Sensor measurements were made at four random locations and composited within each plot. Because soil water content can vary from 0 to 5 cm, precipitation data preceding RS data acquisitions have been provided (Fig. 1). In addition, composite soil samples were collected within each plot at the onset of the study (0–20 cm) for soil texture on the <2 mm fraction (Kilmer and Alexander, 1949).

Residue Assessments

Line Transect Measurements

Line transect measurements of rye residue cover were performed by adapting the methods of Thoma et al. (2004) and others (Shelton et al., 1993; Eck et al., 2001). Line-transect estimates were made in the laboratory using reproduced digital images of rye residue. Each sample location was approximately 50% of the sample area suggested by Thoma et al. (2004) (3.05 m length marked at 2.5-cm intervals) and was reproduced on poster board at 50% of actual size. To accommodate for the sample size and reproduction, we used a 0.75-m transect with tick marks at 0.63-cm intervals.

The line transect was a flat, plastic measuring stick marked with tape beginning at zero and continuing at 0.63-cm intervals to 0.75 m (120 tick marks). A tick mark was counted each time a piece of residue touched the outside, left edge of the tape (Shelton et al., 1993; Eck et al., 2001). Only crop residues having a width >0.25 cm were counted (Shelton et al., 1993). Percent cover was calculated by dividing the counted number of ticks by total ticks (n = 120) along the transect and multiplying by 100. To evaluate variability in the line transect approach, two transects were established for each image: (i) upper left corner to lower right corner, and (ii) lower left corner to upper right corner.

CropScan Multispectral Radiometer

Reflectance measurements were collected using a handheld CropScan Multispectral Radiometer (CropScan, Rochester, MN). The CropScan uses narrow band interference filters to select discrete bands in the VIS and NIR regions of the electromagnetic spectrum. Eight bands were measured in this study within the 485 to 1650 nm range (Table 2). The CropScan is equipped with upward and downward looking sensors in each band, and simultaneously acquires irradiance as well as radiance over the target. It is assumed that irradiance over the sensor head is equal to irradiance over the target. Radiance and irradiance were measured in millivolts, adjusted for temperature of the Cropscan, and converted to an energy term. Percent reflectance was determined using the following equation:

$$\text{Radiance}/\text{Irradiance} \times 100 = \%\ \text{Reflectance} \quad [2]$$

All plot data were collected as close to solar noon as possible, under clear conditions. Data were collected at nadir, over row middles, from a distance of 2 m to approximate a 1m^2 spatial resolution on the ground. In the ST treatments, where crop

Table 1. Crop residue cover determined via digital image classification for strip tillage (ST) treatments at the Coastal Plain and no-tillage (NT) treatments at the Piedmont study sites. Image acquisition dates and days after planting (DAP) are given. Average crop residue cover estimates are given with standard errors in parentheses.

Site	Date	DAP	Treatment	Cover: Soil		Crop residue		Vegetation		Shadow	
		days		%							
Coastal Plain	24 May 2004	12	ST	33	(3)	30	(2)	4	(1)	34	(4)
			CT	73	(3)	-	-	5	(3)	22	(5)
	8 June 2004	27	ST	30	(1)	28	(2)	20	(2)	22	(2)
			CT	62	(2)	-	-	24	(2)	15	(6)
	16 June 2004	35	ST	22	(2)	29	(3)	36	(4)	21	(2)
			CT	41	(7)	-	-	48	(4)	11	(4)
Piedmont	19 Apr. 2005	1	NT	26	(14)	36	(5)	0	-	38	(5)
			CT	49	(6)	-	-	0	-	35	(2)
	27 Apr. 2005	9	NT	23	(10)	52	(4)	8	(6)	22	(14)
			CT	57	(12)	-	-	0	-	28	(4)
	9 May 2005	21	NT	11	(10)	47	(6)	6	(5)	36	(5)
			CT	66	(6)	-	-	0	-	30	(4)

