Spectral Reflectance Properties of Winter Cover Crops in the Southeastern Coastal Plain

D.G. Sullivan,* J.N. Shaw, A. Price, and E. van Santen

ABSTRACT

Conservation tillage is a commonly adopted best management practice for reducing runoff and erosion, and increasing infiltration. Yet current methodologies in place to monitor conservation tillage adoption are largely inappropriate for regional or national assessments. A major goal of this study was to evaluate the spectral response properties of four alternative winter cover crops using remotely derived crop residue cover indices. Experimental plots were located in east-central Alabama on a coarse-loamy siliceous, subactive, thermic Plinthic Paleudult. The experiment was a randomized complete block design having four replications of each of the following treatments: one fallow conventional tillage treatment and four no-tillage treatments with black oat (*Avena strigosa* Schreb.), crimson clover (*Trifolium incarnatum* L.), turnip (*Brassica rapa* L. *subsp.rapa*), or rye (*Secale cereale* L.) cover crops. Remotely sensed data were acquired three times using a ~14 d sampling interval beginning near planting and using a handheld multispectral radiometer (485–1650 nm) in 2005 and 2006. Three crop residue cover indices using combinations of middle-infrared and visible spectra were compared and evaluated. Rye, clover, and black oat were spectrally similar, having an overall spectral response ranging from 8 to 45% (440–1650 nm). Increasing soil water content between remotely sensed data acquisitions was evidenced by as much as a 24% decline in middle-infrared reflectance. Despite this variability, a normalized difference ratio of middle-infrared (1650 nm) and blue (445 nm) spectra (Crop Residue Cover Index) provided the most consistent differentiation between tillage systems, varying within 8% of benchmark conditions (low soil water and low canopy cover). Considering the impact that conservation tillage may have on soil and water resources, rapid, watershed scale assessments of conservation tillage adoption may facilitate natural resource inventories, carbon sequestration estimates, and improved agricultural water management regimes.

In 1997 the USDA-NRCS reported 44 million ha (108 million acres) as highly erodible land, which could potentially contribute 1.2 billion tons in erosion (USDA, 1997). In an effort to conserve natural resources, the 2002 Farm Security and Rural Investment Act increased conservation funding by $18.5 billion (Knight, 2003). Conservation tillage, one of the most widely adopted on-farm conservation practices for erosion control, is an accepted conservation practice under the Environmental Quality Incentives Program (EQIP) and the Conservation Security Program (CSP). According to the 1985 Food Security Act, lands considered "highly erodible" must implement an acceptable conservation program to remain eligible for farm benefits. Furthermore, cost-share recipients for reduced tillage systems must maintain a minimum of 30 to 50% crop residue cover to receive program reimbursements.

Recent estimates of conservation tillage practices indicate 41% of row crop producers have adopted conservation tillage practices nationwide (CTIC, 2004). The Conservation Technology Information Center (CTIC) provides the best estimate of conservation tillage adoption at a national scale. However, the CTIC uses a roadside survey, and results may overestimate crop residue cover in the 25 to 35% cover range compared with in-field line-transect estimates (Thoma et al., 2004). Recently, a number of studies have indicated that remote sensing (RS) technologies show promise as a rapid, unbiased estimator of crop residue cover and conservation tillage adoption (Biard and Baret, 1996; Chen and McKyes, 1993; Daughtry, 2001; Daughtry et al., 1995, 2004; Gausman et al., 1975; McMurtrey et al., 1993; Nagler, 2000; Su et al., 1997; Sullivan et al., 2004, 2006). However, few of these studies have evaluated RS of crop residue cover in the southeastern United States in highly weathered soil systems. In the southeastern United States in particular, long-term adoption of conservation tillage has proven an effective remediation strategy to reduce erosion, increase infiltration, sequester soil organic C, improve crop yields, and increase soil quality (Bauer and Reeves, 1999; Schwab et al., 2002; Bosch et al., 2005; Bronson et al., 2001; Endale et al., 2002; Terra et al., 2005; Truman et al., 2003, 2005).

Reflectance patterns between living and senescent vegetation (crop residue) differ primarily as a function of water and chlorophyll content. In living vegetation, a typical spectral response pattern exhibits strong absorption features in the visible (VIS) (300–600 nm) spectra, with a rapid rise in reflectance in the NIR (700–900 nm) (Gausman and Allen, 1973; Hatfield and Pinter, 1993). In portions of the infrared (700–2600 nm), reflectance is dependent on molecular vibrations of functional groups such as sugars, starches, cellulose, and lignins (Murray and Williams, 1988, p. 17–34). In living vegetation, water is the principal determinant of reflectance, attenuating absorbance features associated with lignin and cellulose in the near infrared (NIR) (Murphy, 1995). As the crop senesces, and water is lost, spectral response patterns associated with lignin and cellulose are evidenced by broad absorption bands in the visible (400–600 nm) and NIR (700–900, 1730, 2100,

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Crop Residues
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Abbreviations: CSP, Conservation Security Program; CTIC, Conservation Technology Information Center; CRC1, crop residue cover; EQIP, Environmental Quality Incentives Program; GNDVI, Greenness Normalized Difference Vegetation Index; MIR, middle infrared; NDVI, Normalized Difference Vegetation Index; NIR, near infrared; RS, remote sensing; VIS, visible.

and 2300 nm) (Curran, 1989; Elvidge, 1990; Kokaly and Clark, 1999).

Most studies report a crop residue spectral response curve as increasing without inflection throughout the VIS and NIR (Biard and Baret, 1996; Daughtry, 2001; Daughtry et al., 1995, 2004, 2005; McMurtrey et al., 1993; Sullivan et al., 2004). Differences between soil and crop residue spectra are evident primarily via a difference in the magnitude of response in the VIS and shortwave NIR. However, crop residue spectral response can be greater or less than soil spectra as a function of soil texture, soil water content, crop residue water content, vegetative fraction, and type of crop residue. McMurtrey et al. (1993) showed that sandy surface horizons were significantly more reflective than crop residues—corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean [*Glycine max* (L.) Merr.]—throughout the 400- to 900-nm region. When crop residue reflectance was compared with reflectance from a dark soil, crop residue reflectance was significantly greater in most cases.

