

# Cellulose absorption index (CAI) to quantify mixed soil–plant litter scenes

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## Abstract

Quantification of plant litter cover on the soil surface is necessary in both agricultural and natural systems because the presence of litter influences the flow of nutrients, carbon, water, and energy in terrestrial ecosystems. Although remote sensing methods for measuring plant litter cover provide both a wider area of coverage and a more objective estimate of the spatial variability of litter than manual methods of quantifying the nongreen vegetation landscape components (e.g., litter or soil percent cover), it has been difficult to assess the efficiency of detecting partial litter cover over different soil types. The objectives of this study were (i) to acquire spectral reflectance data for four crop residues and two forest litter types in mixed scenes of soil and plant litter, (ii) to derive relationships that show the spectral variable, cellulose absorption index (CAI), as a function of the amount of litter on the soil surface, and (iii) to test whether the variability of soil background reflectance inhibits the detection of residues and/or the ability to quantify residue cover. Scenes of known amounts of plant litter covering three contrasting soils were prepared and their reflectance spectra (0.4–2.5  $\mu\text{m}$ ) were measured with a hyper-resolution spectroradiometer. Litter from four crop (corn, soybean, rice, and wheat) and two tree species (coniferous and deciduous) were included. The CAI ( $0.5(R_{2.0} + R_{2.2}) - R_{2.1}$ ) describes the average depth of the cellulose absorption feature at 2.1  $\mu\text{m}$  in reflectance spectra. Positive values of CAI indicate the presence of cellulose. The mean CAI of the soils was  $-2.0$  while the mean CAI of the plant litter was 5.2. CAI increased linearly for each plant litter as the amount of plant litter in the scene increased from 0% (bare soil) to 100% cover. The CAI values of mixed scenes with more than 10% litter cover were significantly larger than the CAI values of the soils. The results of this study indicate that CAI is useful for quantifying plant litter cover, even at low percent cover.

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## 1. Introduction

Quantification of plant litter cover on the soil surface is necessary in both agricultural systems, to evaluate the conservation tillage practices which protect soils from erosion, and natural systems, to estimate natural- or human-induced land cover change effects on the carbon source/sink balance. Accurate estimates of plant litter percent cover are important for determining spatial and temporal land cover changes, which affect estimates of the amount of stored carbon,  $\text{CO}_2$  exchanged with the atmosphere (global carbon flux), phytomass production, potential

productivity, and surface energy balance (Daughtry, Gallo, Goward, Prince, & Kustas, 1992; Elvidge, 1990; Goward & Huemmrich, 1992; Goward, Huemmrich, & Waring, 1994; Huete, Jackson, & Post, 1985; Ranson, Daughtry, & Biehl, 1986; van Leeuwen & Huete, 1996). An accurate quantification of nongreen landscape components (plant litter and soils) has impacts and consequences on ecosystem functioning, which, in turn, can be used to assess biodiversity and human health conditions such as disease (Graedel & Crutzen, 1997; Houghton & Skole, 1990; Peters & Lovejoy, 1990; Thomas & Sporton, 1997).

### 1.1. The importance of distinguishing litter from soils in agricultural systems

It is important to leave crop residue on the soil in agricultural systems because it (i) significantly decreases

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erosion by reducing runoff volumes and the movement of nutrients into streams and rivers, (ii) affects soil physical and chemical parameters, including water infiltration, evaporation, porosity, and soil temperatures, (iii) adds nutrients to the soil, improves soil structure, facilitates tilling, and influences fertilization regimes (herbicide and pesticide application), and (iv) impacts carbon sequestration (Aase & Tanaka, 1991; Alberts & Neibling, 1994; Daughtry, 2001; Daughtry et al., 1995; McMurtrey, Chappelle, Daughtry, & Kim, 1993; Nagler, 1997; Nagler, Daughtry, & Goward, 2000; Skidmore & Siddoway, 1978). Because so much tilled United States cropland is classified as highly erodible land (USDA, 1995), leaving residue cover on tilled agricultural land is a powerful management tool and percent residue cover is an important variable to measure. The most common method to estimate percent residue cover is the line transect, but it has been found to be tedious, subjective, prone to errors, and not spatially representative (Morrison, Huang, Lightle, & Daughtry, 1993; Morrison, Lemunyon, & Bogusch, 1995; Shelton & Dickey, 1995). Spectral reflectance in the shortwave infrared wavelength region to distinguish litter from soils has been shown to be an objective, timely, and accurate measurement technique, and is thus the most promising method of quantifying litter while minimizing ground truthing; this remote sensing method is a viable approach to distinguish scenes of litter and soils that are pure (100% cover for each) (Daughtry, 2001; Daughtry et al., 1995; Daughtry, McMurtrey, Chappelle, Hunter, & Steinerb, 1996; Daughtry, McMurtrey, Nagler, Kim, & Chappelle, 1996; Nagler et al., 2000).

### 1.2. The importance of distinguishing litter, soils, and green vegetation in natural systems

Most models which incorporate background reflectance spectra have been designed to evaluate agricultural canopies or desert vegetation cover (Goward & Huemmrich, 1992). Plant litter has been found to absorb a significant amount of photosynthetically active radiation (PAR, 0.4–0.7  $\mu\text{m}$ ) which is not used to produce biomass, and thus it influences estimates of green vegetation, biomass, productivity, and yield (Daughtry et al., 1992). Because litter often increases the estimate of PAR without actually adding to the biomass, the productivity is usually inaccurate due to an inability to distinguish litter from background soils in a scene or in the spectral models that estimate plant productivity, which are used to monitor landscape processes (Nagler, 1997; Nagler et al., 2000).

In natural areas which have seasonal changes that influence the production of tree/shrub litter, productivity is often overestimated during senescence, because ecosystem models assume (i) that the background scene reflectance originates from soil, not litter, because it is a more permanent ground component than litter, and (ii) that litter does not contribute to the estimate of productivity (Nagler,

1997). In dry lands, there are limited reserves of moisture and nutrients, which have the effect of reducing vegetation (biomass), and increasing soil exposure. This leads to consequential changes in the carbon and water cycles and affects the overall ecosystem. Until ecosystem/landscape models can account for energy absorbed by litter and by soils, these models cannot be used to accurately predict plant productivity or the physiological state of plant canopies.