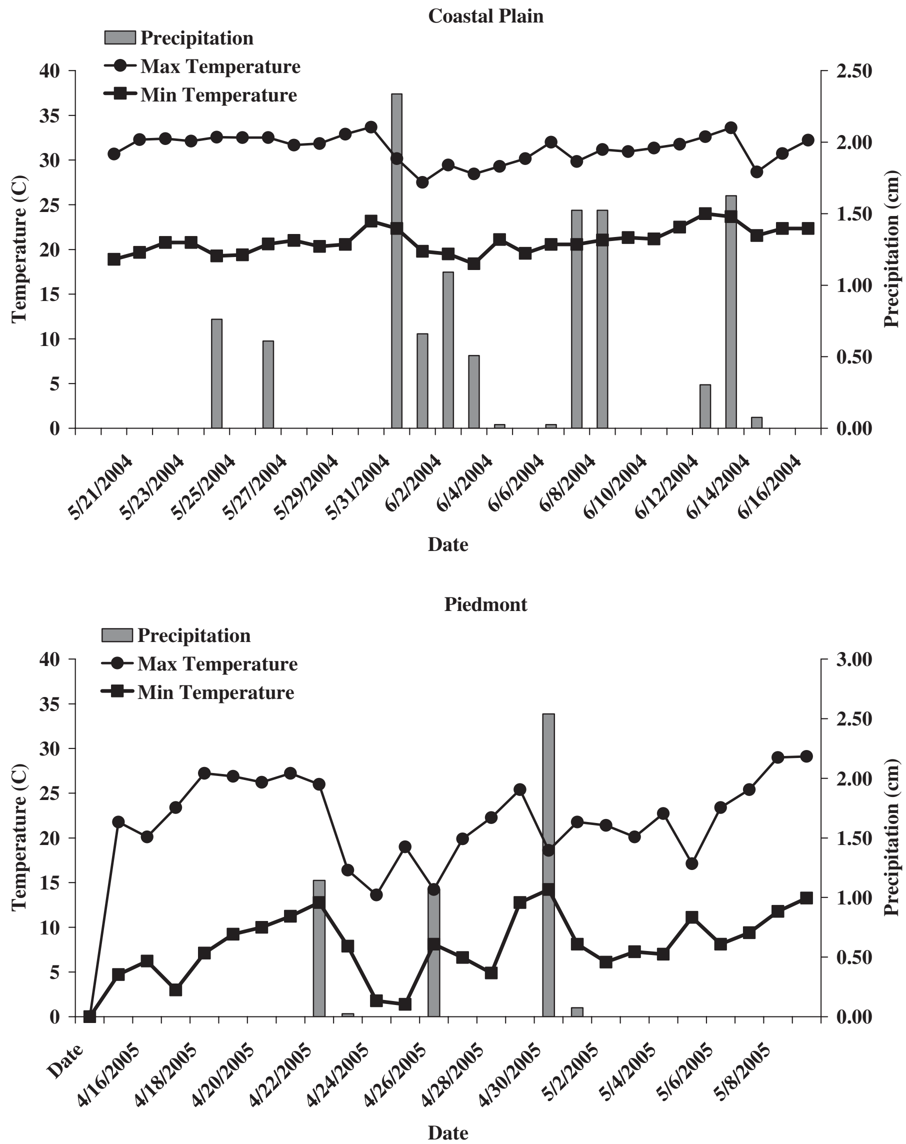

Fig. 1. Daily minimum (min) and maximum (max) air temperature in Celsius, as well as daily precipitation (PPT-cm) for the Coastal Plain (21 May–16 June 2004) and Piedmont (16 Apr.–8 May 2005) study sites. Sampling times are denoted (*) for each site.

residues were not evenly distributed across the plot, CropScan measurements encompassed a 15 to 20 cm tilled strip with 40 cm strips of crop residue cover on either side of the row middle. Data collection consisted of four random points within each plot.

Table 2. Specifications for the CropScan Multispectral Radiometer (1.0 m spatial resolution).

Wavelength			
From	To	Band	Spectrum–region
nm			
485 ± 45		B1	visible - blue
560 ± 40		B2	visible - green
650 ± 20		B3	visible - red
660 ± 30		B4	visible - red
830 ± 70		B5	near infrared
850 ± 35		B6	near infrared
1240 ± 6		B7	near infrared
1640 ± 8		B8	near infrared
1650 ± 100		B9	near infrared

Fluke Ti30 Thermal Infrared Imager

Thermal infrared red data were collected using a hand-held Fluke Ti30 Thermal Infrared Imager (Fluke Corp., Everett, WA). The Fluke Ti30 measures emittance in one broad band (7000–14 000 nm) with a 17° horizontal and 12.8° vertical field of view. Imagery was acquired at nadir from a distance of 2.0 m. At this height the ground resolution was 0.23 by 0.31 m. All data were taken coincident with CropScan measurements between 1000 and 1200 h, looking over the center of the same target. Due to spatial resolution constraints of the Ti30, it was assumed that surface features within a 1m^2 area were similar. To verify this assumption, coefficients of variation were calculated using subsamples ($n = 4$) of TIR data within each treatment. Based on this analysis, variability in emittance within a plot was typically <10%.

Because TIR data were acquired over approximately 1 h, it was necessary to adjust all output for changes in ambient air temperature. Ambient air temperatures were recorded using a HOBO Pro Temp/RH Weatherproof Recorder and radiation shield (Onset Computer Corp., Bourne, MA). Temperatures were recorded every 2 min throughout each RS acquisition and used to calibrate TIR data. Since surface temperatures were highly correlated ($r = 0.91$, $P < 0.10$) with ambient air temperature, each Ti30 measurement was adjusted using a simple difference approach (Sadler et al., 2002). Thus, each TIR measurement was adjusted by adding or subtracting the change in ambient air temperature from initial conditions.

Statistical Analysis

Using the Statistical Analysis System (SAS Inst., Cary, NC), an analysis of variance ($\alpha = 0.10$) was used to evaluate differences in tillage regime using line-transect, visible, NIR, or TIR methods of estimation. Visible and NIR indices included the greenness normalized difference vegetation index (GNDVI) (Gitelson et al., 1996), which was calculated as:

$$\text{GNDVI} = (\text{NIR}_{830\text{nm}} - \text{green}_{560\text{nm}})/(\text{NIR}_{830\text{nm}} + \text{green}_{560\text{nm}}) \quad [3]$$

where NIR corresponds to 830 ± 70 nm and green corresponds to 560 ± 40 nm, and normalized difference vegetation index (NDVI; Rouse et al., 1974) calculated as:

$$\text{NDVI} = (\text{NIR}_{830\text{nm}} - \text{red}_{660\text{nm}})/(\text{NIR}_{830\text{nm}} + \text{red}_{660\text{nm}}) \quad [4]$$

where red corresponds to 660 ± 30 nm portion of the spectrum. Since data encompassed multiple bands within the VIS and NIR spectrum additional RS indices were evaluated based on analysis of spectral response curves.

