

# AGROCLIMATOLOGY

## Discriminating Crop Residues from Soil by Shortwave Infrared Reflectance

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### ABSTRACT

Quantifying crop residue cover on the soil surface is important for evaluating the effectiveness of conservation tillage practices. Current methods of measuring residue cover are inadequate in characterizing the spatial variability of residue cover over large fields. The objectives of this research were to determine the spectral reflectance of crop residues and soils as a function of water content and to evaluate the limits of discrimination that can be expected. Spectral reflectances of corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) residues plus five diverse soils were measured over the 400- to 2400-nm wavelength region at a wide range of moisture conditions in the laboratory. Reflectance factors for scenes with varying proportions of crop residues and soils were simulated. The spectra of dry crop residues displayed a broad absorption feature near 2100 nm, associated with lignin and cellulose, that was absent in spectra of soils. The relative depth of the cellulose-lignin absorption feature, defined as the cellulose absorption index (CAI), was positive for all crop residues, except those saturated with water. In contrast, all soils had negative CAI values. Water significantly altered reflectance spectra of wet crop residues, but it did not prevent the discrimination of crop residues from the soils using the CAI. The wide range of CAI values expected for dry and moist conditions makes quantification of crop residue cover feasible. This reflectance technique appears promising for field- and regional-scale surveys of crop residue cover and conservation tillage practices.

MORE THAN ONE-THIRD of tilled U.S. cropland is classified as highly erodible land (USDA, 1991). Because crop residue coverage on the soil surface reduces soil erosion (Alberts and Neibling, 1994), residue management can be an important factor in controlling soil erosion. By reducing the movement of eroded soil into streams and rivers, the movement of nutrients and pesticides attached to soil particles is also reduced. The overall result is less soil erosion and improved water quality.

The current methods for quantifying crop residue cover are tedious and somewhat subjective (Morrison et al., 1993). The line-transect is a standard technique for measuring crop residue cover used by the USDA Natural Resources Conservation Service (NRCS). Reviews of crop residue measurement techniques document recent modifications and illustrate the unresolved problems with current techniques (Corak et al., 1993; Morrison et al., 1995). Rapid, accurate, and objective methods to quantify residue cover are needed to evaluate the effectiveness of conservation tillage practices. Attempts to replace the human visual judgment utilized

in the line-transect method with a sensor designed to identify crop residue based on its reflectance characteristics have had only limited success. The reflectance of both soils and crop residues lack the unique spectral signature of green vegetation in the visible and near-infrared (400–1100 nm) wavelengths (Aase and Tanaka, 1991; Daughtry et al., 1996a; Gausman et al., 1975). Crop residues and soils are often spectrally similar and differ only in their amplitude at a given wavelength.

Many factors, including organic matter, moisture, texture, iron oxide content, and surface roughness affect the spectral reflectance of soils (Baumgardner et al., 1985; Irons et al., 1989). The moisture content, age of the residue, and degree of decomposition affect the spectral reflectance of crop residues (Daughtry et al., 1996a; Nagler et al., 2000). Thus, the reflectance of crop residues at a particular visible or near-infrared wavelength may be higher or lower than the reflectance of the soil (Daughtry et al., 1995; McMurtrey et al., 1993). This makes discrimination between crop residues and soils difficult or nearly impossible using reflectance techniques alone in the visible and near-infrared wavelengths.

McMurtrey et al. (1993) first demonstrated that crop residues fluoresce more than soils when illuminated with ultraviolet radiation at 337 nm. Daughtry et al. (1995) showed that the fluorescence of crop residues was a broad-band phenomenon centered between 420 to 520 nm and induced by a relatively broad range of excitation wavelengths centered between 350 and 400 nm. The soils had low intensity broad-band emissions over the 400- to 690-nm region for excitations of 300 to 600 nm. Based on these findings, Daughtry et al. (1996a) concluded that fluorescence techniques may be less ambiguous for discriminating crop residues from soils than visible and near-infrared reflectance techniques. Chappelle et al. (1995) made considerable progress in developing a portable agricultural residue sensor based on the fluorescence of soil and residues and have a patent on the technique. However promising, several problems that must be addressed include (i) the excitation energy, which must be supplied to induce fluorescence; and (ii) the fluorescence signal, which is small relative to normal, ambient sunlight.