Because residue and soil are spectrally similar, researchers have begun investigating tillage indices designed to reduce soil background effects, and enhance small differences between soil and crop residue spectra (Biard and Baret, 1996; Daughtry et al., 1996; McMurtrey et al., 1993; McNairn and Protz, 1993; Sullivan et al., 2006). Biard and Baret (1996) developed a linear mixing model by defining a "residue line" using a combination of two spectral bands. The linear mixing model explained 98% of the variability in crop residue cover, with a root mean square error of 3.5%. 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 at 2100 nm, which are highly correlated with the presence of cellulose and lignin in organic materials (Elvidge, 1990; Daughtry et al., 1996). Daughtry et al. (2005) indicated that 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 ($r^2 = 0.88$) when the vegetative cover fraction was <0.30.

Laboratory and field studies have successfully demonstrated the potential of remotely derived estimates of crop residue cover. Much of this work suggests that remotely derived estimates of crop residue cover are significantly impacted by soil property variability. However, few studies have quantified the impact of variability in soil water content on crop residue estimation in the southeastern United States, where conservation tillage practices are becoming increasingly common. Moreover, fewer have evaluated the variability in spectral response patterns for alternative winter cover crops in a subtropical production area. Therefore, the goals of this study were: (i) to compare spectral response patterns of four winter covers and (ii) to evaluate spectral indices as a tool for rapidly identifying tillage regime under variable soil water content, canopy conditions, and crop residues.

MATERIALS AND METHODS

Study Site

The study site was located at the E.V. Smith Research and Extension Center of the Alabama Agricultural Experiment Station in central Alabama (85°53′50″ W, 32°25′22″ N). The site is part of an experiment (established in 2001) designed to evaluate the impact of crop rotations and winter cover crop management in conservation tillage systems. For a more detailed description of the original study the reader is referred to (Saini et al., 2006).

In the current study, the experiment was a completely randomized design having four replications of each of the following treatments: one fallow conventional tillage treatment and four no-tillage treatments with black oat, crimson clover, turnip, or rye cover crops. Experimental plots were 9 m wide by 18.3 m long. All winter covers were selected such that the crimson clover, black oat, and rye fell within a continuous cotton system. However, turnip treatments were a component of a cotton–corn rotation. Turnip treatments typically followed cotton and were terminated 1 mo earlier than other covers in preparation for planting corn. It should be noted that all phases of the continuous corn and the cotton–corn rotation were present in each year.

Winter covers were planted with a no-tillage drill in early November at the following seeding rates: turnips at 4.48 kg ha^{-1}, clover at 22.4 kg ha^{-1}, black oat at 90 kg ha^{-1}, and rye at 90 kg ha^{-1}. Cover crops were terminated each spring approximately 6 to 15 d before planting using glufosinate at 0.52 kg ha^{-1}. A complete listing of cover crop planting, termination of winter cover, and cotton–corn planting dates is provided in Table 1, along with the corresponding RS data acquisitions.

Conventional tillage treatments were disked and then leveled using a rotortiller or field cultivator approximately 1 wk before planting cotton or corn. Planting dates for each crop are provided in Table 1.

All plots were maintained as weed-free throughout the RS data acquisition periods.

Ground Truth

Ground truth and RS data were collected three times during a 4-wk period in 2005 and 2006 (six times total). This time frame corresponded to 16 May to 15 June 2005 and 27 Apr. to 30 May 2006 (Table 1). Sampling times were chosen to evaluate the impact of increasing summer crop canopy on remotely sensed estimates of winter crop residue. Ground truth consisted of digital images, soil water content (0–5 cm), and residue C concentration.

Two digital images were taken at nadir from random locations within each plot to quantify the extent of winter residue cover. Digital images were acquired without a flash, using a 5-mega pixel Olympus C-505 Zoom (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. An

Table 1. Dates of site management operations (cover crop planting, cover crop termination, and spring crop establishment) and remotely sensed (RS) data acquisitions for cotton and corn.

Year	Crop	Winter cover: Planting	Winter cover: Termination	Spring planting	RS acquisitions
2005	cotton	13 Oct.	4 May	10 May	16 May
	corn	13 Oct.	4 Mar.	19 Apr.	3 June
					15 June
2006	cotton	3 Nov.	6 Apr.	20 Apr.	27 Apr.
	corn	3 Nov.	2 Mar.	14 Mar.	15 May
					30 May

unsupervised classification was used to estimate the total percentage of winter residue using ERDAS Imagine 8.4 (Leica Geosystems, Heerbrugg, Switzerland). Percentage residue cover was calculated by dividing pixels classified as residue by the total pixel count in each image.

An accuracy assessment of the classified images was conducted on a random selection of four images (conservation tillage plots only) from each RS acquisition date. Accuracy assessments were conducted using an adaptation of the line-transect method (Shelton et al., 1993; Eck et al., 2001; Thoma et al., 2004; Sullivan et al., 2006). Line-transect measurements were conducted on reproductions of digital images collected for classification of cover. Each digital image represented approximately 50% of the sample area (as 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 measuring stick marked with tape beginning 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 residues having a width >0.25 cm were counted (Shelton et al., 1993). Percentage cover was calculated by dividing the counted number of ticks by total ticks and multiplying by 100. Results indicate that cover estimates using an unsupervised classification were highly linearly related to the line-transect estimate, having an $r^2 = 0.91$ ($P \leq 0.05$).

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 the dielectric constant of the soil matrix to estimate volumetric water content (Topp et al., 1980; Whalley, 1993):

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

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 WetSensor has an accuracy of ±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. In addition, precipitation data preceding RS data acquisitions are provided (Fig. 1). On average, the field capacity and permanent wilting point are 14.7 and 5% (by volume), respectively (Miller and Donahue, 1990).

Crop residues were sampled biweekly, coincident with remotely sensed data acquisition. Crop residue was dried and roll ground before measuring total carbon content via dry combustion using a LECO CHN-600 analyzer (Leco Corp., St Joesph, MI).