Next, linear regression analyses were used to determine the degree of variability between tillage treatments that could be explained via the line transect, VIS/NIR indices or TIR methods. It should be noted that a significant linear relationship between RS data (VIS, NIR, and TIR) and increasing crop residue cover has been established (Biard and Baret, 1997; Nagler et al., 2003; Sullivan et al., 2004). Thus, extreme residue cover conditions (NT or ST vs. CT) were sufficient to establish a relationship between residue cover and RS data. Because tillage regimes differed between sites (NT vs. ST) statistical analyses were run individually for each site. Average crop residue cover estimates for NT and ST treatments during each RS acquisition were used in the regression analyses.

RESULTS AND DISCUSSION

Spectral Response Curves

Coastal Plain

The overall shape of spectral response curves in the VIS and NIR region (485–1650 nm) was similar for CT and ST treatments, indicating that residue and soil spectra behave similarly (Fig. 2). However significant ($P < 0.10$) differences in the magnitude of spectral response were observed throughout the VIS and NIR. Typically, CT treatments were more reflective compared to ST treatments. This is likely attributable to the inherently sandy soil surfaces common in the Coastal Plain (sand = 85%). Many studies report increasing spectral response with increasing proportions of sand content (Mathews et al., 1973; Stoner and Baumgardner, 1981; Salisbury and D'Aria, 1992). Because surface soil water has a tendency to absorb incoming light energy, sandy soils with low water-holding capacities are more reflective (Capehart and Carlson, 1997).

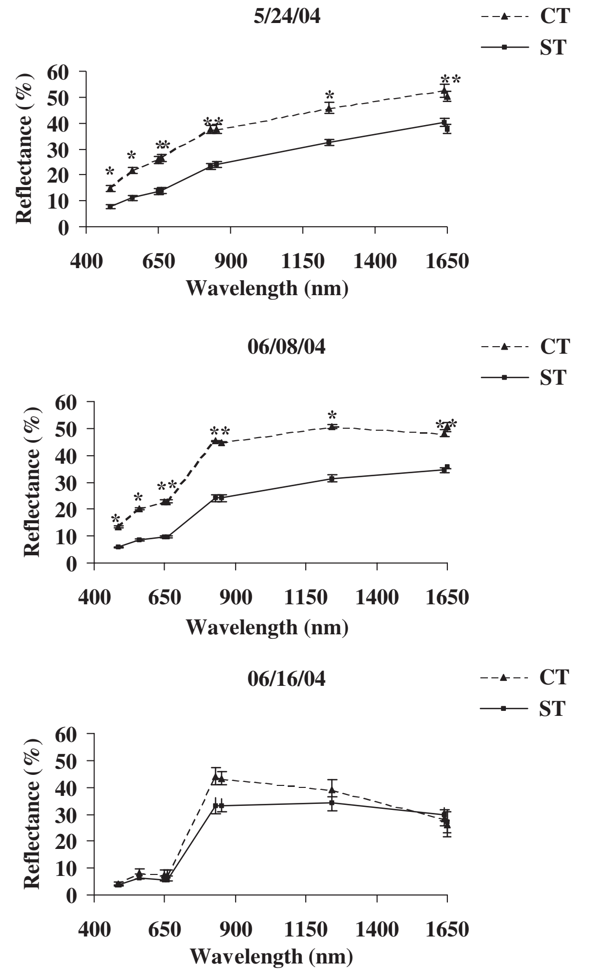

Fig. 2. Spectral response curves for conventional (CT) and strip tillage (ST) treatments at the Coastal Plain study site. Data represent average reflectance (%) along the *y* axis and wavelength (485–1650 nm) along the *x* axis for remotely sensed data acquisitions on 24 May, 8 June, and 16 June 2004. Significant treatment differences for each wavelength are denoted (*) ($\alpha = 0.10$).

Differences in the shape and magnitude of spectral response curves were observed over time as well (Fig. 2). Treatment differences were best observed during dry conditions (<1 $\text{cm}^3\ \text{cm}^{-3}$) and early stages of crop development (Table 1). During the May sampling, spectral response curves increased without inflection from 485 to 1650 nm. Similar results, showing increasing spectral response without inflection have also been reported (Baumgardner et al., 1985; Aase and Tanaka, 1991; Daughtry et al., 1996; Sullivan et al., 2004). Reflectance was greatest from CT treatments ranging from 15 to 53% compared to 8 to 40% for ST treatments. At this time, significant differences between treatments were greatest in the 1240 to 1650 nm range ($P < 0.10$). A similar response was observed on the 8 June acquisition; however, presence of a growing peanut canopy was evident by a characteristic change in slope between 650 and 830 nm. During the 8 June acquisition, the peanut canopy represented 20 to 24% of the target area. This corresponds to a NDVI value of 0.33 for CT and 0.42 for ST. Despite the increasing canopy coverage, significant treatment differences were observed between 1240 and 1650 nm. As the canopy exceeded 25% cover, peanut canopy predominated spectral response curves and limited our ability to differentiate between treatments. Thus no significant differences in spectral response were observed between treatments during the 16 June RS acquisition. Daughtry et al. (2005) also found that increasing canopy cover limited crop residue cover estimates. In their study, when the fraction of green canopy exceeded 0.3, estimates of crop residue cover were lower than expected.