Many compounds found in plants contain functional groups with fundamental molecular vibrations that produce overtones and combination tones throughout the 700- to 2600-nm wavelength region (Murray and Williams, 1988). The absorption spectrum is a function of

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all of the absorbing molecules present in a sample and is affected by the composition of the molecules, the presence and magnitude of the dipoles, and the interactions between functional groups on a molecule and between different molecules (Murray and Williams, 1988). For example, the  $-OH$  group shows two very broad absorptions centered near 1600 and 2100 nm. The broader band near 2100 nm appears in all compounds possessing alcoholic  $-OH$  groups such as sugars, starch, and cellulose (Murray and Williams, 1988). Daughtry et al. (1996b) observed this absorption band at 2100 nm in the reflectance spectra of dry plant residues and proposed a cellulose absorption index (CAI) based on the reflectance in three 50-nm-wide bands—two on the shoulders at 2021 and 2213 nm and one at 2100 nm (cellulose-lignin absorption max.). Although Daughtry et al. (1996b) demonstrated that the CAI could discriminate crop residues from soils, they examined only the extremes of moisture conditions (saturated vs. dry) for a limited selection of crop residues (corn and soybean). Additional laboratory research is needed to elucidate the shortwave infrared spectral response of crop residues and soils to varied moisture conditions before testing the concept in the field.

In summary, the current methods for measuring crop residue cover are tedious, somewhat subjective, and possibly biased. New methods are needed to measure crop residue cover that are rapid, accurate, and unbiased. The objectives of this research were to (i) determine the spectral reflectance of crop residues and soils as a function of the relative water content and (ii) evaluate the limits of discrimination that can be expected using the CAI. This research extends the initial observations of Daughtry et al. (1996b) to diverse soils and crop residues under a wide range of moisture conditions. This research provides the scientific foundation that is required for sensor development and field testing.

## MATERIALS AND METHODS

### Reflectance Spectra

Reflectance spectra were acquired with a GER 3700 spectroradiometer (Geophysical Environ. Res. Corp., Millbrook, NY) over the 400- to 2500-nm wavelength region at 1.5-nm intervals in the 400- to 1050-nm region and at 9-nm intervals in the region  $>1050$  nm. The samples were illuminated by two 300 W quartz-halogen lamps mounted on the arms of a camera copy stand 50 cm above the sample at a  $45^\circ$  illumination zenith angle. The spectroradiometer was positioned 40 cm from the sample surface at a  $0^\circ$  view zenith angle. With the  $3^\circ$  optics on the spectroradiometer, the diameter of the

field of view at the sample was 2.1 cm. The illumination and view angles were chosen to minimize shadowing and emphasize the fundamental spectral properties of the soils and crop residues. Spectral data were acquired at nine evenly spaced locations on each sample. Before each sample, a 25-cm square Spectralon reference panel (Labsphere, North Sutton, NH) was placed in the field of view, illuminated, and measured in the same manner as the samples.

Reflectance factors were calculated as described by Robinson and Biehl (1979). The mean reflectance spectra ( $n = 9$ ) were plotted as a function of wavelength and moisture condition. In addition, the reflectance spectra were integrated over the wavelength to evaluate the relatively broad bands of the Landsat Thematic Mapper (TM): TM3 (630–690 nm), TM4 (760–900 nm), TM5 (1550–1750 nm), and TM7 (2080–2350 nm). The CAI was calculated as

$$CAI = 0.5(R_{2.0} + R_{2.2}) - R_{2.1}$$

where  $R_{2.0}$  and  $R_{2.2}$  are the reflectance factors in 27-nm bands on the shoulders at 2019 nm and 2206 nm, respectively, and  $R_{2.1}$  is the minimum reflectance in a 36-nm band at 2109 nm. Daughtry et al. (1996b) used 50-nm-wide bands.