Spectral Reflectance

CropScan Multispectral Radiometer

Reflectance measurements were collected using a hand-held CropScan Multispectral Radiometer (CropScan, Minnesota). The CropScan utilizes narrow band interference filters to select discrete bands in the VIS and NIR regions of the electromagnetic spectrum. Nine 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 energy. Percentage reflectance was determined using the following equation:

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

All plot data were collected as close to solar noon as possible, under clear conditions, with sampling times typically spanning a 45-min time frame. Data were collected at nadir, over row middles, from a distance of 2 m to approximate a 1 m^2 ground resolution. Data collection consisted of four random points within each plot.

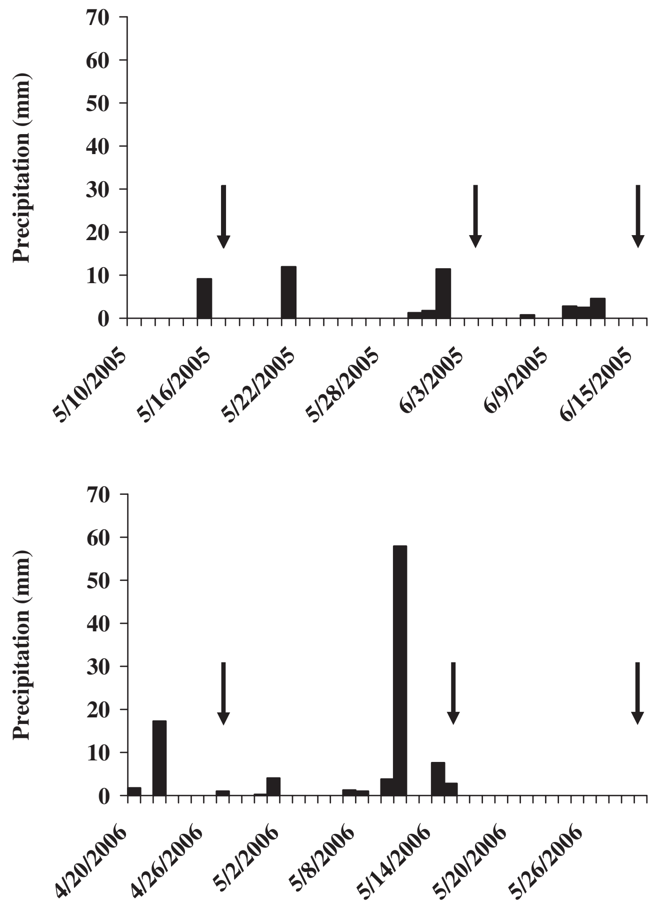

Fig. 1. Daily precipitation (mm) 2005 (10 May–15 June) and 2006 (20 Apr.–30 May) data acquisition periods. Sampling times are denoted by arrows.

Data Analysis

Using the Statistical Analysis System (SAS Institute, Cary, NC), an analysis of variance ($\alpha = 0.05$) was used to evaluate

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

Wavelength	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	infrared
850 ± 35	B6	infrared
1240 ± 6	B7	infrared
1640 ± 8	B8	infrared
1650 ± 100	B9	infrared

spectral response properties of winter cover crops under variable canopy cover, soil water content, and stages of winter cover decomposition. The effect of year, treatment, sampling date, and all possible interactions was evaluated for RS data, carbon concentration, vegetative canopy cover, and soil water content. Because a significant interaction was observed between treatments, sampling date, and year, data were analyzed separately for each. One exception was observed for carbon concentration, showing no significant differences between years or sampling dates.

Three band ratios were evaluated: a modified greenness normalized difference vegetation index (GNDVI) (Gitelson et al., 1996), which was calculated as:

$$\mathrm{GNDVI} = (\mathrm{MIR}_{1650\mathrm{nm}} - \mathrm{green}_{560\mathrm{nm}})/(\mathrm{MIR}_{1650\mathrm{nm}} + \mathrm{green}_{560\mathrm{nm}}) \quad [3]$$

where MIR corresponds to 1650 ± 100 nm and green corresponds to 560 ± 40 nm, a modified normalized difference vegetation index (NDVI) (Rouse et al., 1974) calculated as:

$$\mathrm{NDVI} = (\mathrm{MIR}_{1650\mathrm{nm}} - \mathrm{red}_{660\mathrm{nm}})/(\mathrm{MIR}_{1650\mathrm{nm}} + \mathrm{red}_{660\mathrm{nm}}) \quad [4]$$

where red corresponds to 660 ± 30 nm portion of the spectrum. The GNDVI and NDVI were calculated using the 1650-nm region, which is a longer wave near-infrared band than is typically used to calculate vegetation indices. This region was chosen following an analysis of the degree of separability between treatments using all possible NIR and MIR bands as input to the GNDVI or NDVI.

The crop residue cover index 1 (CRC1) (van Deventeer et al., 1997; Sullivan et al., 2006) was calculated as:

$$\mathrm{CRC1} = (\mathrm{MIR}_{1,650\mathrm{nm}} - \mathrm{blue}_{485\mathrm{nm}})/(\mathrm{MIR}_{1,650\mathrm{nm}} + \mathrm{blue}_{485\mathrm{nm}}) \quad [5]$$

where MIR corresponds to 1650 ± 100 nm, and blue corresponds to 485 ± 45nm.

Spectral response curves were created for each sampling event. Because no significant differences were observed between black oat, rye, and clover covers, spectral response was averaged over these treatments and is referred to as combined cover throughout the presentation of results. Spectral response curves were used to evaluate general trends in the shape and magnitude of reflectance patterns.

RESULTS AND DISCUSSION

Descriptive Data

Crop residue cover varied by treatment and acquisition date. No significant differences in residue cover were observed between rye, black oat, or clover during any one acquisition; however, in both years percentage crop residue cover decreased over time (Table 3). In 2005, the average combined crop residue cover for black oat, rye, and clover ranged from 50 to 67%. A similar trend was observed in 2006, with percentage crop residue ranging from 37 to 68%. Turnip residues were significantly lower compared with the rye, black oat, and clover treatments, averaging from 0 to 18% cover in both years. This may be associated with decomposition of plant materials, since turnips typically preceded corn and were killed 4 wk earlier in the growing season compared to the rye, black oat, and clover. As a result, in

Table 3. Crop residue cover determined via digital image classification for all winter covers [black oat (*Avena strigosa* Schreb.), crimson clover (*Trifolium incarnatum* L.), turnip (*Brassica rapa* L. *subsp.rapa*), and rye (*Secale cereale* L.)]. Means followed by the same letter are not statistically different (alpha = 0.05).