In the TIR, no treatment differences were observed ($P < 0.10$). Direct measures of ground temperature showed no significant differences between treatments and suggest that heat capacities of mineral soil and crop residues had not yet been reached. Results contradict previous findings by Sullivan et al. (2004), which showed significant differences between bare soil emittance and varying degrees of wheat residue cover (10–80% cover). Conflicting results were likely associated with differences in the time of RS acquisition. Sullivan et al. (2004) collected airborne imagery at 1430 h EST, compared to 1100 h EST in this study. Perhaps the earlier acquisition time in our study may not have been adequate to capture differences in surface emittance associated with contrasting heat capacities of soil and crop residue. Future work is necessary to evaluate the impact of image acquisition time for TIR assessments of cover.

Piedmont

At the Piedmont site, the overall shape of the spectral response curve was similar for NT and CT treatments, steadily increasing from 485 to 1650 nm (Fig. 3). Differences in spectral response were greatest in the NIR compared to the VIS. As a result of higher clay content at this site, surface soil water contents were relatively higher in the Piedmont compared to the Coastal Plain site, ranging from 8 to 18 cm^3 cm^{-3} (Table 3). Thus, compared to the Coastal Plain site, more irradiant energy was absorbed at the soil surface and NT treatments were more reflective compared CT treatments. Data demonstrate the impact that surface soil properties can have on spectral response and our ability to accurately differentiate between conservation tillage and CT systems in two different physiographic regions.

Because RS data were acquired before crop emergence, canopy interference was minimal at this site. Thus, spectral differences observed over time were primarily associated with changes in soil water content between RS acquisitions (Table 3). Soil water contents were significantly lower ($x = 7.8$ cm^3 cm^{-3}, $P < 0.10$) during the 19 April and 9 May data acquisitions compared to the 27 April acquisition ($x = 18.0$ cm^3 cm^{-3}). Under relatively dry conditions reflectance ranged from 8.5 to 40% for NT and 5 to 34.2% for CT treatments (Fig. 3). Differences between treatments were greatest in the 1240 to 1650 nm region ($P < 0.10$). As soil water content increased, reflectance decreased by as much as 10.8 and 13.1% (absolute) for NT and CT treatments, respectively. Despite increasing soil water content, significant spectral differences were observed in the 830 to 1240 nm range (LSD > 7%, $P < 0.10$).

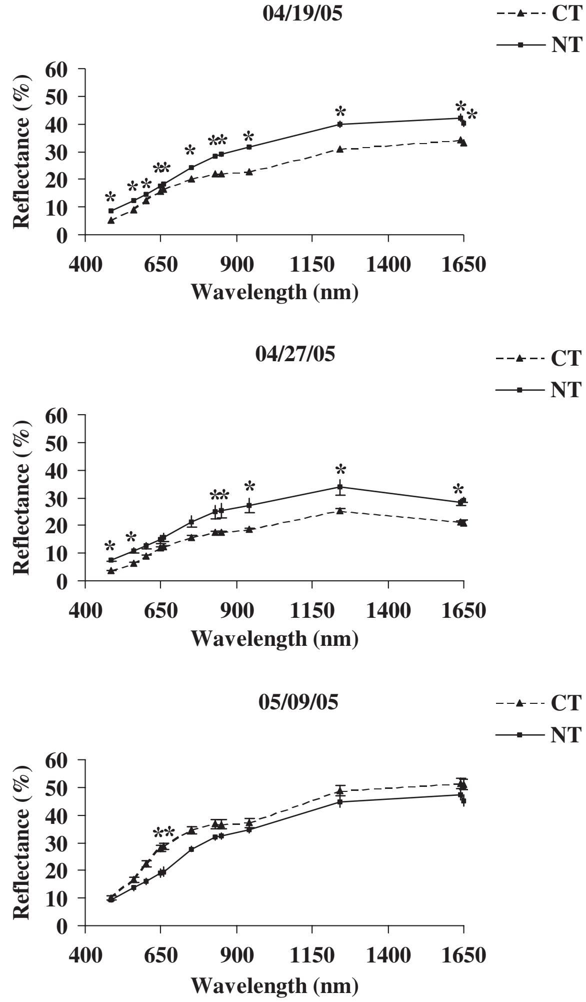

Fig. 3. Spectral response curves for conventional (CT) and no-tillage (NT) treatments at the Piedmont study site. Data represent average reflectance (%) along the *y* axis and wavelength (485–1650 nm) along the *x* axis for remotely sensed data acquisitions on 19 Apr., 27 Apr., and 9 May 2005. Significant treatment differences for each wavelength are denoted (*) (α = 0.10).

In the TIR, no significant differences between treatments were observed. As previously mentioned, this may be related to pre-noon RS acquisitions. Additional research is necessary to identify timing for optimal TIR acquisitions.

Table 3. Volumetric surface soil water content (SWC) variability and surface texture at the Coastal Plain and Piedmont study sites. Means followed by the same letter are not significantly different at alpha = 0.10. Least significant differences were 1.11% at the Coastal Plain and 3.30% at the Piedmont study sites.

Site	Date	SWC	Surface texture	Sand	Clay
		cm^3 cm^{-3}		%	
Coastal Plain	24 May 2004	0.37 B	loamy sand	85	4
	8 June 2004	1.39 B			
	16 June 2004	8.57 A			
Piedmont	19 Apr. 2005	7.79 B	sandy loam	65	22
	27 Apr. 2005	18.00 A			
	9 May 2005	7.82 B			

Cover Estimates

Remotely sensed crop residue cover indices were compared to line-transect estimates of cover to evaluate the utility and accuracy of a rapid, RS residue cover assessment.