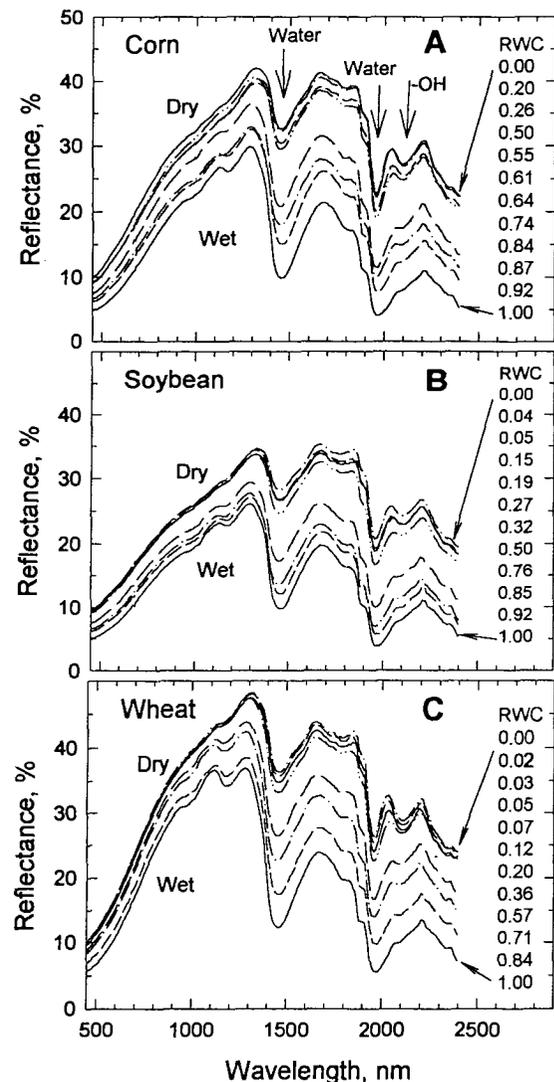


Fig. 1. Reflectance spectra of corn, soybean, and wheat residues at a range of relative water contents (RWC) from oven dry (RWC = 0.0) to water saturated (RWC = 1.0).

Table 1. Soil names and sources of the top soils used in this study.

Soil series	Location	Classification
Barnes	Morris, MN	coarse-loamy, mixed Udic Haploboroll
Cecil	Watkinsville, GA	clayey, kaolinitic, thermic Typic Hapludult
Codorus	Beltsville, MD	fine-loamy, mixed mesic, Fluvaquentic Dystrachrept
Houston Black Clay	Temple, TX	fine, montmorillonitic, thermic Udic Pellustert
Othello	Salisbury, MD	fine-silty, mixed mesic Typic Ochraqult

**Soils**

Five topsoil samples were acquired for this study and provided a wide range of colors and textures (Table 1). Each sample was oven-dried at 105°C, crushed to pass through a 2-mm screen, and placed to a depth of 0.5 cm in a 45-cm square sample tray that was painted flat black. After acquiring the spectral reflectance data from the oven-dried soils, the soils in the trays were saturated with water, allowed to drain freely for 2 h, and weighed before the spectral reflectance was measured again. The soils were dried slowly in a forced-air oven at 40°C until approximately 10 to 20% of the water mass from the sample had evaporated. The soils in the trays were removed from the oven, placed in large plastic bags, and allowed to equilibrate at 25°C for several hours before the next set of reflectance measurements. This sequence of soil drying and reflectance measurements was repeated until the soils were oven dry at 105°C. The relative water content (RWC) was calculated as the water content divided by the maximum water content of each samples (i.e., RWC = 0.0 is oven dry and RWC = 1.0 is saturated).