Additionally, fixed carbon in the terrestrial ecosystem is largely found in the cellulose of plant litter and influences atmospheric carbon dioxide ( $\text{CO}_2$ ) concentrations and contributes to nitrogen and oxygen cycles (Elvidge, 1990). Therefore, to evaluate the condition and yield of vegetation correctly, it is critical that plant litter is distinguished, labeled, and modeled separately from soils, and, that the quantification of the presence of plant litter be improved upon.

### 1.3. Wavelength regions used to distinguish soils from litter

It has been difficult to use remote sensing methods to get an accurate assessment of the ground conditions because the nongreen components, soil and litter, are not easily discriminated in the visible (VIS) and near infrared (NIR) wavelength region. Two problems encountered in discriminating pure plant litter from pure soils in the VIS–NIR are (i) neither plant litter nor soil has any unique spectral feature in the visible–near infrared (0.4–1.1  $\mu\text{m}$ ) wavelength region, and (ii) the reflectance of plant litter can be greater or less than the reflectance of soil (Aase & Tanaka, 1991). Plant litter affects vegetation indices (VI), and variations in the VI can also be seen in arid, semi-arid, or standing litter scenes, or when plant litter and soil cross-plots are shown (Huete et al., 1985; van Leeuwen & Huete, 1996). Fluorescence techniques have been useful in distinguishing litters from soils (0.32–0.40  $\mu\text{m}$ ), but careful attention must be given to the source of excitation energy and relatively small fluorescence signal when illuminating the litter and soils with ultraviolet radiation in the field (Daughtry et al., 1995; Daughtry, McMurtrey, Kim, & Chappelle, 1997).

Elvidge (1988) used Airborne Visible Infrared Imaging Spectrometer (AVIRIS) data and calculated a lingo-cellulose index based on the difference between reflectance in the 2.18–2.22 and 2.31–2.38  $\mu\text{m}$  bands. A lignocellulose absorption trough at 2.1  $\mu\text{m}$  in the reflectance spectra of dried shrubs has been observed and is likely due to cellulose, hemicellulose, lignin, and other structural compounds, since sugars, starches, and other nonstructural compounds are readily degraded to these compounds by microorganisms (Elvidge, 1990; Murray & Williams, 1988; Roberts, Smith, & Adams, 1993; Roberts et al., 1990). Daughtry, McMurtrey, Nagler, et al. (1996) recognized that this absorption feature could be used for discriminating plant litter from soil and defined a spectral variable, called cellulose absorption index (CAI), which described the depth

of the lignocellulose absorption feature in the shortwave infrared region (2.0–2.2  $\mu\text{m}$ ) as shown in Eq. (1):

$$\text{CAI} = 0.5 (R_{2.0} + R_{2.2}) - R_{2.1} \quad (1)$$

where  $R_{2.0}$ ,  $R_{2.1}$ , and  $R_{2.2}$  are reflectance factors in bands at 2.00–2.05, 2.08–2.13, and 2.19–2.24  $\mu\text{m}$ , respectively.

It has been possible to discriminate pure scenes of soils from pure scenes of some crop residues and tree litters in the laboratory using CAI (Daughtry, McMurtrey, Nagler, et al., 1996; Nagler, 1997; Nagler et al., 2000). In these studies, the CAI of dry litter was significantly greater than the CAI of dry soils. Although water absorption dominated the spectral properties of both soils and litters, the CAI of wet litter was significantly greater than that of wet soils. The decay of plant litter over time, or the age of the litter especially when dry, was found to have a significant effect on reflectance, presumably a result of cellulose and/or lignin decomposition (Elvidge, 1990; Nagler, 1997; Nagler et al., 2000). Daughtry (2001) has further assessed crop residues and soils to evaluate how water content affects the limits of their discrimination, not only for the extremes of moisture conditions (dry and wet), but also for varied moisture conditions over a large selection of crop residues; he reported that moisture conditions are important for determining crop residue cover in mixed scenes. Measurements on the ability to discriminate plant litter from background soils in a scene have examined neither the effect of the background soil in mixed scenes of both crop residues and tree litters, nor the minimum detection limit of CAI in mixed scenes.

This study evaluates the effectiveness of CAI for quantifying plant litter (four crop residues and two tree litters) on the soils surface. The objectives were to show CAI as a function of the litter level (amount by weight) and its density ( $\text{g}/\text{m}^2$ ) on the soil surface and to test whether the variability of soil background reflectance inhibits the detection of residues and/or the ability to quantify residue cover.

## 2. Materials and methods

### 2.1. Plant litter and soil samples

Corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) residues were collected from National Institute of Agro-Environmental Sciences (NIAES) agricultural fields in July 1996 in Tsukuba, Japan, while still green, and were then allowed to weather at natural temperatures and precipitation conditions over 2 weeks. Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) residues were collected shortly after harvest and were stored in a greenhouse for 8 months. Corn husks and soybean pods were present in samples collected. All crop residues were shredded to about 15 cm by harvesting equipment to

simulate actual residue conditions before the spectral measurements were made. Coniferous needles (*Cedrus deodra*) and deciduous broadleaf litter (*Quercus serrata*) were collected from the forest floor approximately 6 months after leaf drop and air-dried.

Surface samples of three soils were collected from fields at NIAES (Table 1). Each soil was air-dried and crushed to pass through a 2-mm screen. The inherent variability within soils (i.e., color, texture) has been shown to have marked differences in the reflectance spectra (Stoner & Baumgartner, 1981; Stoner, Baumgardner, Weismiller, Biehl, & Robinson, 1980); thus, these soil properties may have an impact on the ability to discriminate crop residue from soils and or to detect the residue amount or quantify its presence.