Line Transect

Pairs of transects were compared to evaluate variability in the line-transect approach. At both sites, no significant differences were observed between pairs of transects. However, differences in estimated residue cover over time were observed ($P < 0.10$). Since cover estimates were acquired over a short sampling period, differences in estimated cover were likely due to variability in sample location within a plot. Although treatment differences between NT or ST and CT treatments were significant, variability in cover estimates over time suggest that point-based sampling methodologies may not yield spatially representative estimates.

Using the line-transect technique in linear regression, the line-transect explained >95% of the variability in residue coverage at both sites despite differences in surface conditions at the time of data acquisition (Table 4).

Table 4. Regression parameters describing the relationship between crop residue cover and the line transect, greenness vegetation index (GNDVI = (830 − 560 nm)/(830 + 560 nm)), normalized vegetation index (NDVI = (830 − 660 nm)/(830 + 660 nm)), and crop residue cover indices (CRC1 = (1650 − 485 nm)/(1650 + 485 nm), CRC2 = (1650 − 650 nm)/(1650 + 650 nm), and CRC3 = (1650 − 660 nm)/(1650 + 485 nm)). Dashed lines indicate no significant treatment differences were observed (alpha = 0.10).

Site	Date	Index	Intercept	Slope	r^2
Coastal Plain	24 May 2004	Line	0.30	1.23	0.98
		GNDVI	−86.75	322.33	0.84
		NDVI	–	–	–
		CRC1	−120.00	223.45	0.84
		CRC2	−54.19	179.38	0.91
		CRC3	−72.79	185.81	0.92
Coastal Plain	8 June 2004	Line	0.44	1.20	0.97
		GNDVI	−107.71	281.58	0.85
		NDVI	–	–	–
		CRC1	−115.58	198.35	0.99
		CRC2	−51.25	137.24	0.98
		CRC3	−63.22	147.42	0.98
Coastal Plain	16 June 2004	Line	−0.10	0.89	0.99
		GNDVI	–	–	–
		NDVI	–	–	–
		CRC1	–	–	–
		CRC2	–	–	–
		CRC3	–	–	–
Watkinsville	19 Apr. 2005	Line	14.66	1.01	0.96
		GNDVI	–	–	–
		NDVI	−105.25	808.32	0.93
		CRC1	594.79	−801.03	0.96
		CRC2	−481.83	1469.06	0.88
		CRC3	747.42	−1274.67	0.90
Watkinsville	27 Apr. 2005	Line	5.56	1.30	0.95
		GNDVI	403.36	−855.38	0.85
		NDVI	−96.03	760.52	0.60
		CRC1	399.19	−550.17	0.93
		CRC2	–	–	–
		CRC3	378.66	−684.40	0.85
Watkinsville	9 May 2005	Line	1.00	1.53	1.00
		GNDVI	–	–	–
		NDVI	−60.30	561.97	0.89
		CRC1	–	–	–
		CRC2	−156.07	589.49	0.92
		CRC3	–	–	–

Spectral Indices

Five spectral indices were evaluated as a means to estimate crop residue cover remotely. Indices were created as a normalized ratio between two RS bands to minimize differences in spectral response associated with illumination, shadow, surface roughness, and atmospheric attenuation. Two indices comprised commonly used vegetation indices: the GNDVI and the NDVI. Three additional crop residue cover (CRC1, CRC2, and CRC3) indices were developed based on highly significant differences between bare soil and crop residue reflectance in the NIR. The first spectral index (CRC1) was developed to capture the greatest range in spectral response:

$$\mathrm{CRC1} = (\mathrm{NIR}_{1650\mathrm{nm}} - \mathrm{Blue}_{485\mathrm{nm}})/(\mathrm{NIR}_{1650\mathrm{nm}} + \mathrm{Blue}_{485\mathrm{nm}}) \quad [5]$$

where NIR corresponds to 1650 ± 100 nm, and blue corresponds to 485 ± 45nm (Fig. 2 and 3). van Deventer et al. (1997) used a similar index, based on the normalized difference of LandSat TM bands 1 (450–520 nm) and 5 (1550–1750 nm) to detect conservation tillage in selected fields in Ohio. The LandSat band ratio resulted in an overall accuracy of 81.5%. Because red spectra have also been correlated with residue coverage (McMurtrey et al., 1993; Sullivan et al., 2004) CRC2 and CRC3 were developed using a combination of red and NIR spectra as follows:

$$\mathrm{CRC2} = (\mathrm{NIR}_{1650\mathrm{nm}} - \mathrm{Red}_{650\mathrm{nm}})/(\mathrm{NIR}_{1650\mathrm{nm}} + \mathrm{Red}_{650\mathrm{nm}}) \quad [6]$$

$$\mathrm{CRC3} = (\mathrm{NIR}_{1650\mathrm{nm}} - \mathrm{Red}_{660\mathrm{nm}})/(\mathrm{NIR}_{1650\mathrm{nm}} + \mathrm{Red}_{660\mathrm{nm}}) \quad [7];$$

where $\mathrm{Red}_{650\mathrm{nm}}$ corresponds to 650 ± 20 nm, and $\mathrm{Red}_{660\mathrm{nm}}$ corresponds to 660 ± 30 nm.