Date	Turnip	Black oat	Rye	Fallow	Clover	LSD
			%			
16 May 2005	1B	61A	67A	1B	58A	21
3 June 2005	3B	50A		1B	46A	16
15 June 2005		44A	54A	0B	51A	17
27 Apr. 2006	18B	62A	61A	0B	68A	21
15 May 2006	7BC	37AB	53A	2C	63A	32
30 May 2006	0C	39AB	53A	0C	53A	14

2005 turnip residue cover was not significantly different than the minimal amount of residue remaining on fallow treatments.

Canopy contributions from the spring crop were monitored to evaluate the impact of increasing green canopy on our ability to quantify differences among crop residue cover. As expected, canopy contributions increased throughout the collection period each year. No significant differences were observed in canopy closure between treatments during the first sampling event. However, as the season progressed, significantly greater canopy cover was observed for turnip treatments, ranging from 10 to 40%, compared with 0 to 14% for all other treatments. This was associated with a rapidly developing corn crop in those treatments.

No differences in soil water content were observed between plots; however, significant differences were observed between data acquisitions. Soil water content ranged from <5 to 15 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$ throughout the study period (Table 4). Soil water contents were highest during the 3 June 2005 and 15 May 2006 acquisitions ($\theta_v = 13\ \mathrm{cm}^3\ \mathrm{cm}^{-3}$) and lowest during the 30 May 2006 acquisition ($\theta_v = <5\ \mathrm{cm}^3\ \mathrm{cm}^{-3}$). A figure showing rainfall patterns proximate to RS acquisitions has also been provided (Fig. 1).

Residue C contents were monitored as a means to approximate the degree of decomposition and evaluate the impact of variable C content on spectral reflectance patterns. Although no differences in C content were observed over time in either growing season, differences between cover types were observed. Specifically, rye residues were significantly higher in C content (43%) compared with black oat and clover (38%) or turnip (29%) treatments. No differences between black oat and

Table 4. Surface volumetric soil water content (θ_v) (0–5 cm) for each remotely sensed (RS) data acquisition. Differences in soil water content between sampling events in each year are shown. Within year means followed by the same letter are not statistically different (alpha = 0.05).

Date	Soil water content
	$\mathrm{cm}^3\ \mathrm{cm}^{-3}$
16 May 2005	9B
3 June 2005	15A
15 June 2005	7C
27 Apr. 2006	8BC
15 May 2006	13†
30 May 2006	<5D
LSD	2

† Denotes an estimated soil water content, due to equipment failure.

clover were observed. The lower C content observed for turnip residues is likely indicative of advanced decomposition, considering the turnip covers were killed 4 wk earlier than the other cover crops.

Spectral Response Curves (SRCs)

For the winter covers evaluated in this study, black oat, clover, and rye are spectrally similar throughout the VIS, NIR, and MIR ($p < 0.05$). Thus black oat, clover, and rye will be referred to as the combined cover treatment from this point forward. Daughtry (2001) evaluated spectral reflectance patterns for corn, soybean, and wheat residues in the 400- to 2500-nm region. Results from that study showed that crop residue reflectance was similar to soil reflectance patterns, and that residue water content was the primary cause of variability in observed reflectance patterns.

Turnip

In 2005, spectral response patterns from turnip winter cover treatments were primarily a function of increasing canopy contributions. During the first RS acquisition, when the corn canopy represented <5% of the sampling area, spectral reflectance from all treatments increased gradually from 445 to 1650 nm without inflection (Fig. 2). In general, few significant differences were observed between turnip and fallow treatments throughout the 445- to 1650-nm range (data not shown). This was likely due to low residue cover remaining after cover crop kill (ranging from 1 to 3%). However, by the second and third RS acquisitions, a developing corn canopy (5–40% cover) was evident as a characteristic increase in NIR spectra between 600 and 800 nm (Fig. 2).

In 2006, turnip residue cover ranged from 0 to 18% (Table 3). During the 27 Apr. 2006 acquisition, when the corn canopy was minimal (<5%) and turnip residue cover was greatest (18%), spectral reflectance was significantly higher from turnip residues compared with the combined cover treatment (Fig. 3). Specifically, turnip residue reflectance ranged from 12 to 51%, compared to 8 to 39% for the combined cover treatment in the VIS, NIR, and MIR. Moreover, turnip residue reflectance was significantly less compared with conventionally tilled fallow treatments (17–53%). It is difficult to determine from this study whether or not differences in magnitude of spectral response are solely attributable to cover amount and bare soil contribution, lower carbon content of the turnip residue at the time of acquisition, or a combination of the two. In the final two RS acquisitions, canopy interference (canopy fraction ≥40%) predominated spectral reflectance in plots containing turnip as a winter cover.

Combined Cover-Fallow

The overall shape and magnitude of SRCs was a function of soil water conditions and increasing vegetative canopy cover (Fig. 2 and 3). In 2005 and 2006, initial RS data acquisitions exemplified the expected crop residue spectral response function, increasing in reflectance from 450 to 1650 nm, without inflection (Aase and