### 2.2. Preparing the sample trays

For soil-only samples, sample trays (27  $\times$  37  $\times$  3.5 cm) were filled to a depth of 3.0 cm. For mixed samples, trays were filled to 2.0 cm with each soil and known amounts of litter were scattered evenly over the soil surface. To determine the various levels of litter cover, each plant litter was spread to completely cover the bottom of a sample tray. The litter was weighed to obtain 100% cover. Since it was difficult to determine how much litter should be added to make the residue level 100% cover, an arbitrary amount of 500, 700, or 1000 g was selected depending on the litter type. Then, the litter was divided into tenths by weight; in this study, each tenth level is called the “level” estimated by weight (Rel.%C). The actual residue weight (g) at each level was then recorded and the density ( $\text{g}/\text{m}^2$ ) was calculated for each type of crop residue or tree litter. After each increment of litter was added to the soil in the sample tray, spectral reflectance of the mixed scene was measured.

For experiment 1, reflectance measurements of the mixed scenes included the four crop residues and two tree litters over three soils (black, gray, and red). The first set of spectral measurements acquired were for black soil alone (0% litter level), then with six different levels of residue, such that there were trays of black soil covered with 10%, 20%, 30%, 40%, 70%, and 100% wheat residue by relative weight, followed by 100% wheat residue alone. The sample tray was rotated 90° after each reflectance measurement to sample the scene ( $n=4$ ). Then, these four reflectance spectra, taken over the 0.4–2.5  $\mu\text{m}$  wavelength region, were

Table 1  
Description of the three soil used as backgrounds for the mixed scenes

Brief name	Soil taxonomy	Surface texture	Munsell color, dry	Munsell soil name
Black	Pachic Melandand	loam	10YR 2/3	brownish black
Gray	Typic Fluvaquent	sandy clay loam	10YR 6/2	grayish yellow brown
Red	Typic Hapludult	sandy clay loam	5YR 5/6	bright reddish brown

Table 2

Significant differences in CAI for crop residues (A) and tree litter (B) by level estimated from litter weight (Rel.%C), density (g/m<sup>2</sup>), percent cover (%C) by video, and CAI

(A) Crop residues												
Level by weight (Rel.%C)	Corn			Wheat			Rice			Soybean		
	Density (g/m <sup>2</sup> )	%C (n=3)	CAI <sup>a</sup> (n=3)	Density (g/m <sup>2</sup> )	%C (n=3)	CAI <sup>a</sup> (n=3)	Density (g/m <sup>2</sup> )	%C (n=3)	CAI <sup>a</sup> (n=3)	Density (g/m <sup>2</sup> )	%C (n=3)	CAI <sup>a</sup> (n=3)
0	0	0a	-2.12a									
10	50	20.6b	0.16b	50	20.6b	-0.33a	70	28.9b	-0.12b	70	18.1b	-0.83b
20	100	32.5c	1.81b	100	32.5c	2.35a	140	48.8b	2.58c	140	28.6b	0.52c
30	150	46.0c	3.47b	150	46.0c	3.11b	210	57.3bc	3.43cd	210	38.3b	1.17d
40	200	61.8c	3.88bc	200	61.8c	4.24b	280	72.6c	4.03cd	280	51.2bc	2.39ef
70	350	79.2c	4.75bc	350	79.2c	5.82b	490	89.3cd	4.51cd	490	62.6c	3.25f
100	501	82.1c	5.37c	501	82.1c	6.30b	701	95.8d	5.50d	701	78.9c	3.43f

(B) Tree litter						
Level weight (Rel.%C)	Deciduous			Coniferous		
	Density (g/m <sup>2</sup> )	%C (n=3)	CAI <sup>a</sup> (n=3)	Density (g/m <sup>2</sup> )	%C (n=3)	CAI <sup>a</sup> (n=3)
0	0	0a	-2.12a	0	0a	-2.12a
10	46	20.9b	-0.98a	100	26.2b	-0.54a
15	69	26.4bc	-0.29a	150	37.3bc	-0.86a
20	92	40.6bc	0.19a	200	51.9bc	2.31a
30	138	52.6bc	1.13a	300	61.3c	2.28a
100	461	100.0d	1.46a	1001	100.0d	1.85a

<sup>a</sup> In columns, CAI and percent cover means followed by the same letter are not significantly different according to the Tukey test at the  $t_{0.05}$  level.

used to calculate the average spectrum from which a CAI was determined. The four spectra from each plate are considered repetitions within a single sample, not statistical replications. This procedure was next repeated with the red soil, and lastly, the gray soil.

After one complete set of samples was taken for wheat with the three soils, the next residue was tested. The order the crop residues were tested was as follows: wheat, rice, soybean, and corn. Soils were used as blocks with each set of treatments replicated within each soil type. This is similar to the blocking procedure used in agricultural experiments conducted over varying soil types (Sokal & Rohlf, 1997).

For experiment 2, tree litters for coniferous and deciduous leaves were then tested in the same manner, except that the percent litter cover varied somewhat, such that black soil alone was measured, then black soil covered with 10%, 20%, 30%, and 100% tree litter by weight, followed by 100% tree litter alone. After finding that the critical residue or litter cover for detection was between 10% and 20% by weight, trays of 15% cover by weight were prepared and another 18 sets of reflectance measurements were acquired (4 crop residues  $\times$  3 soils, and 2 tree litters  $\times$  3 soils, with  $n=4$  repetitions).

The last set of trays to be measured was prepared to test the effect of moisture. These measurements included wet samples (for only wheat residue on black soil) with more residue levels for the low amounts represented, such that spectral measurements were obtained at levels of 0%, 5%, 10%, 15%, 20%, 30%, 40%, 70%, and 100% wheat residue on black soil.

### 2.3. Estimating percent cover using colored slides

Color slides of each tray were taken and analyzed using a video image system to determine percent litter cover for each scene. Using this system, 8-bit digital images in red, green, blue, and natural color bands can be produced from each color slide. However, only the natural color image was used since it was clearer than the other single-band images. The pixels in each image were classified as either litter or soil and litter cover was calculated. In this paper, the residue percent cover (%C) estimated from colored slides is referred to as “%C by video”. In total, there were 106 samples for which %C by video was determined.

### 2.4. Reflectance measurements

Spectral reflectance data over the 0.4–2.5  $\mu\text{m}$  wavelength region were acquired with a MSR-7000<sup>3</sup> spectroradiometer (Opto-Research, Japan) at 2-nm intervals. The end of a 1-m-long optical fiber from the spectroradiometer was positioned 32 cm above the surface of each sample at a zenith view angle of 0°. The field of view of the probe was 22°, which resulted in an area viewed that was 12 cm wide. Four 200-W quartz-halogen lamps illuminated an area larger than the field of view of the spectroradiometer.