At the Coastal Plain study site, significant differences between ST and CT treatments were observed using all RS indices, except the NDVI (Fig. 4). Differences in spectral response between CT and ST treatments were best observed before 25% canopy closure. Once the peanut canopy exceeded 25% cover (NDVI > 0.33), reflectance from the developing peanut canopy masked crop residue reflectance. Furthermore, increasing canopy cover was positively correlated with GNDVI and NDVI indices ($r = 0.82$, $P < 0.10$), which limits our ability to accurately assess crop residue cover in the presence of developing vegetation. Daughtry et al. (2005) also reported a linear relationship between vegetative indices and canopy cover, which limited the utility of vegetative indices in crop residue cover determination.

To determine the impact of changing canopy conditions and soil water content on our ability to distinguish between tillage regimes, a sensitivity analysis was conducted comparing the magnitude of change in remotely sensed index values to a benchmark index value. Remotely sensed data collected before canopy closure with low soil water content were used to calculate benchmark indices (24 May 2004). In our study, GNDVI and NDVI index values increased 40 to 180% as a result of increasing canopy closure (Fig. 4).

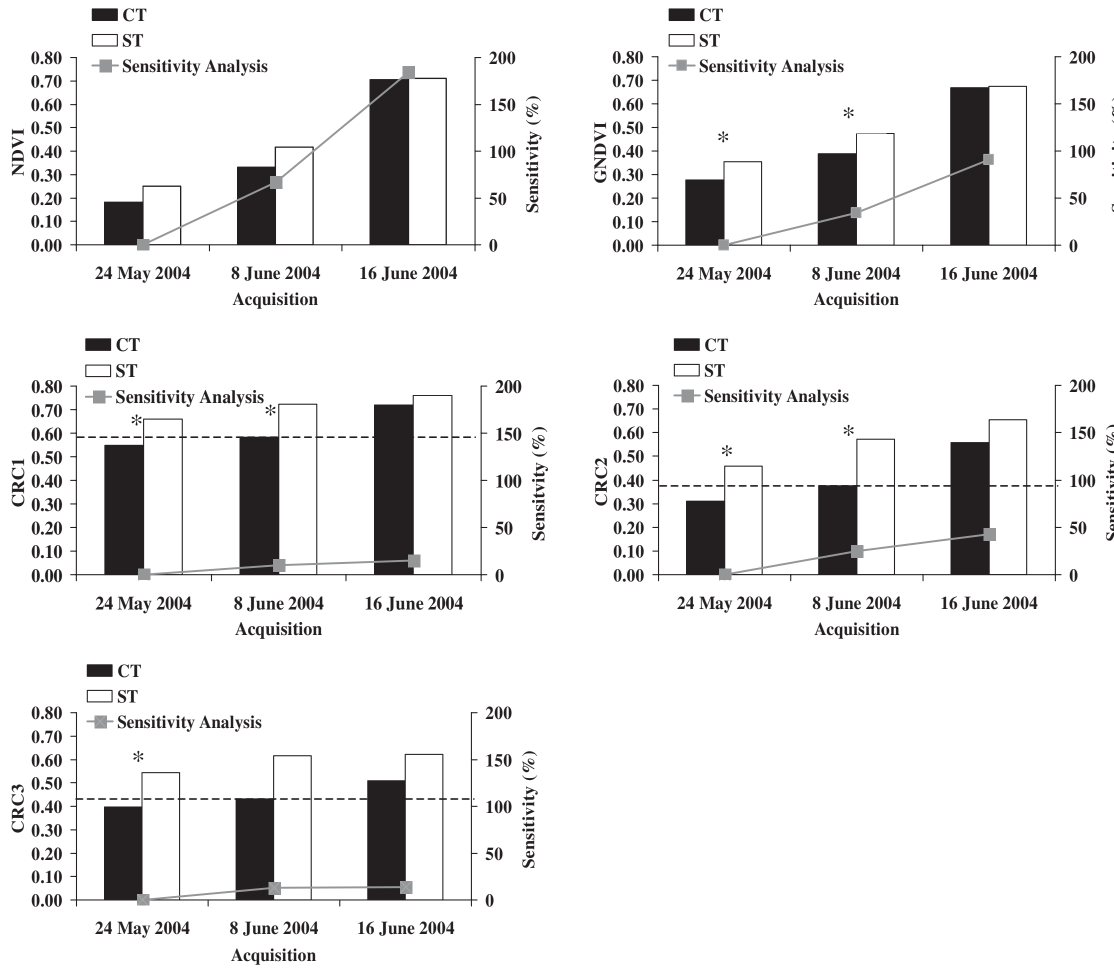

Fig. 4. Data represent analysis of variance results between conventional (CT) and strip-tillage (ST) treatments at the Coastal Plain study site for each remotely sensed index. Remotely sensed index values are listed along the primary *y* axis, percent change from initial surface conditions along the secondary *y* axis, and wavelength (485–1650 nm) along the *x* axis for remotely sensed data acquisitions on 24 May, 8 June, and 16 June 2004. Remotely sensed indices include the greenness normalized difference index (GNDVI), the normalized difference vegetation index (NDVI), crop residue index 1 [CRC1 = (1650 − 485 nm)/(1650 + 485 nm)], crop residue index 2 [CRC2 = (1650 − 650 nm)/(1650 + 650 nm)], and crop residue index 3 [CRC3 = (1650 − 660 nm)/(1650 + 660 nm)]. Significant treatment differences for each wavelength are denoted (*) (α = 0.10). Dashed lines represent minimum threshold values for distinguishing between treatments.