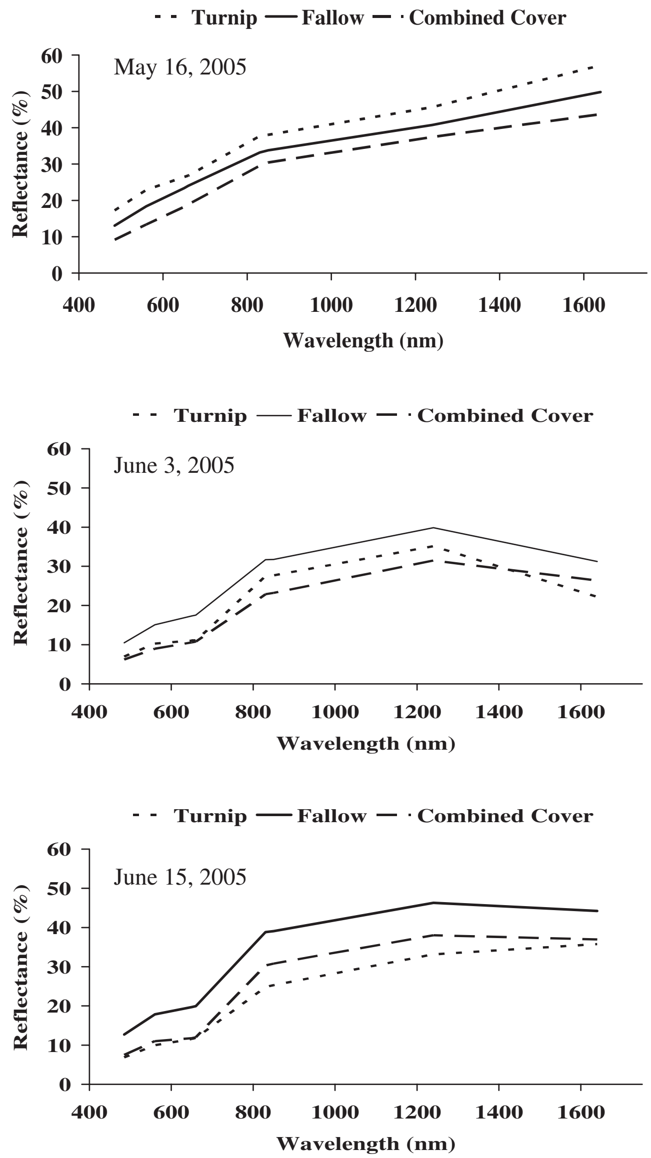

Fig. 2. Spectral response curves for the combined cover, turnip and conventional tillage fallow treatments in 2005. Black oat, rye, and clover comprise the combined cover due to lack of significant differences in spectral response (alpha = 0.05). Data represent general trends in reflectance (%) throughout the 485- to 1650-nm range.

Tanaka, 1991; Daughtry, 2001; Daughtry et al., 2004, 2005; McMurtrey et al., 1993; Nagler, 2000; Sullivan et al., 2004; Sullivan et al., 2006). The combined cover treatments were typically less reflective, ranging in reflectance from 8 to 45%, compared with conventional tillage treatments, which ranged in reflectance from 17 to 57%. Similar results were reported by Sullivan et al. (2006) for a sandy loam–textured surface horizon in the Coastal Plain. Their results showed that under relatively dry surface conditions and low canopy cover (<25%), bare soil reflectance ranged from 15 to 53% compared with 8 to 40% for strip tillage treatments (30% cover).

The second RS acquisition in both years was accompanied by higher surface soil water contents (13–15 $cm^3\ cm^{-3}$). This is equivalent to an absolute increase of 5 $cm^3\ cm^{-3}$, compared with initial soil water con-

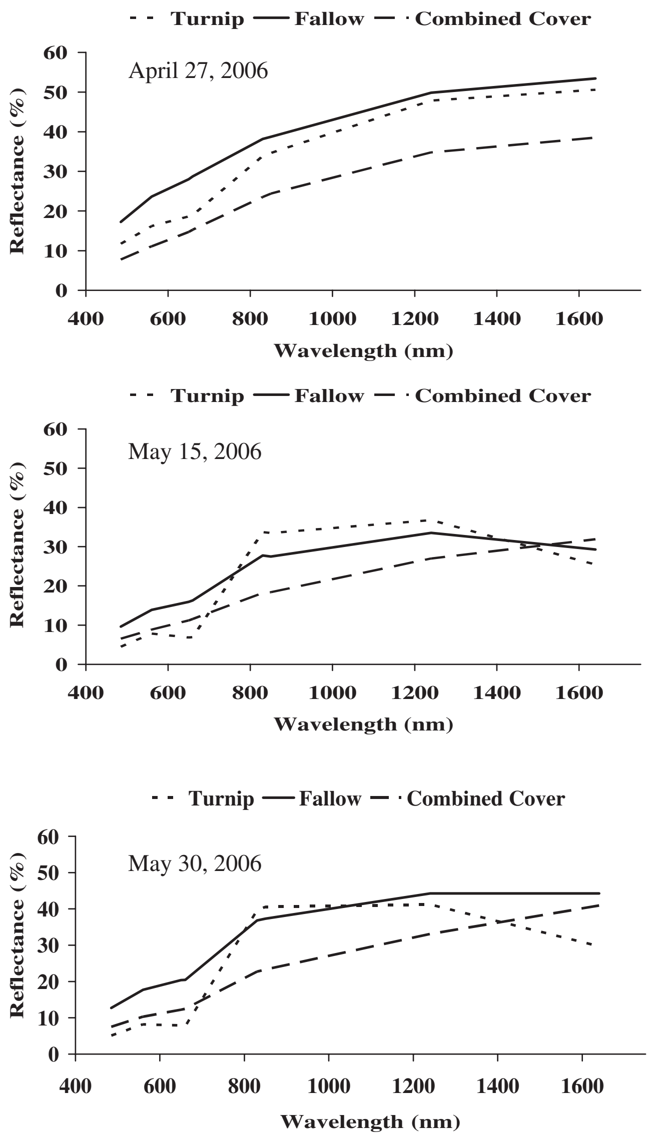

Fig. 3. Spectral response curves for the combined cover, turnip and conventional tillage fallow treatments in 2006. Black oat, rye, and clover comprise the combined cover due to lack of significant differences in spectral response (alpha = 0.05). Data represent general trends in reflectance (%) throughout the 485- to 1650-nm range.

ditions in either year (Table 4). Because surface soil water has a tendency to absorb incoming light, spectral reflectance decreased throughout the VIS, NIR, and MIR spectrum compared with the first RS acquisitions (Fig. 2 and 3). Looking at a single band in the MIR (1650 nm), spectral reflectance decreased 20 to 24% (absolute) on conventionally tilled fallow treatments and from 7 to 17% on the combined cover treatment compared with reflectance observed under drier conditions. Results are consistent with other studies, which demonstrate the impact of soil water content on reflectance (Daughtry et al., 1995; Sullivan et al., 2004). Sullivan et al. (2004) showed that surface reflectance in the 600- to 630-nm range from a bare soil varied from 15 to 34%, peaking during periods of low soil water content. Similarly, Daughtry et al. (1995) demonstrated that reflectance from air dry soils were nearly twice the reflectance of the same soil at field capacity.