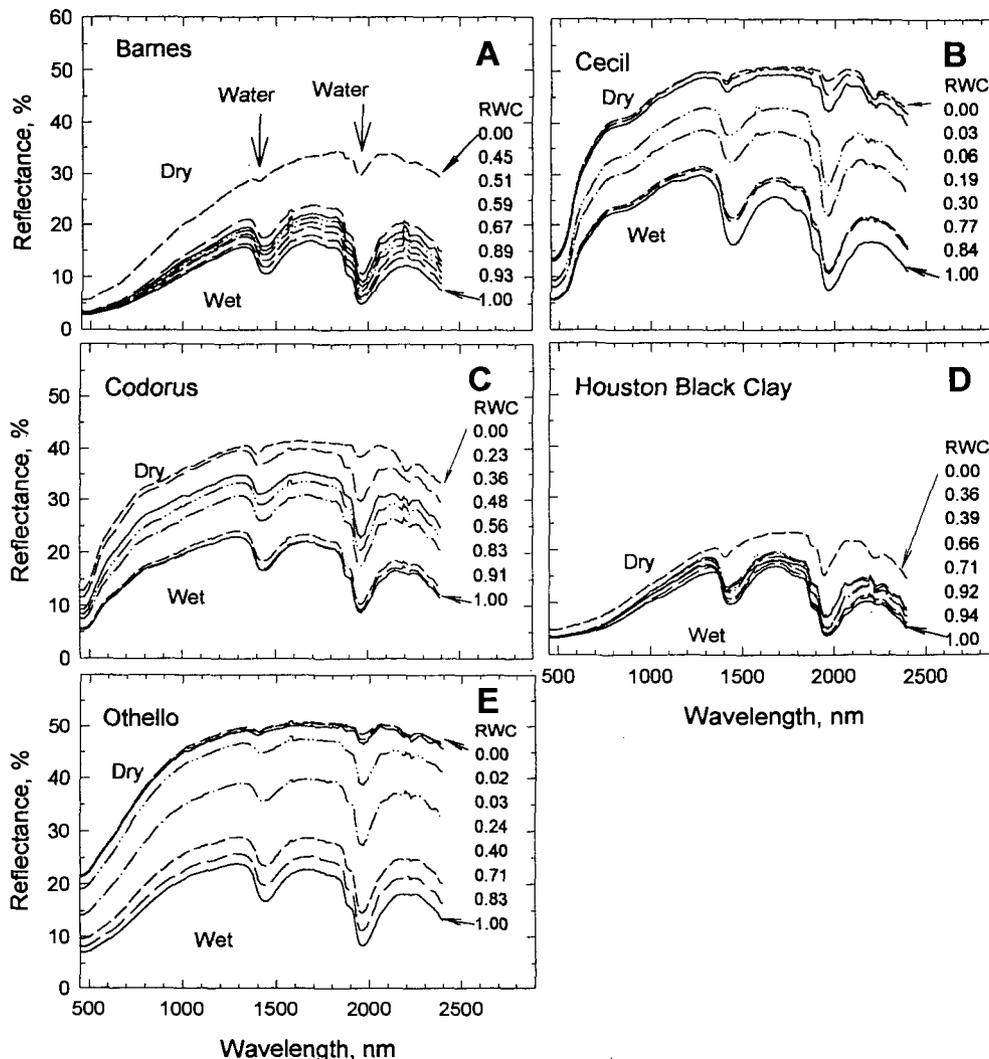
**Crop Residues**

The crop residues of corn and soybean were collected from agricultural fields near Beltsville, Maryland at 1, 4, and 8 mo

after harvest. Wheat residues were collected from wheat straw that had been baled shortly after harvest, stored in a barn, and redistributed in the field for the same 4 and 8 mo as the corn and soybean residues. The crop residues were dried at 70°C and then stored at room temperature. The spectral reflectance of intact dry crop residues were measured in 45-cm square sample trays filled to a depth of 3 cm. The samples and trays were then placed in mesh bags, immersed in water for 2 h, allowed to drain freely for 2 h, and weighed before the spectral reflectance was remeasured. The crop residues were then dried slowly at room temperature until approximately 10 to 20% of the water mass from the sample had evaporated. The crop residues and trays were placed in large plastic bags and allowed to equilibrate for several hours before the next set of reflectance measurements. The sequence of crop residue drying and spectral measurements was repeated until the crop residues were air-dry and then the residues were dried at 70°C for at least 48 h. The water content was expressed as the RWC.

**Crop Residue + Soil**

In practice, reflectance spectra often represent mixed scenes with varying proportions of crop residues and soils. The reflectance factors of these mixed scenes [ $R_{(M,S)}$ ] were simulated



**Fig. 2.** Reflectance spectra of five soils at a range of relative water contents (RWC) from oven dry (RWC = 0.0) to water saturated (RWC = 1.0).