Compared with vegetative indices, CRC indices more consistently differentiated between tillage treatments over time. Treatment differences were best observed during the 24 May and 8 June RS acquisitions. Although CRC indices use a portion of the NIR spectrum, the correlation between CRC indices and canopy cover ($r <$ 0.56, $P < 0.10$) was generally lower compared to vegetation indices. Before canopy closure, CRC index values varied as much as 10 to 38% as a function of soil water content (Table 3) with CRC1 and CRC3 exhibiting the greatest stability (Fig. 4). However, given the low range in soil water content studied here, future research is necessary to determine the effects of changing soil water content on our ability to distinguish between CT and ST using the CRC1 or CRC3.

Threshold values, based on separability of ST and CT plots, were established for each of the three crop residue indices for the 24 May and 8 June 2004 RS acquisition dates. During this time, tillage treatments were separable using a unique CRC threshold value. Specifically, ST treatments exhibited a CRC index value greater than the established threshold of 0.58, 0.38, or 0.43 for the CRC1, CRC2, and CRC3, respectively (Fig. 4).

At the Piedmont study site, significant treatment differences were a function of RS index and surface (residue and soil) conditions at the time of data acquisition. Treatment differences were best observed using the NDVI, CRC1, and CRC3 indices (Fig. 5). Keeping in mind that canopy interference was minimal at this site, the NDVI accurately and consistently differentiated between CT and NT treatments, despite differences in soil water content between RS acquisitions. No-tillage treatments typically exhibited a threshold NDVI > 0.16. Moreover, volumetric water content ranged from 8 to 18 $cm^3\ cm^{-3}$ with NDVI values fluctuating within 2% of the benchmark index calculated using RS data acquired on 19 Apr. 2005. Results suggest that the NDVI, if acquired proximate to planting, is relatively stable under the range in soil water content studied here, and may be used to differentiate between tillage regimes in the Southern Piedmont physiographic region.