The final RS acquisitions in both years were acquired in lower soil water contents. Although canopy cover was considered to be low at this point (<10%), characteristic changes in spectral response between 600 and 800 nm were observed and are indicative of a developing crop canopy. Soil water contents were <8% $cm^3\ cm^{-3}$ during the final acquisitions in 2005 and 2006. This is equivalent to a decrease in soil water content of more than 50% compared with the second RS acquisitions, with the greatest reduction in soil water content observed in 2006. Due to drier surface soil conditions, reflectance increased throughout the VIS, NIR, and MIR region for all treatments (Fig. 2 and 3). The greatest change in reflectance was observed in 2006, with an absolute increase in MIR (1650 nm) of 9 and 15% for combined cover and fallow treatments, respectively. Comparatively, NIR spectra increased by only 2 and 9% for combined cover and fallow treatments in 2005. Because surface soil water has a tendency to absorb incoming light energy, the lower soil water conditions observed in 2006 resulted in a more highly reflective soil surface compared to previous RS acquisitions (Capehart and Carlson, 1997).

Slight differences in the amount of reflected energy were observed from year to year and are likely a function of variability in cover amount, soil water content, and atmospheric conditions at the time of RS data acquisition. Pearson's correlation coefficients for each sampling event were analyzed to evaluate the strength of the relationship between reflectance and soil water content. A strong linear relationship was observed between soil water content and reflectance, having correlation coefficients ranging from −0.48 to −0.74 throughout the study period. However, the presence of a relationship was not consistent between spectral bands or sampling events. This is likely associated with the dynamic nature of surface soil water content and an inability to acquire all data simultaneously.

Spectral Indices

Three spectral indices were evaluated as a means to differentiate between conventional tillage and no-tillage treatments (described in methods). Indices include two modified vegetation indices (GNDVI and NDVI) as well as a CRC1.

In 2005, significant differences ($p < 0.05$) between fallow and combined cover treatments were observed in nearly all instances using any of the proposed RS indices (Fig. 4). One exception was observed during the first RS acquisition, where significant differences were observed between combined cover and fallow treatments using only the GNDVI. However, during the final acquisition that year, the GNDVI failed to differentiate between cover treatments, and likely due to higher canopy contributions at that time. Due to low crop residue cover for the turnip treatment, no differences were observed between turnip and conventionally tilled fallow treatments.