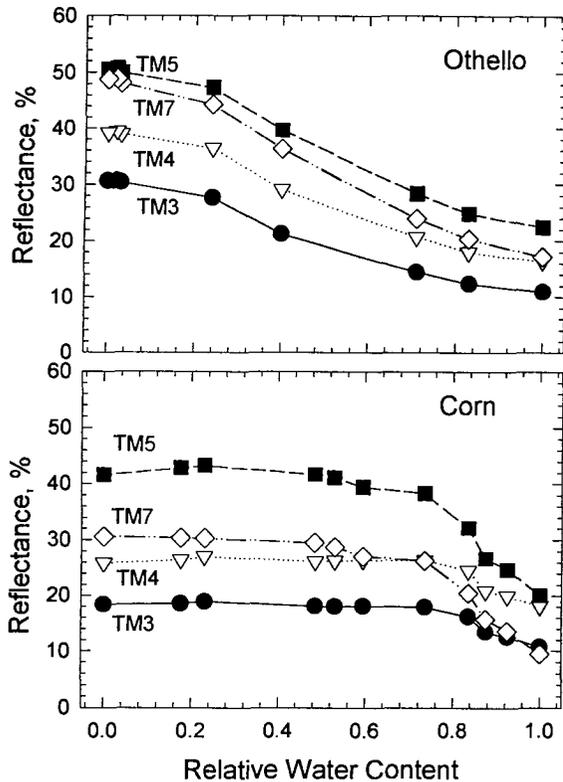


Fig. 3. Reflectance of Othello soil and corn residues in selected wavelength bands as a function of the relative water content (RWC). TM3 = 630 to 690 nm; TM4 = 760 to 900 nm; TM5 = 1550 to 1750 nm; and TM7 = 2080 to 2350 nm.

using linear combinations of the reflectance factors for crop residues and soils:

$$R_{(M,\lambda)} = R_{(S,\lambda)} (1 - f_R) + R_{(R,\lambda)} (f_R)$$

where  $R_{(S,\lambda)}$  and  $R_{(R,\lambda)}$  are reflectance factors in waveband  $\lambda$  for soils and crop residues, respectively, and  $f_R$  is the fraction residue cover that ranged from 0 (100% soil) to 1.0 (100% crop residue). Scenarios for dry (RWC = 0.0), moderately moist (RWC = 0.5), and wet (RWC = 1.0) mixtures of corn residues and Othello soil were simulated. Nagler et al. (1997) evaluated this simple mixture model for scenes with known

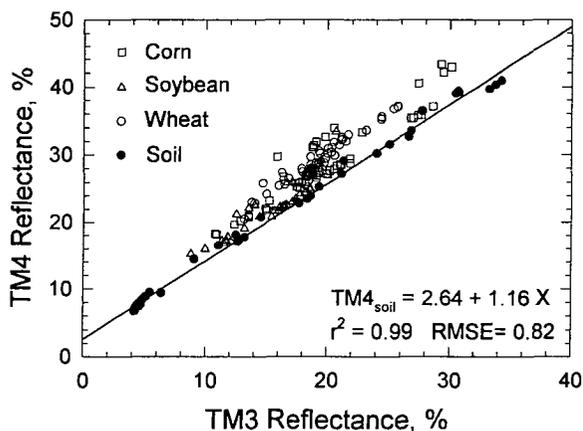


Fig. 4. Reflectance of crop residues and soils in a visible (TM3, 630–690 nm) and near-infrared (TM4, 760–900 nm) band. The regression line was developed using all of the soil samples. RMSE is the root mean square error.

