Spectral reflectance of soils and crop residues

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Introduction

Crop residue is the portion of a crop left in the field after harvest. As the fraction of the soil surface covered by crop residue is increased, soil erosion from cropland is significantly reduced. Thus management of crop residue is an important conservation practice for reducing soil erosion. By reducing the movement of eroded soil into streams and rivers, the movement of nutrients and pesticides attached to colloidal soil particles is also reduced. The overall result is less soil erosion and correspondingly improved water quality.

Unfortunately, current methods for quantifying crop residue cover are difficult, tedious and somewhat subjective. In order to evaluate the effectiveness of conservation tillage practices and to assure compliance with federal laws (e.g. Public Laws 99–198 and 101–624), rapid, accurate and objective techniques are needed for measuring crop residue cover.

The current standard technique for measuring residue cover by the USDA Natural Resources Conservation Service (formerly the Soil Conservation Service, SCS) is the line-transect.¹ Reviews of crop residue cover measurement techniques document recent modifications and illustrate the unresolved problems of current techniques.^{1,2} For example, Morrison *et al.*³ evaluated several modifications of the line-transect method and found that the variation among the USDA-trained observers was nearly nine percentage points for the same device on the same site. They concluded that it would be preferable to replace visual measurement with sensor-based devices to obtain consistently objective measurements.

However, attempts to replace the human visual judgment required in the line-transect method with a sensor designed to identify residue based on its reflectance characteristics have had only limited success. Unfortunately, the reflectances of both soils and crop residues lack the unique spectral signature of green vegetation and their reflectances typically increase monotonically with

wavelength from 400 to 1000 nm.^{4,5} Crop residues and soils are often spectrally similar and differ only in amplitude at a given wavelength.

Many factors, including organic matter, moisture, texture, iron oxide content and surface roughness affect the spectral reflectance of soils.^{6,7} Moisture content, age of the residue and degree of decomposition affect the spectral reflectance of crop residues.⁸ Thus, the reflectance crop residues in the 400–1000 nm wavelength region may be higher or lower than the reflectance of soil.^{4,9} This makes discrimination of crop residues from soils, using conventional reflectance techniques alone, difficult or nearly impossible.

Until recently, all automated methods have relied on measuring reflected radiation. McMurtrey *et al.*⁹ first demonstrated that crop residues fluoresce more than soils when illuminated with ultraviolet radiation at 337 nm. Daughtry *et al.*⁴ showed that the fluorescence of crop residues was a broad band phenomenon centered between 420 and 520 nm and was induced by a relatively broad range of excitation wavelengths centered between 350 and 400 nm. Soils had low intensity broad band emissions over the 400–690 nm region for excitations of 300–600 nm. Based on these findings, Daughtry *et al.*⁸ concluded that fluorescence techniques may be less ambiguous than reflectance techniques for discriminating crop residues from soils. However, several problems associated with the fluorescence technique that must be addressed include (i) the need for excitation energy to induce fluorescence and (ii) the difficulty of detecting a fluorescence signal that is small relative to normal, ambient sunlight. We have made considerable progress in developing a portable agricultural residue sensor based on soil and residue fluorescence and have a patent on the technique.¹⁰

Our overall objective was to develop new methods to measure crop residue cover that are rapid, accurate and objective. In this paper, we evaluated the feasibility of using lignin–cellulose absorption features to discriminate intact dry and wet crop residues from dry and wet soils. We also modelled the reflectances for mixed pixels (i.e. with varying proportions of soil and residue) to evaluate the limits of discrimination that can be expected in the field.

Materials and methods

Soils

Topsoil samples from four US cropland soils (Codorus, Cecil, Othello and Houston) were acquired for this study. These soils provided a wide range of colors and textures: a nearly black clay (Houston), a very light gray, silt loam (Othello), a yellowish-brown, silty clay (Codorus) and a yellowish-red, sandy clay (Cecil). Each soil was air-dried, crushed to pass a 2 mm screen and placed in a $45 \times 45 \times 2$ cm sample tray. After acquiring the spectral reflectance data from the air-dried soils, the soils were saturated with water and allowed to drain overnight before acquiring the spectral data of the wet soils.

Crop residues

Crop residues were collected on several dates from agricultural fields near Beltsville, MD. Corn (*Zea mays* L.) residues were collected at 0.1 (3 days), 6 and 8 months after harvest (MAH); soybean (*Glycine max* Merr.) residues at 1, 6 and 8 MAH. The residues were dried at 70°C and stored at room temperature. Sample trays were filled to a depth of 3–5 cm with intact residues and the spectral reflectance was measured. The samples were then immersed in water for 2 hours and allowed to drain overnight before acquiring the spectral data of the wet residues.