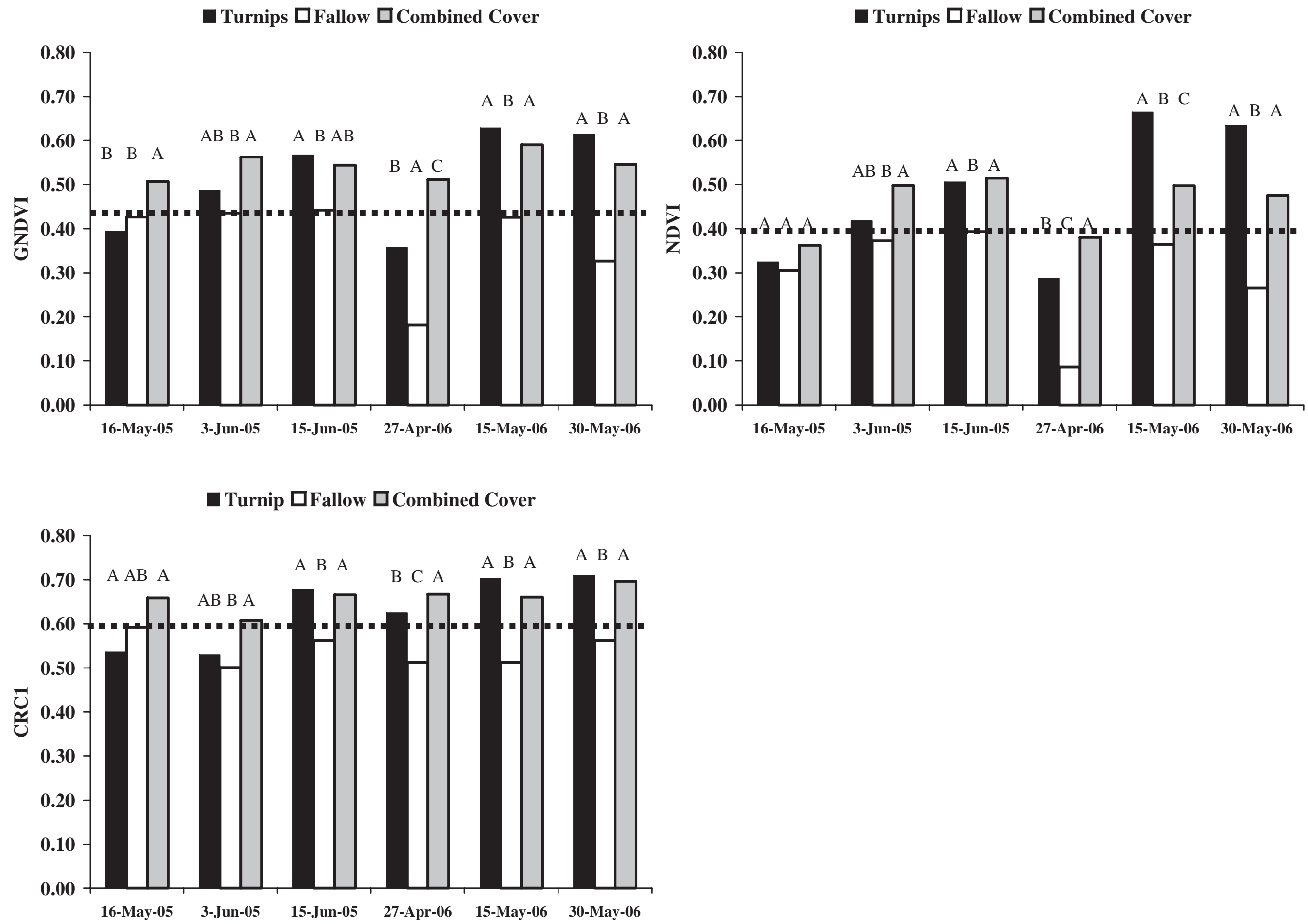

Fig. 4. Analysis of variance for the combined cover (black oat, rye, and clover covers), turnip, and conventional tillage fallow treatments for each remotely sensed index. Remotely sensed indices include the greenness normalized difference index (GNDVI), the normalized difference vegetation index (NDVI), and the crop residue cover index1 (CRC1). Significant interactions were observed between dates and treatments; thus, treatment differences were analyzed by date. Means followed by the same letter are not significantly different (alpha = 0.05). Dashed lines represent minimum threshold values for the crop residue cover index and distinguish between conventional and no-tillage systems.

In 2006, significant differences were observed between combined cover and fallow treatments using all three RS indices (Fig. 4). However, it is interesting to note that during the first acquisition of 2006, RS indices successfully differentiated between turnip (18% cover), combined cover (64%) and fallow (0%). This suggests that under low soil water conditions ($<8\%$ cm^3 cm^{-3}) and minimal canopy cover ($<5\%$), spectral indices are sensitive to variability crop residue when residue cover is $\geq 18\%$. Our results are in contrast to recently published data by Daughtry et al. (2005). In their study, results suggest that crop residue is not related to vegetative indices and only weakly correlated to the normalized difference tillage index developed by McNairn and Protz (1993). Observed differences between the two studies may be related to the fact that a modified vegetation index, based on longer wave spectra (MIR), was used here to calculate vegetation indices. Due to high canopy contributions and low crop residue cover during acquisitions two and three, no other assessments of cover were made over turnip treatments.

To better evaluate the utility of each RS index over a variety of soil water contents and canopy conditions, an analysis was conducted comparing the magnitude of change in each index as soil water content and crop canopy conditions changed. Percentage change between RS acquisitions was estimated using a benchmark indicator. The first RS acquisition in each year was selected to represent benchmark conditions (low soil water content, minimal canopy contributions).

During 2005, significant differences in RS index values between sampling events were observed for the combined cover and turnip treatments only (Fig. 5). For combined cover treatments, the GNDVI and CRC did not vary significantly between sampling events, remaining within 6 to 10% of benchmark conditions. However, for turnip treatments, the GNDVI and CRC increased as much as 22 to 26% between the first and second RS acquisitions. This corresponds with observed changes in the shape and magnitude of the spectral response curve during the second RS acquisition, where a rapidly developing canopy is evidenced by a characteristic peak in NIR reflectance.

In 2006, a similar observation was made over combined cover treatments, demonstrating stability in the GNDVI and CRC between sampling events. The CRC