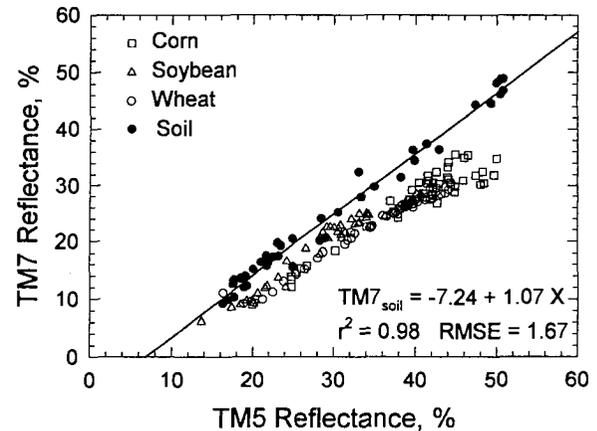


Fig. 5. Reflectance of crop residues and soils in two shortwave infrared bands (TM5, 1550–1750 nm; TM7, 2080–2350 nm). The regression line was developed using all of the soil samples. RMSE is the root mean square error.

proportions of soil and crop residues and reported an excellent agreement between the model and the empirical results.

## RESULTS AND DISCUSSION

The mean reflectance spectra of corn, soybean, and wheat residues during a drying cycle are presented in Fig. 1. For each crop residue, the uppermost spectrum is the oven-dried residue, and the lowest spectrum is the water-saturated residue. The presence of water in the crop residue reduced the reflectance across all wavelengths. Two major water absorption bands at 1450 and 1960 nm dominate the reflectance spectra at wavelengths >1300 nm. A broad absorption feature at 2100 nm is also evident in the reflectance spectra of all three dry crop residues and is probably associated with lignin and cellulose in the crop residues (Murray and Williams, 1988). Similar absorption bands in the reflectance spectra of dry, intact plant materials have also been observed (Elvidge, 1990; Asner et al., 1998; Nagler et al., 2000).

The effects of water absorption on the reflectance spectra gradually diminished as the water content of the crop residues decreased from water saturated to oven dry. The -OH absorption feature at 2100 nm was nearly

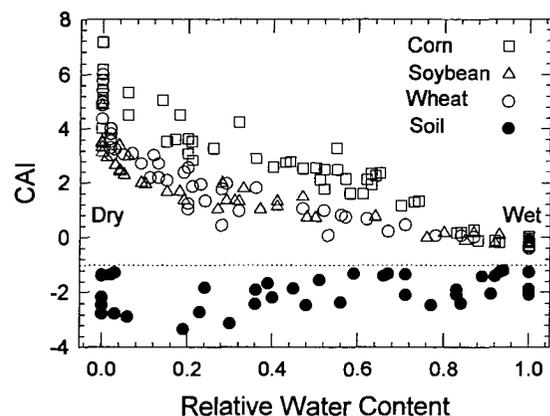


Fig. 6. Cellulose absorption index (CAI) of crop residues and soils plotted as function of the relative water content (RWC). The dashed line is at CAI = -1.0. All soils are located below the line, and all crop residues are located above the line.

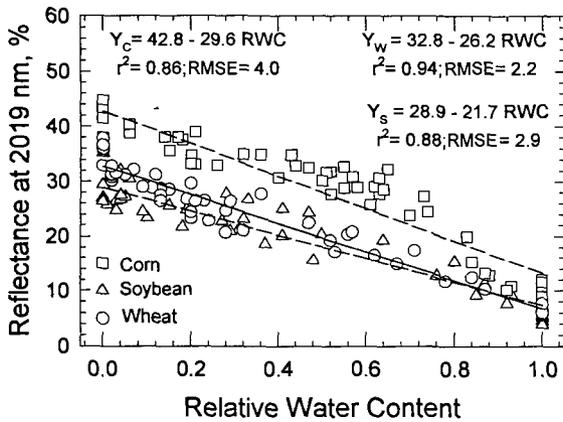


Fig. 7. Reflectance of corn, soybean, and wheat crop residues at 2019 nm plotted as function of the relative water content (RWC). RMSE is the root mean square error.

obscured at a high RWC. Nevertheless, Gao and Goetz (1994) showed that cellulose and lignin absorption features can be identified even in reflectance spectra that are dominated by water absorption.

The mean reflectance spectra of the five soils during a drying cycle are shown in Fig. 2. As for the crop residue, the water content reduced the reflectance across all wavelengths. In addition to the two major water absorption features, a clay mineral absorption feature near 2200 nm is also evident (Baumgardner et al., 1985). The broad cellulose and lignin absorption feature near 2100 nm is not evident in the spectra of the soils.