Spectral reflectance

Spectral reflectance data were acquired with an IRIS Mark IV Spectroradiometer (Geophysical Environmental Research, Corp., Millbrook, NY) over the 400–2500 nm wavelength region at 2–4 nm intervals. The samples were illuminated by sixteen 62 W quartz-halogen lamps in a hemisphere painted with BaSO₄ as described by Williams and Wood.¹¹ The hemisphere provided nearly uniform illumination over an area larger than the field of view of the spectroradiometer. Although the spectroradiometer had dual $2 \times 6^{\circ}$ fields of view, we operated the spectroradiometer as a single beam instrument, i.e. both sample and reference channels viewed different areas of the same target. The spectroradiometer was positioned at a zenith view angle of 30° resulting in views of two areas approximately 2×7 cm each. Nine pairs of spectral data were acquired at different locations on each sample. Reflectance factors were calculated using a Spectralon reference panel (Labsphere, Inc., North Sutton, NH) as described by Robinson and Biehl.¹²

Reflectance factors (R) were plotted as a function of wavelength for each sample. Minor discontinuities in the spectra at 1062 nm and 1772 nm were associated with changes in detectors and/or changes in the diffraction gratings. For this preliminary study, we deleted these data rather than force the spectra to match.

Results and discussion

In Figure 1, we present several pairs of reflectance spectra for corn, soybean and soil. The upper curve of each pair is the spectrum of the dry sample and the lower is the spectrum for the wet sample. Although we measured reflectance from 400–2500 nm, only the 1500–2500 nm wavelength region is shown.

Other research has clearly demonstrated that crop residues may be brighter or darker in the 400–1100 nm range depending on moisture content and age of the residue.^{4,5} This makes discrimination of crop residues from soil difficult and requires frequent adjustment of the discrimination thresholds for consistent results. In Figure 1, the spectra of dry residues appear quite different from the spectra of dry soil, but the wet spectra are very similar. The dry Houston clay soil contained more water (0.06 g_{water} / g_{soil}) and had lower reflectance than the other three dry soils (0.01 g_{water} / g_{soil}).

Many compounds found in plants contain functional groups with fundamental molecular vibrations that occur at wavelengths greater than 2600 nm. These fundamental absorption bands produce overtones and combination tones throughout the near infrared (700–2600 nm). The absorption spectrum is a function of all of the absorbing molecules present in a sample and is affected by the composition of the molecules, by the presence and magnitude of dipoles and by interactions between functional groups on a molecule and between different molecules.¹³ For example, the hydroxyl group shows two very broad absorptions bands centered about 1600 nm and 2100 nm. The broader band near 2100 nm appears in all compounds possessing alcoholic –OH groups, such as sugars, starch and cellulose.¹³ Thus, the strong absorption at 2100 nm, which is clearly evident in the reflectance spectra of the dry crop residues in Figures 1(a) and 1(b), is probably associated with cellulose in the crop residues. Elvidge¹⁴ observed similar absorption bands in his reflectance spectra of dry, intact plant materials. This cellulose absorption feature is absent in the spectra of the soils [Figure 1(c)].

The effects of water absorption nearly obscured the cellulose absorption in the spectra of the wet residues [Figures 1(a)–(b)]. Gao and Goetz¹⁵ examined subtle shape changes in the reflectance spectra of water and green leaves and concluded that absorption features of the plant material (primarily cellulose and lignin) in the 1000–2500 nm region can be identified even in spectra dominated by water absorption.





Figure 1. Spectral reflectance of corn residues (a), soybean residues (b) and soils (c). The upper curve of each pair is the spectrum for the dry sample and the lower is for the wet sample. MAH is months after harvest. The five spectral bands are indicated along the x-axis.

Since the cellulose absorption feature at 2100 nm is relatively broad in Figures 1(a) and 1(b), we selected three 50 nm-wide (approximately) bands—one at the reflectance minimum (cellulose absorption maximum) and the other two bands on the shoulders of the reflectance minimum. Additional bands were selected at 1930 nm (major water absorption region) and at 1660 nm (window between two major water absorption bands). The cellulose absorption index (*CAI*) was calculated as follows: CAI = 0.5(RF3 + RF5) - RF4; where *RF3* and *RF5* are the reflectance factors on the shoulders at 2021 nm and 2213 nm, respectively and *RF4* is minimum reflectance at 2100 nm.