<sup>3</sup> Company and trade names are given for the benefit of the reader and do not imply any endorsement of the product or company.

Reflectance factors were calculated as the response of the instrument to the sample scene divided by the response of the instrument to a painted-BaSO<sub>4</sub> reference standard (30 × 45 cm); however, the nonideal reflectance properties of the reference standard were not corrected for, causing an overall decrease in reflectance above 1.8 μm (Biehl & Robinson, 1983). The reflectance spectra were smoothed using a binomial filter, a weighted moving average, and the means ( $n=4$ ) were plotted as a function of wavelength.

### 2.5. Statistics

Only dry litter samples were used in the statistical analyses. Systat software (Systat, 2003) was used to acquire the statistics. Experiments 1 (agricultural residues) and 2 (tree litter) were analyzed separately using an unreplicated, three-way, factorial, ANOVA (Sokal & Rohlf, 1997). The experimental design in both was set up to test whether (i) soil color, (ii) litter type, or (iii) different levels of residues by weight (independent variables) would affect the quantification of litter using the CAI algorithm (dependent variable).

For Table 2, the soils were pooled ( $n=3$ ) to assess the dependent variable, CAI, at each residue level by weight, and the independent variable, percent cover (%C) by video, was evaluated for each litter type (Table 2). Density (g/m<sup>2</sup>) levels are also provided. Significant differences according to the Tukey test at the  $t_{0.05}$  level are listed next to the means

by different letters in columns for both percent cover (%C) by video and for CAI.

## 3. Results and discussion

### 3.1. Reflectance spectra (0.4–2.4 μm) of pure scenes of plant litter, soils, and green vegetation

Mean reflectance spectra of three soils, green vegetation, and six plant litters are shown in Fig. 1. The reflectance spectra of the three soils illustrate that the reflectance in the visible wavelength region is not always indicative of the reflectance at other wavelengths. For example, the black soil had the lowest reflectance in the visible and near infrared (0.4–1.1 μm), but had the highest reflectance at wavelengths greater than 1.4 μm. The gray and red soils also differed in their reflectance as a function of wavelength. Thus, these soils provided a wide range of reflectance spectra for this experiment. The variability was large enough to possibly inhibit the detection of residues on some soil types.

The spectrum of green leaves was obtained from wheat and corn leaves by Inoue, Morinaga, and Shibayama (1993) using the same instrument. The spectral reflectance curve of green vegetation was a step–function curve with low reflectance in the visible (0.4–0.7 μm) and high reflectance in the near infrared (NIR, 0.7–1.1 μm). Pigments (e.g., chloro-

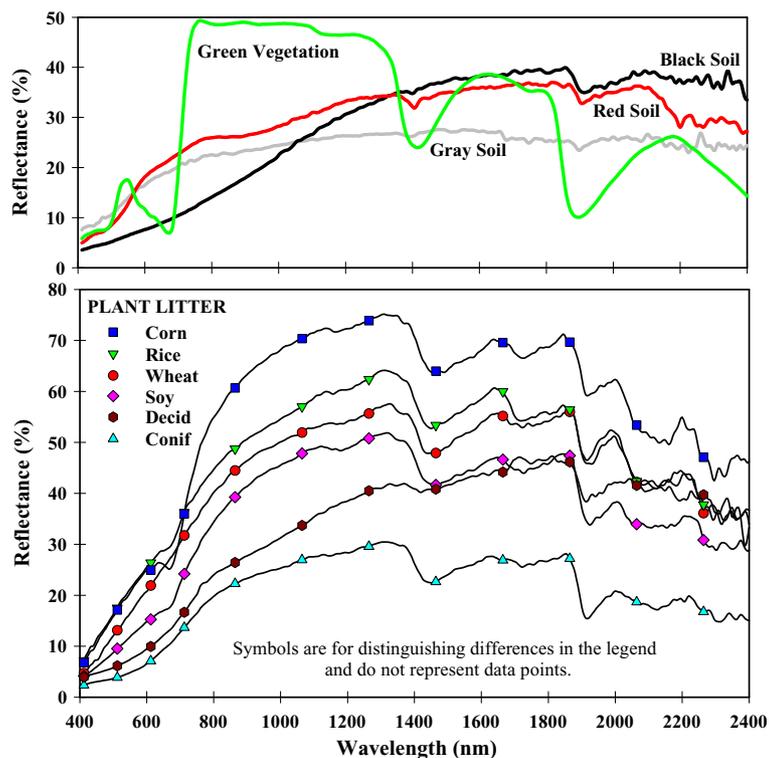


Fig. 1. Typical reflectance spectra (400–2400 nm) of black, red, and gray soils and green vegetation (top figure) and spectra of four crop residues and two tree litters (bottom figure). The symbols in the bottom figure do not represent data sampling points, but rather are placed on the spectral lines for clarity.

phylls, carotenoids, xanthophylls) in green leaves strongly absorb in the visible wavelengths and thus reflectance is low in the visible. In the NIR, multiple scattering at cell wall–air interfaces within leaves produces high NIR reflectance (Bauer, 1975; Gates, Keegan, Schleter, & Weidner, 1965). In contrast to green vegetation, the spectra of plant litter and soils do not show the step–function curve of green vegetation and are generally featureless in the visible and near infrared (Aase & Tanaka, 1991). During senescence, visible reflectance increases as green leaves lose pigments, NIR reflectance increases as intercellular air spaces increase, and shortwave infrared (SWIR, 1.2–2.5  $\mu\text{m}$ ) reflectance increases as leaves lose water (Woolley, 1971). Thus, the reflectance from dried plant material is often greater than green vegetation at nearly all wavelengths.