The spectra of these crop residues and soils have similar shapes (Fig. 1 and 2). The crop residues may be brighter or darker than a particular soil depending on the moisture content. Thus, the discrimination of crop residues from soils using reflectance in any single wavelength band in the 400- to 2400-nm wavelength region would be difficult and would require frequent adjustments of the discrimination thresholds for consistent results (Gausman et al., 1975; Aase and Tanaka, 1991; Daughtry et al., 1995).

As illustrated in Fig. 3, the changes in reflectance in the Landsat visible (TM3), near-infrared (TM4), and shortwave infrared (TM5 and TM7) bands are not linear functions of the RWC. Reflectance increased rapidly as the RWC of the water-saturated corn residues decreased to 0.75 and remained nearly constant as the

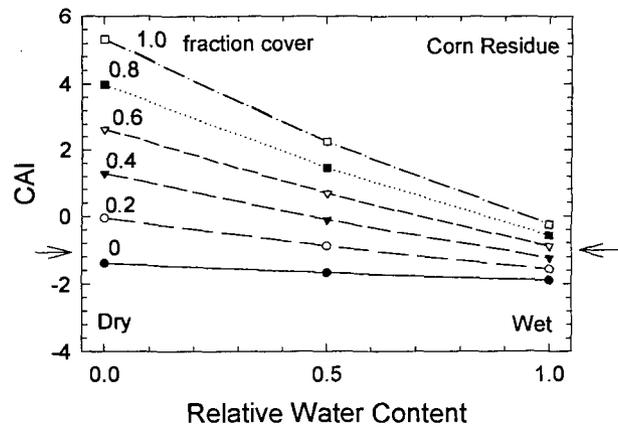


Fig. 8. Expected changes in the cellulose absorption index (CAI) for mixed scenes of crop residue and soil as a function of the relative water content (RWC). The fraction of residue cover ranged from 0 (100% Othello soil) to 1.0 (100% corn residue). Arrows indicate the CAI = -1.0.

residues continued to dry. The Othello soil reflectance increased gradually as the soils dried to a RWC of about 0.25. Changes in the reflectance for other crop residues and soils were similar but are not shown. The RWC represented the average water content in the 3-cm layer of crop residues and the 0.5-cm layer of soils. However, most of the reflected radiation originated within a few millimeters of the soil and residue surfaces (Irons et al., 1989; Nagler et al., 2000). Even though care was taken to equilibrate the samples in plastic bags before the reflectance measurements, the surfaces of the samples were probably drier than the bulk of the sample. Thus, the sample volumes represented by the RWC and the reflectance spectra were not identical and undoubtedly contributed to the nonlinear responses in Fig. 3.

Soil reflectance in TM4 was a linear function of the TM3 reflectance (Fig. 4) and has often been referred to as the soil line (Baret and Guyot, 1991). The crop residues had slightly higher near-infrared reflectance than the soils and were located above the soil line. However, their distances from the soil line were small and changed with the moisture content. The wet crop residue reflectance in TM3 and TM4 was closer to the soil line than the dry residue reflectance. In contrast, the reflectance of green vegetation departed from the soil line as its leaf area increased and could be readily distinguished from soil reflectance (Baret and Guyot, 1991). The rela-

Table 2. Correlations of the reflectance factors, cellulose absorption index (CAI), and relative water content (RWC) for all samples (residue  $n = 184$ ; soil  $n = 40$ ).<sup>†</sup>

Bands	TM3	TM4	TM5	TM7	R1960	R2019	R2109	R2206	CAI	RWC
TM3	1.0									
TM4	0.968	1.0								
TM5	0.842	0.816	1.0							
TM7	0.777	0.687	0.932	1.0						
R1960	0.757	0.689	0.929	0.963	1.0					
R2019	0.762	0.695	0.956	0.965	0.994	1.0				
R2109	0.771	0.675	0.921	0.999	0.962	0.961	1.0			
R2206	0.786	0.713	0.964	0.992	0.970	0.981	0.986	1.0		
CAI	0.335	0.409	0.561	0.324	0.501	0.544	0.298	0.434	1.0	
RWC	-0.483	-0.424	-0.724	-0.740	-0.824	-0.830	-0.744	-0.764	-0.567	1.0