Figure 2 is a scatter plot of *CAI* as a function of reflectance in the water absorption band at 1930 nm (RF2 in Table 1). The data formed four clusters of points. The means of the crop residues and soils are presented in Table 1. Reflectance factors of the crop residues generally were not significantly different from the reflectance factors of the soils (Table 1). The reflectance of the wet samples were always less than the reflectance of the dry ones. The mean *CAI* of the dry residues (4.4 ± 0.9) was significantly greater than the mean *CAI* of dry soils (-2.1 ± 0.7) . Although water absorption dominated the spectral properties of both soils and residues and nearly masked differences between the wet soils and the wet residues, the mean *CAI* of the wet residues (0.3 ± 0.1) was significantly greater than the *CAI* of the wet soils (-1.0 ± 0.1) . Thus, the *CAI* may be used to distinguish between crop residue and soil regardless of wetness.

The previous figures and analyses have considered only spectra from pure soil or residue samples. In practice, many spectra will be a real mixtures of soil and residues. We simulated these mixed spectra (RF_{mix}) using the following equation: $RF_{mix} = (RF_S) (f_S) + (RF_R) (f_R)$, where RF_S and RF_R are the reflectance factors of soil and residue, respectively and f_S and f_R are the fractions of soil and residue, respectively. The expected *CAIs* for targets with fractions of crop residue ranging from 0 (100% soil) to 1.0 (100% crop residue) are shown in Figure 3. Using the *RMSE* for *CAI* from Table 1, we calculated that a 0.1 change in the fraction of residue cover should



Figure 2. Cellulose absorption index (*CAI*) for the residues and soils plotted as a function of reflectance in the water absorption band at 1930 nm. The means of the four clusters of points are significantly different from each other (Table 1).

Target	n	Moisture ^a	RF1 ^b	RF2	RF3	RF4	RF5	CAI
		g/g	Percent					
			Dry					
Corn	3	0.29	49.7 a	32.8 a	38.5 a	32.9 a	35.9 a	4.9 a
Soybean	3	0.41	37.7 b	26.5 a	30.4 b	25.7 b	28.5 a	3.8 b
Soil	4	0.02	38.2 b	32.9 a	35.9 ab	36.6 ab	33.2 a	-2.1 e
			Wet					
Corn	3	2.62	27.1 c	5.6 b	9.2 c	11.5 c	14.6 b	0.4 c
Soybean	3	2.26	19.5 c	2.8 b	5.5 c	7.7 c	9.9 b	0.2 c
Soil	4	0.40	22.9 c	4.7 b	8.1 c	12.0 c	13.9 b	-1.0 d
RMSE			3.9	4.9	4.0	3.6	3.7	0.5

Table 1. Mean percent reflectance and cellulose absorption index (CAI) of crop residues and soils.

^aMoisture is mass of water per mass of dry matter. The dry Houston clay soil contained more water (0.06 g_{water} / g_{soil}) the other three dry soils (0.01 g_{water} / g_{soil}). ^bReflectance factors in 50 nm wide bands centered at the following: RF1 = 1660 nm. RF2 = 1930 nm, RF3 = 2021 nm, RF4 = 2100 nm and RF5 = 2215 nm. CAI = 0.5(RF3 + RF5) – RF4. Within each column, means followed by the same letter are not significantly different at $\alpha = 0.05$ level by the Student–Newman–Keuls test.



Figure 3. Expected changes in the cellulose absorption index (*CAI*) values as a function of the fraction of residue cover.

produce significant differences in *CAI* for mixtures of dry residues and dry soils. The wide range in *CAI* values for the dry mixtures made discrimination of various mixtures relatively easy. However, the narrow range of *CAI* values for the mixtures of wet soil and wet residues made discrimination more difficult. Examination of the clusters in Figure 2 reveals that the variation among the wet samples is much less than that of the dry samples. Thus, overall *RMSE* from Table 1 may be too large and the test of significance is probably too conservative for the wet samples. The moisture content of samples also could be monitored by using reflectance in the water absorption region of the spectrum.¹³

A new technique for determining crop residue cover is suggested by the results of this exploratory study. The crop residue spectra displayed a cellulose absorption at 2100 nm which was absent in the soil spectra. Water altered the reflectance spectra but did not completely obscure the cellulose absorption feature in wet residues.

Although we selected the crop residues and soils to represent a wide range of conditions, the sample set was very small. Additional work is needed to determine whether these differences are detectable in other residues and, most importantly, in field situations.

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