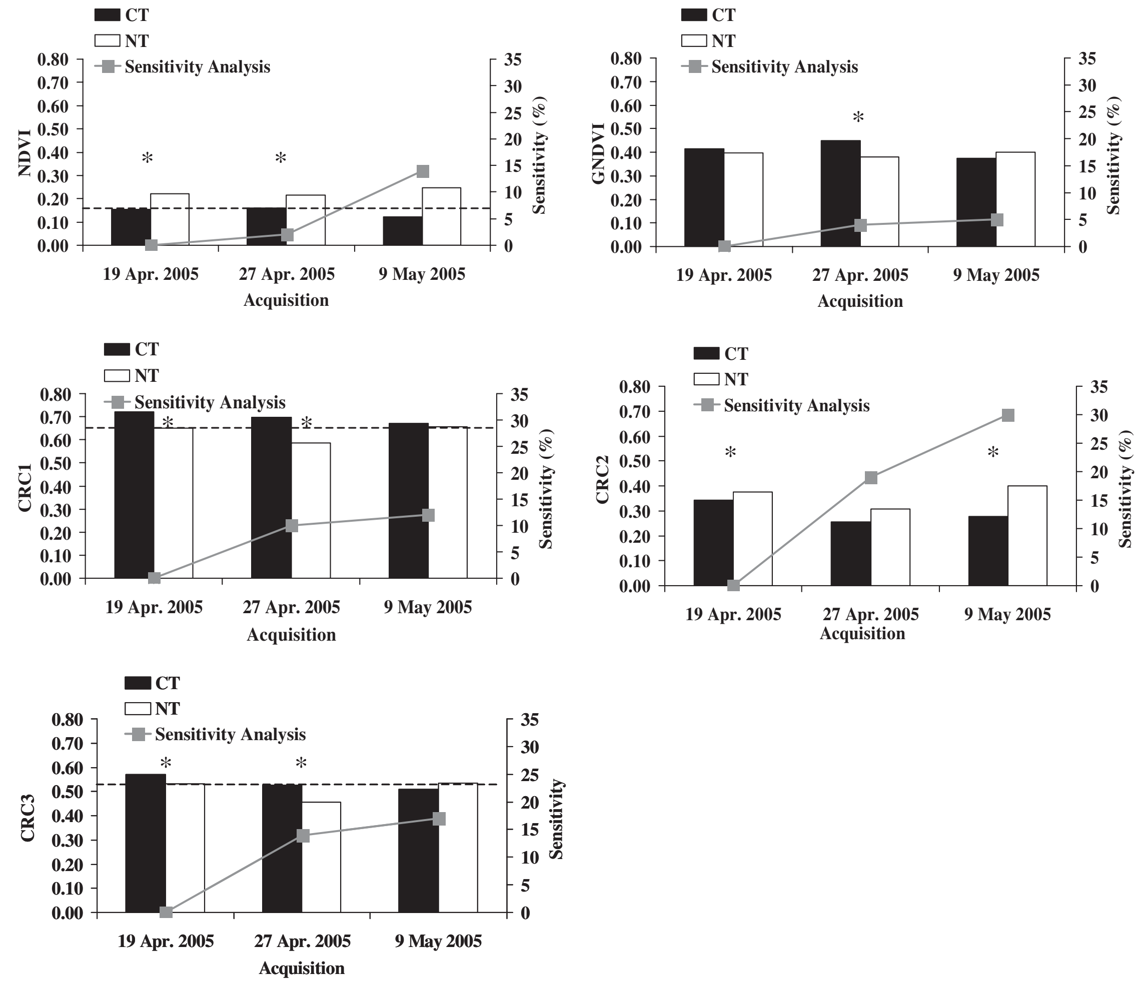

Fig. 5. Data represent analysis of variance results between conventional (CT) and no-tillage (NT) treatments at the Piedmont study site for each remotely sensed index. Remotely sensed index values are listed along the primary *y* axis, percent change from initial surface conditions along the secondary *y* axis, and wavelength (485–1650 nm) along the *x* axis for remotely sensed data acquisitions on 19 Apr., 27 Apr., and 9 May 2005. Remotely sensed indices include the greenness normalized difference index (GNDVI), the normalized difference vegetation index (NDVI), crop residue index 1 [CRC1 = (1650 − 485 nm)/(1650 + 485 nm)], crop residue index 2 [CRC2 = (1650 − 650 nm)/(1650 + 650 nm)], and crop residue index 3 [CRC3 = (1650 − 660 nm)/(1650 + 660 nm)]. Significant treatment differences for each wavelength are denoted (*) (α = 0.10). Dashed lines represent minimum threshold values for distinguishing between treatments.

Crop residue cover indices best differentiated between tillage treatments during the 19 and 27 April RS acquisitions. Lack of a significant treatment difference during the 9 May acquisition is unclear given surface soil water contents had returned to 19 April conditions (Table 3). Since reflectance properties are indicative of surface conditions only, dry and dusty conditions during the 9 May acquisition may have contributed to our inability to differentiate between treatments at this time.

Crop residue cover index values varied from 10 to 30% of the benchmark index calculated on 19 Apr. 2005 (Fig. 5). The CRC1 provided the most consistent results, exceeding benchmark CRC1 values by 10% under moist soil conditions (Table 3). Using the CRC1, NT treatments were separated using a threshold value <0.65. Significant treatment differences were also observed using CRC3 for both April RS acquisitions, however, the CRC3 was more sensitive to changes in soil water content. For NT treatments the maximum observed CRC3 value ranged from 0.46 under moist soil conditions to 0.53 under dry soil conditions, compared to 0.53 and 0.57 for CT treatments under dry and wet conditions, respectively (Fig. 5). Because the observed CRC3 values for CT and NT treatments overlap as soil conditions change, it would be difficult to differentiate between tillage systems using CRC3 without a priori knowledge of surface soil water content. Other studies confirm, that variability in surface conditions at the time of RS data acquisition significantly impact estimates of vegetative cover (Daughtry et al., 1995; Guerif and Duke, 2000; Nagler et al., 2003).

Linear regression was used to compare the amount of variability between tillage treatments explained using the line transect approach and RS indices (Table 4). Only RS indices that exhibited significant ($P < 0.10$) differences between CT and ST or NT treatments were used in the analysis. At the Coastal Plain site the GNDVI and CRC indices explained >84% of the variability in crop residue cover. In Piedmont, the NDVI, CRC1, and CRC3 were best during the April RS acquisitions, having coefficients of determination from 0.60 to 0.96 with CRC1 explaining the greatest degree of variability between tillage treatments (Table 4).

Crop residue cover indices, particularly CRC1 and CRC3, performed similarly to the line transect method of crop residue estimation (Table 4). Although, the line transect method was not sensitive to changes in soil water content and canopy cover, the line transect approach may not provide spatially representative estimates of crop residue cover distribution.

CONCLUSIONS

Remotely sensed data in the VIS, NIR, and TIR spectrum were used to determine threshold index values as a means to differentiate between tillage regimes in two different physiographic regions in Georgia. Two common band ratios, the GNDVI and the NDVI, a TIR band (8000–12 000 nm), and three crop residue indices were compared to the standard line-transect method of crop residue cover estimation. Remotely sensed indices (crop residue cover indices and vegetation indices) performed similarly to the line-transect method of estimation, however, no significant correlation between cover and the TIR band was observed. Crop residue cover index 1, encompassing the NIR (1650 nm) and blue (485 nm) regions of the spectrum, was less highly correlated with vegetation ($r = 0.55$, $P < 0.10$)) and least sensitive to changes in soil water content at each site compared to ratios combining NIR with red (660 nm) or green (520 nm) regions of the spectrum.

Surface soil property variability between sites, was perhaps the greatest single variable affecting the crop residue cover indices. In our study, crop residue reflectance generally ranged from 8 to 40% (485–1650 nm), however, the magnitude of response was greater or less than bare soil reflectance as a function of surface soil texture and soil water content. Surface soil texture was the greatest determining factor of crop residue cover index threshold values. Variability in soil water content was secondary to differences in soil texture, however, additional information is necessary to determine the robustness of CRC Index 1 over a wider range of soil water content.

Considering that line-transect estimates are time and resource intensive, results are promising and suggest that threshold RS index values, when used in combination with commonly available soil survey data, may be used to more rapidly differentiate between CT and ST systems compared to the line-transect approach. Remotely-derived crop residue cover maps are necessary to determine eligibility for federal conservation program resources, assess changes in watershed hydrology, and better determine the impact that conservation tillage practices have on soil and water quality.

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