<sup>†</sup> Reflectance factors; TM3 (630–690 nm); TM4 (760–900 nm); TM5 (1550–1750 nm); TM7 (2080–2350 nm); R1960 (1950–1970 nm); R2019 (2005–2032 nm); R2109 (2091–2127 nm); and R2206 (2192–2219 nm).

tively broad Landsat TM7 band, which included the lignin and cellulose absorption feature near 2100 nm, is shown in Fig. 5 as a function of TM5. The dry crop residues had a lower TM7 reflectance than the soils, but as the water content increased, the reflectance decreased, and the crop residues and soils became less distinct. Thus without *a priori* knowledge of the soil and residue moisture content, it would be difficult to reliably discriminate crop residues from soils using the TM bands.

The CAI of the crop residues and soils also changed as a function of the RWC (Fig. 6). All crop residues except those saturated with water (i.e., RWC = 1.0) had positive CAI values while all soils had negative CAI values. The broken line at CAI = -1.0 separated all crop residues from the soils, regardless of the moisture conditions. As the RWC of the crop residues increased, the CAI decreased from a mean of  $5.0 \pm 1.13$  for the dry residues (RWC = 0.0) to a mean of  $-0.3 \pm 0.15$  for the water-saturated crop residues (RWC = 1.0). The mean CAI of the soils remained essentially unchanged, with  $-2.0 \pm 0.63$  for the dry soils (RWC = 0.0) and  $-1.7 \pm 0.39$  for the saturated soils (RWC = 1.0). Water affected the CAI of the crop residues more than it affected that of the soils. As the RWC increased, the differences in the CAI between the crop residues and the soils diminished (Fig. 6).

Thus, a knowledge of the water content of the crop residues and soils in the scene could be crucial for the quantification of the crop residue cover. Direct measurement of scene moisture conditions is labor intensive and time consuming. Infrared reflectance has been used as a surrogate for sample water content in numerous applications (Murray and Williams, 1988). The crop residue reflectance at 2019 nm decreased as the RWC of the crop residues increased (Fig. 7). Reflectance in other bands was also significantly correlated to the RWC and each other (Table 2). Thus, it appears that both the CAI and RWC can be determined from reflectance factors measured in as few as three spectral bands (i.e., R2019, R2109, and R2206).

In the field, most reflectance spectra will represent scenes with mixtures of crop residues and soils. Changes in the fraction of crop residue cover produced significant differences in the CAI for mixtures of dry (RWC = 0.0) and moderately moist (RWC = 0.5) crop residues and soils (Fig. 8). The wide range in CAI values for the dry and moderately moist mixtures made the discrimination of various mixtures relatively easy. The narrow range of CAI values for the mixtures of wet soil and wet residues (RWC = 1.0) increased the uncertainty of the crop residue cover estimates. For example, a CAI value of -1.0 from a scene with unknown proportions of corn residue and soil could represent a dry scene (RWC = 0.0) with less than 5% corn residue cover or a wet scene (RWC = 1.0) with a 55% corn residue cover (Fig. 8). However, if the scene reflectance at 2019 nm is 40%, then the scene RWC is <0.1 (Fig. 7), and the CAI value of -1.0 represents a scene with low (<5%) residue cover. On the other hand, if the scene reflectance at 2019 nm is 20%, then the scene RWC is >0.8, and the

CAI value of -1.0 represents a wet scene with high (>55%) residue cover. Clearly, moisture conditions are important for determining crop residue cover in mixed scenes.

In summary, quantifying crop residue cover is important for evaluating the effectiveness of conservation tillage practices and for estimating surface energy balance, nutrient cycling, and C storage. The traditional methods of quantifying crop residue cover are labor intensive and generally inadequate for a rapid assessment of the crop residue cover in many fields. A multiband radiometer with at least the three CAI bands could be used as a replacement for the line-transect technique to measure the crop residue cover in fields. Regional surveys and maps of crop residue cover and conservation tillage practices may also be feasible using hyperspectral imaging systems [e.g., Airborne Visible Infrared Imaging Spectrometer (AVIRIS)] that have the required spatial and spectral resolution.

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