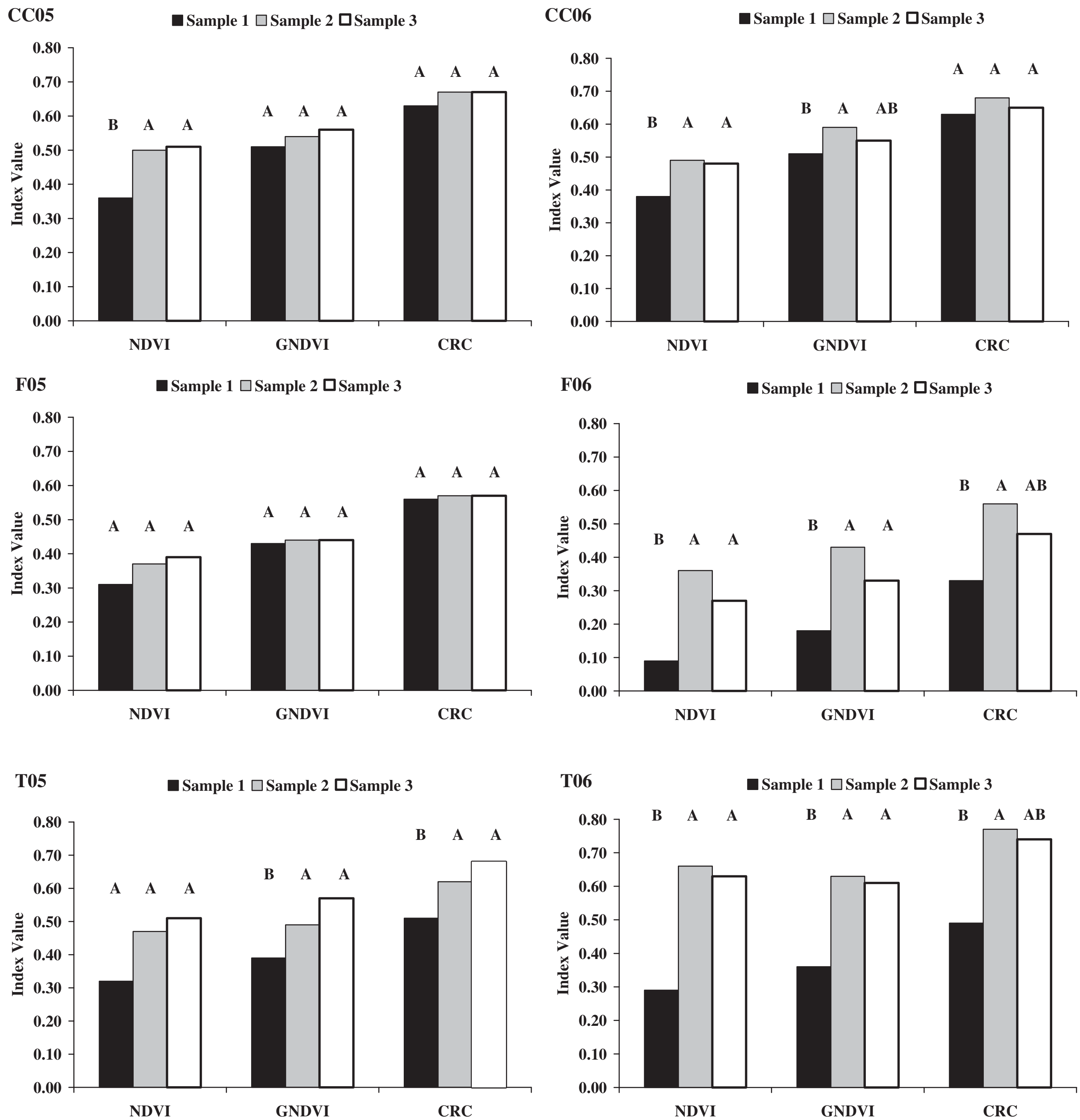

Fig. 5. Analysis of variance showing variability in index values between sampling events for each cover treatment. Remotely sensed indices include the greenness normalized difference index (GNDVI), the normalized difference vegetation index (NDVI), and the crop residue cover index1 (CRC1). Means followed by the same letter are not significantly different (alpha = 0.05). Treatments are identified as follows: CC05 = combined cover 2005, CC06 = combined cover 2006, F05 = fallow 2005, F06 = fallow 2006, T05 = turnip 2005, and T06 = turnip 2006. The combined cover treatments are comprised of black oat, rye, and clover due to a lack of significant differences in spectral response (alpha = 0.05).

was most consistent, varying within 3 to 8% of benchmark conditions. The greatest change in RS indices was observed during the second RS acquisition period, corresponding with periods of higher surface soil water contents (Table 4). When surface soil conditions returned to near benchmark conditions, the GNDVI and CRC1 approached benchmark values, with the CRC1 within only 3% of the benchmark.

Greater variability in index values between sampling events was observed for fallow and turnip treatments (Fig. 5). Both the GNDVI and NDVI were sensitive to a developing crop canopy between sampling events one and two. However, no differences in index values were observed between sampling events two and three. The CRC was most stable between sampling events, varying within 51 to 57% of benchmark.

Because the CRC1 has proven to be less sensitive to canopy and soil water content variability compared to modified vegetative indices, a threshold value was determined for separating conventional tilled fallow and combined cover (no-tillage) treatments. Threshold values represent the minimum CRC1 value that can be used to differentiate ($p < 0.05$) between fallow and combined cover treatments. Similar thresholds are denoted for the GNDVI and NDVI in Fig. 4. However, because these indices demonstrated a higher sensitivity to variability in canopy cover compared with the CRC1, the CRC1 was considered more reliable. Turnip treatments were not considered in 2005 due to low cover amount and similarity to fallow treatments.

In both years, the minimum CRC1 threshold value for differentiating between combined cover and fallow treatments was 0.59 (Fig. 4). Treatments having a CRC1 $>$ 0.59 had a corresponding amount of crop residue cover of 48 to 64% (conservation–tillage–combined cover) and treatments having a CRC1 $\leq$ 0.59 had a corresponding amount of crop residue cover of $<$5% (conventional tillage–fallow). This is consistent with earlier findings by Sullivan et al. (2006), where the CRC1 threshold for differentiating between strip-tillage (rye residue cover) and conventional tillage treatments was 0.58.

Care should be taken when using the CRC1 as the principal determinant for differentiating between conventional and conservation tillage systems. For instance, in 2005 and 2006, high CRC1 values observed for turnip treatments could have been easily mistaken for a heavy cover crop (48–64% cover) (Fig. 4). More likely, the high CRC1 values observed in this case are due to a rapidly developing corn canopy. Keeping this in mind, it appears that the NDVI may be an instrumental prerequisite to using a CRC1 threshold.

The concept of using the NDVI as a prerequisite for the CRC1 threshold is best demonstrated using the 2005 dataset. In 2005, no significant differences in crop residue cover were observed between turnip and fallow treatments. Instead, the primary difference between fallow and turnip treatments was a rapidly developing corn canopy in plots having a turnip winter cover. During the 3 June 2005 RS acquisition, turnip and fallow treatments exhibited a CRC1 value of 0.50 to 0.53, which is below the established threshold for detecting crop residue cover in conservation-tillage treatments, and a corresponding NDVI = 0.37 to 0.42 (Fig. 4). However, by 15 June 2005 the NDVI for turnip treatments reached 0.51, significantly higher than fallow treatment (NDVI = 0.39). Coincidentally, the CRC1 for turnip treatments reached 0.68, exceeding the threshold for the combined cover treatments. Data suggest that when the NDVI exceeds 0.42, the CRC1 threshold approach for identifying conservation tillage is no longer applicable.

CONCLUSION

Crop residue spectral response properties were evaluated for four different winter cover crops (rye, black oat, clover, and turnip) in a conservation-tillage system and one fallow, conventional tillage system. Black oat, clover, and rye residues were found to be spectrally similar. Because turnip cover was generally low in both years, it is difficult to discern whether or not these residues are spectrally unique. Spectral reflectance curves were typical of crop residue, increasing steadily from 450 to 1650 nm differing from soil spectra only in magnitude of spectral response. Spectral reflectance was greatest from conventional tillage fallow treatments, followed by conservation-tillage treatments. Variability in soil water content and increasing crop canopy were evident in spectral response curves. Increasing soil water contents tended to decrease spectral response, while increasing canopy contributions were evident as a peak in the near-infrared (600–800 nm).

Three indices were evaluated as a method to rapidly differentiate between tillage systems. The crop residue cover index proved least sensitive to variability in soil water content and increasing canopy contributions compared to the modified greenness normalized difference vegetation index and normalized difference vegetation index. Because the crop residue index remained relatively stable over time, varying within 8% of initial conditions, a threshold value was determined for delineating tillage regime. Treatments having a CRC1 $>$ 0.59 can be identified as meeting the minimum requirements for a conservation tillage system. It should be noted that when the NDVI exceeds 0.42, the CRC1 threshold method should not be used.

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