The plant litters showed greater variation in their reflectance spectra than the spectra of the three soils. No single wavelength band can uniquely distinguish all of these plant litters from these soils. Although the spectra in Fig. 1 only represent a small sampling of dry soils, plant litter, and green vegetation, it is clear that plant litter reflectance is distinguishable from green vegetation, but may be higher or lower than soil reflectance depending on physical attributes (i.e., type, age, moisture) of the plant litter (Daughtry, 2001; Daughtry et al., 1995; Nagler et al., 2000). Aase and Tanaka (1991) reached similar conclusions for the visible and near infrared (0.4–1.1  $\mu\text{m}$ ) wavelength regions, which was the limit of their instrument. However, there are unique features in the shortwave infrared reflectance spectra that may allow discrimination of plant litter from soil (Daughtry et al., 1995; Daughtry, McMurtrey, Nagler, et al., 1996).

The soils and litter spectra were generally featureless to about 1.1  $\mu\text{m}$ , while the green vegetation and recently harvested residue (i.e., corn) showed pigment absorptions (Fig. 1). Absorptions at 1.4, 1.9, 2.1, and 2.2  $\mu\text{m}$  are discernable in the spectra. The features at 1.4 and 1.9  $\mu\text{m}$  can be attributed to water absorptions (Murray & Williams, 1988). The feature at 2.1  $\mu\text{m}$  is associated with lignin and cellulose in plant litter (Elvidge, 1988, 1990), but is not visible in the soil spectra. The feature at 2.2  $\mu\text{m}$  is associated with clay minerals of soils (Ben-Dor & Banin, 1995), but is absent in the plant litter spectra.

### 3.2. Reflectance spectra (0.4–2.4 $\mu\text{m}$ ) of mixed scenes of plant litter and soils at two moisture levels

In the field, soils are rarely completely bare (0% litter cover) or completely covered with plant litter (100% cover), except in some no-till cropping systems. Daughtry (2001) varied the moisture content of soils and litter samples but only simulated the effect of mixed scenes; in the present work, the reflectance spectra of wet and dry scenes with different proportions of soil and litter were measured. Fig. 2 shows the dry (upper graph) and wet (lower graph) reflectance spectra for various amounts of wheat litter on the surface of the black soil. As the

coverage of plant litter increased in the dry samples, the prominence of the 2.1  $\mu\text{m}$  absorption feature also increased. Moisture reduced reflectance and masked the absorption feature at 2.1  $\mu\text{m}$  in all the wet, mixed samples. Nagler et al. (2000) also showed that discrimination of wet, pure soils from wet, pure litter was possible using CAI, but in this study, the wet, mixed samples with >20% litter cover did not show negative CAI values as was seen in the dry, mixed samples. Regardless of moisture, adding wheat litter to the black soil increased reflectance at all wavelengths. On the other hand, adding soybean residue to the gray soil reduced reflectance in the visible wavelength region, but increased reflectance at other wavelengths.

### 3.3. CAI values at increasing litter levels

The CAI spectral variable describes the average depth of the cellulose absorption feature at 2.1  $\mu\text{m}$ . Positive values of CAI represent the presence of cellulose, and thus, plant litters typically had positive CAI values. Negative values of CAI indicate the absence of cellulose. CAI of soils is typically negative (Nagler, 1997; Nagler et al., 2000). Daughtry, McMurtrey, Nagler, et al. (1996) observed that in the wet samples, absorption by water dominated the reflectance spectra and nearly obscured the differences in their CAI values.

In this work, the CAI of all three soils was negative, but as the amount of litter on the soil surface increased, CAI of the mixed scenes also increased (Fig. 3). For experiment 1 with the crop residues, all four residue types showed that mixed scenes with 0% and 10% residue level by weight and black soil underneath were negative, showing that small amounts of residue on black soil could not be discriminated from bare soil. However, for gray soils, the mixed scene litter limit varied depending on the litter type. For corn and soybean residues, the mixed scenes with 0% and 10% residue level and gray soil underneath were negative, as was with the black soil, showing that small amounts of residue on gray soil could not be discriminated from bare soil. However, for wheat and rice residue, the mixed scenes with 10% residue level and gray soil underneath were positive, showing that these could be discriminated from bare soil. For red soil, for wheat and soybean residue, the mixed scenes at the 0% and 10% levels were negative, but were positive with corn and rice residue at these percent cover levels. All four crop residue types had positive CAI values for mixed scenes of more than 20% residue level. These were significantly different from the CAI values of the soils.

For experiment 2 with the tree litters, both types showed that mixed scenes with 0% litter level for the black soil were negative, but that any amount of litter (10%, 15%, and 20% litter level or higher) could be discriminated from the black soils using CAI. The situation was different for the gray and red soils. Deciduous, broadleaf tree litter at 10%, 15%, and 20% litter level had negative CAI values and could not be discriminated from the underlying gray or

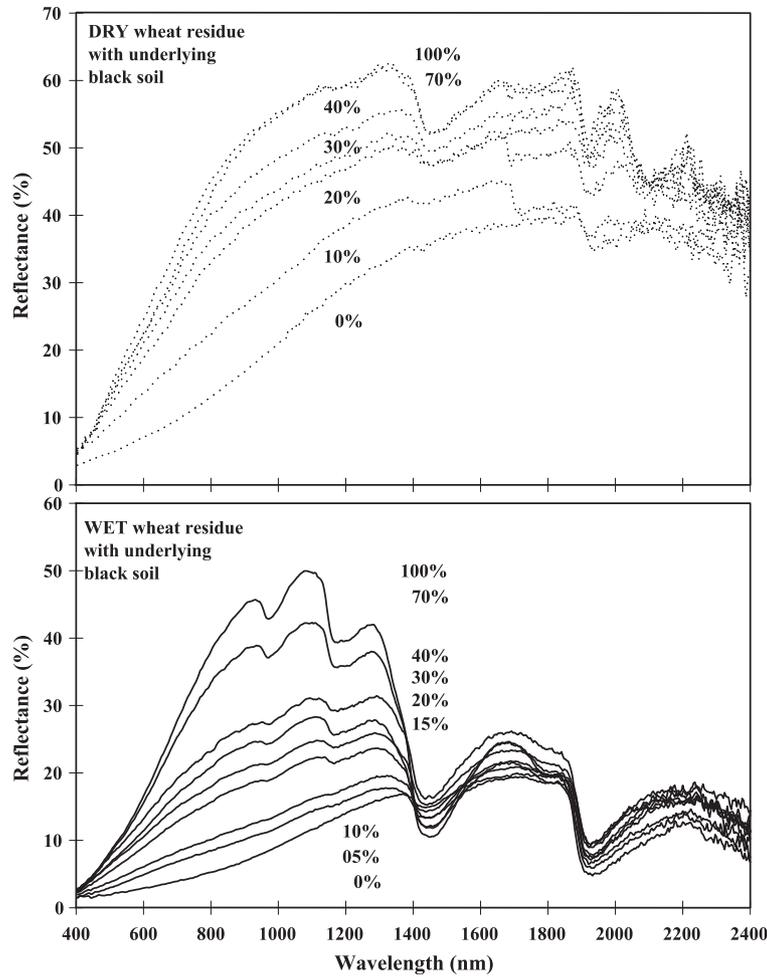


Fig. 2. Mean reflectance spectra for a series of wet and dry mixed scenes of wheat residue with underlying black soil. The litter level, estimated from its weight, of wheat residue in the dry scenes (top figure) were 0% (black soil), 10%, 20%, 30%, 40%, 70%, and 100%. The levels in the wet scenes (bottom figure) were 0% (black soil), 5%, 10%, 15%, 20%, 30%, 40%, 70%, and 100%.

red soils. The mixed scene CAI values only became positive at levels greater than 30% litter level. For coniferous tree litter over gray soil, the CAI values were positive for litter levels greater than 10%, showing that this residue could be easily discriminated from a gray background soil. For coniferous tree litter over red soil, the CAI was negative for 10% and 15% residue levels, but was positive at 20% residue level.

#### 3.4. The effect of moisture content on CAI

The CAI of each scene was plotted as a function of reflectance in the water absorption band at 1.91–1.95  $\mu\text{m}$  (Fig. 4). Mean CAI increased significantly from bare soils (CAI = -0.2) as the amount of plant litter on the soil increased to 100% cover (CAI = 5.2). The plant litter had positive values of CAI and the soils had negative values. The CAI of green leaves from Inoue et al. (1993) were also large negative values, which indicated that the cellulose absorption feature was obscured by the abundance of water

in green leaves. CAI can be used to distinguish green canopy cover from underlying nongreen landscape components, but it is possible given CAI as a function of reflectance in the water absorption band (1.91–1.95  $\mu\text{m}$ ). A multispectral approach may also be employed; for example, the simple ratio (reflectance in the 0.76–0.90  $\mu\text{m}$  band divided by reflectance in the 0.63–0.69  $\mu\text{m}$  band (Wiegand & Richardson, 1992)) could be used to distinguish green vegetation from bare soil and the CAI could be used to separate plant litter from soil. Thus, the CAI is relevant to situations where it is important to distinguish residues from soils (agricultural systems) and to discern green vegetation canopies from underlying nongreen vegetation components (natural systems).

#### 3.5. Mean CAI and percent cover by image analysis (%C by video) for each litter type

The CAI of each residue level (by relative weight) was averaged across soils ( $n = 3$ ) and evaluated by density ( $\text{g}/\text{m}^2$ )

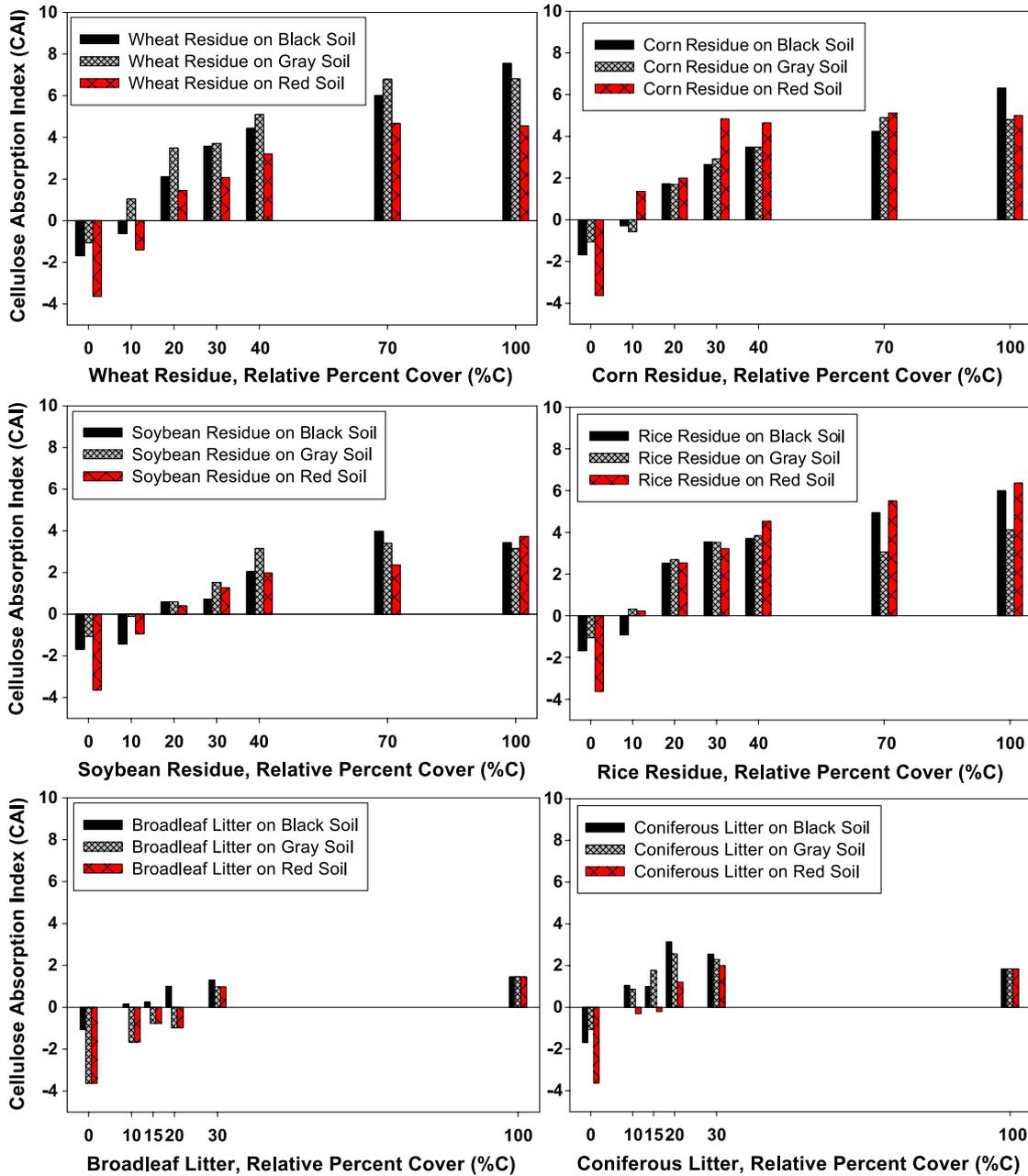


Fig. 3. Cellulose absorption index (CAI) as a function of the amount of residue for mixed scenes of varying amounts of each crop residue and tree litter, shown for each of the three soils.

and percent cover by image analysis (%C by video) for each litter type (Table 2). Statistics to separate the means by the litter level (amount or Rel.%C) and its density ( $g/m^2$ ) on the soil surface were employed. For %C by video, significant differences in the means ( $n = 3$ ) according to the Tukey test at the  $t_{0.05}$  level were found to exist for corn and wheat residue levels between 0% (soil) and 10% residue levels, and between 10% and 20% residue level or higher (three levels of significantly different means). For soybean, there were also three levels of significantly different means, but they did not separate out until reaching 40% residue level

and higher. For rice, there were four levels of significantly different means, separating at 0% (soil), 10%, and 20% residue levels, and again at the 70% level. For both deciduous and coniferous tree litter, there were four levels of significantly different means, separating at much lower residue levels, such as at 0% (soil), 10%, and 15% litter levels, and also at the 100% level. Significant differences in the means (across soils), according to the Tukey test at the  $t_{0.05}$  level, exist for all the crop residue CAI values, but not the tree litter CAI values, as is shown in the CAI columns of Table 2.

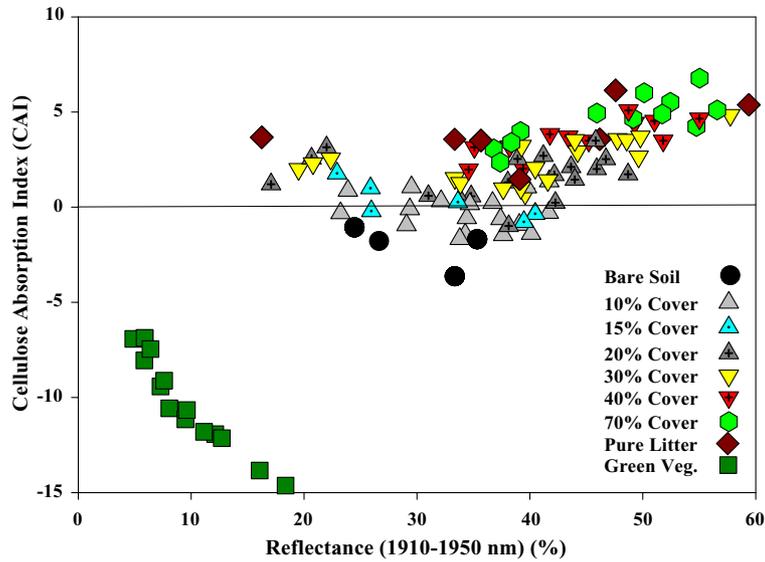
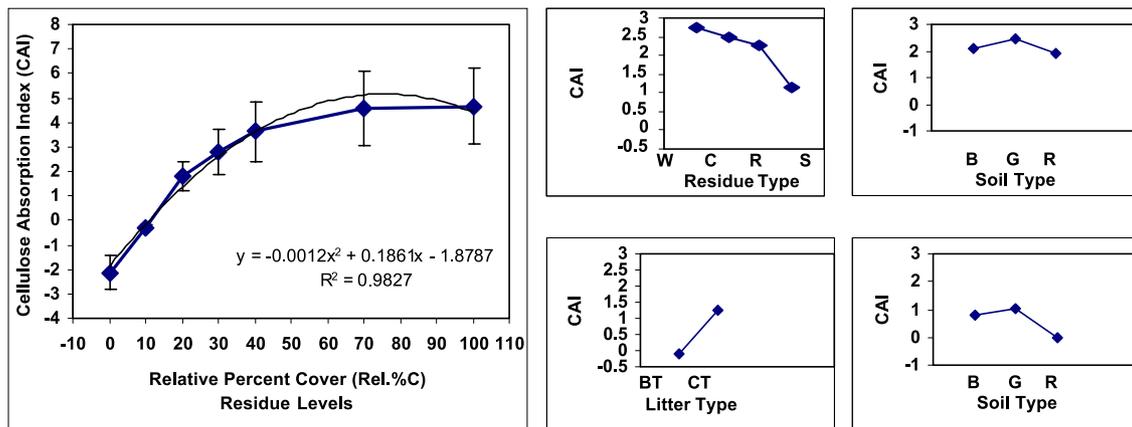


Fig. 4. Cellulose absorption index (CAI) of all the pure soils, mixed scenes of plant litter with different levels of cover, and green vegetation as a function of percent reflectance (%) in the water absorption band (1910–1950 nm).



Source	Sum of Squares	df	Mean Square	F-ratio	P
Soil Color	4.572	2	2.286	2.956	0.058
Crop Residue Species	31.944	3	10.648	13.769	0.000
Residue Level	468.899	6	78.151	101.054	0.000
Error	55.681	72	0.773		
Crop Residues: $r = 0.949$ , $r^2 = 0.901$ , $n = 84$					

Source	Sum of Squares	df	Mean Square	F-ratio	P
Soil Color	9.910	2	4.955	10.507	0.000
Tree Litter Species	16.578	1	16.578	35.153	0.000
Litter Level	85.532	5	16.506	35.001	0.000
Error	12.733	27	0.472		
Tree Litters: $r = 0.946$ , $r^2 = 0.895$ , $n = 36$					

Fig. 5. Cellulose absorption index (CAI) as a function of level for all crop residues and tree litters over three soils (left figure). CAI means are shown for experiments 1 (crop residue and soil types) and 2 (tree litter and soil types) (right four figures). Statistics for the two experiments are shown in the upper table (crop residues) and lower table (tree litters). For soils, B = black, R = red, G = gray; for residues, W = wheat, C = corn, R = rice, S = soybean, BT = broadleaf tree litter, and CT = coniferous tree litter.

3.6. Statistical results

The experimental design allowed the testing of whether the variability of soil background reflectance inhibits the detection of residues and/or the ability to quantify residue cover. The ANOVA tables and summary graphs show the results for both litter types (Fig. 5). In experiment 1 (top table), there were 84 crop residue samples and the degrees of freedom (*df*) were calculated by four crop residues (4 – 1 = 3 *df*), three soils (3 – 1 = 2 *df*), seven levels (7 – 1 = 6 *df*), and the error term had 72 *df*. In experiment 1, the soils were not significantly different ( $P=0.058$ ), but the soybean residue was significantly different than rice, wheat, and corn residues. In experiment 2 (bottom table), there were 36 tree litter samples and the degrees of freedom (*df*) were calculated by two tree litters (2 – 1 = 1 *df*), three soils (3 – 1 = 2 *df*), six levels (6 – 1 = 5 *df*), and the error term had 27 *df*. Soils were significant ( $P=0.001$ ); the red

soil showed a significantly lower CAI from the black and gray soils. The tree litter type and level were also significant. The results show that, while soils did influence the CAI–litter relationship in every case, the relationship was highly significant ( $r^2=0.9827$ ) (Fig. 5).

3.7. Curvilinear relationships between CAI and litter level

Cellulose absorption index (CAI) as a polynomial function of residue level by weight (Rel.%C) is shown for four crop residues and two tree litters (Fig. 6). For each type of litter, regression equations are provided for the three soils. The coefficients of determination ( $r^2$ ) values show high correlations between CAI and level. The poorest relationship for discerning residue from underlying soil exists for the following combinations: rice residue from a gray background soil ( $r^2=0.84$ ), coniferous tree litter on black soil ( $r^2=0.88$ ), corn residue on red soil ( $r^2=0.89$ ), and

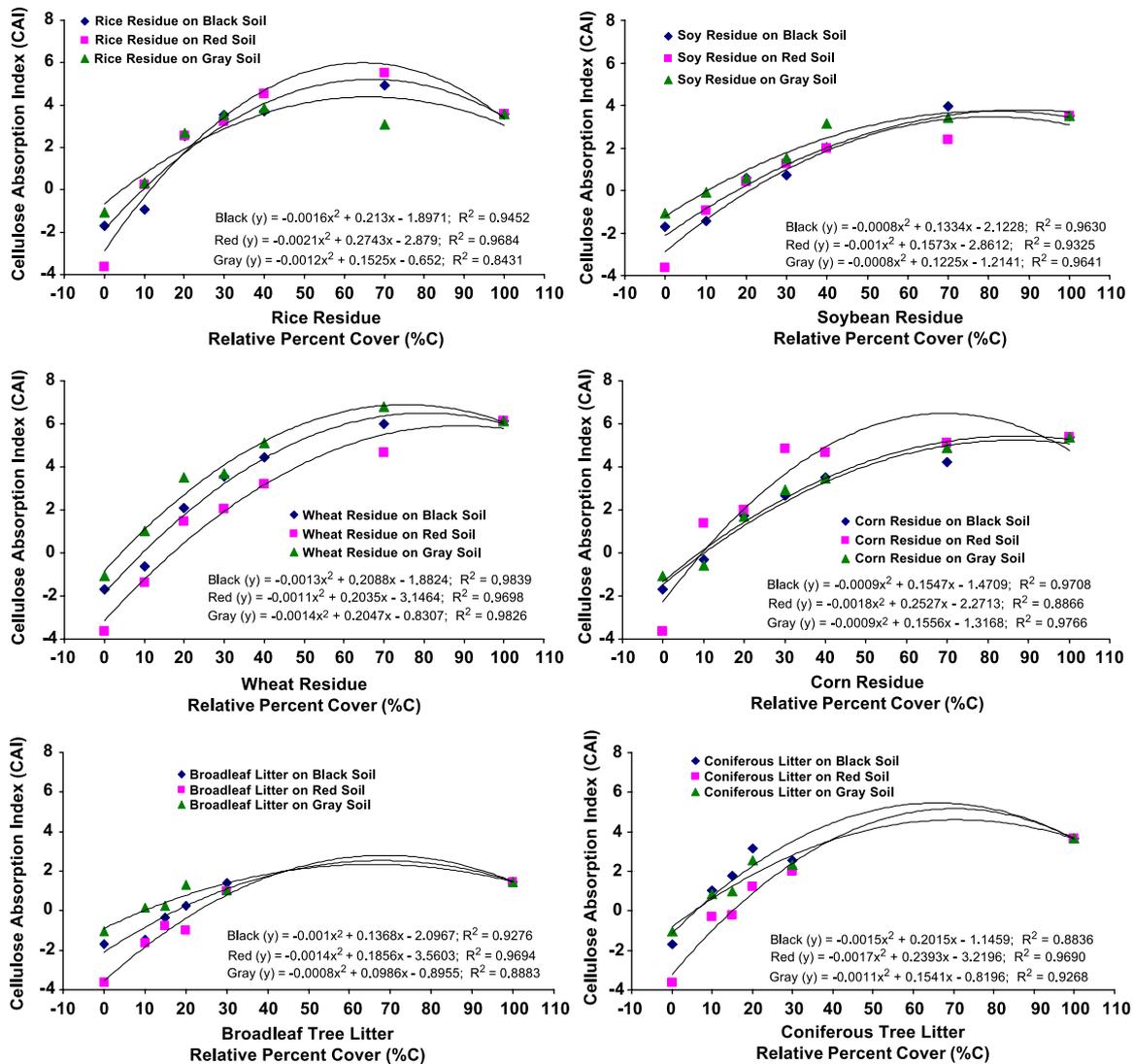


Fig. 6. Cellulose absorption index (CAI) as a polynomial function of level for four crop residues and two tree litters. Regression equations and coefficients of determination ( $r^2$ ) values are provided for each of the three soils underlying the residues.

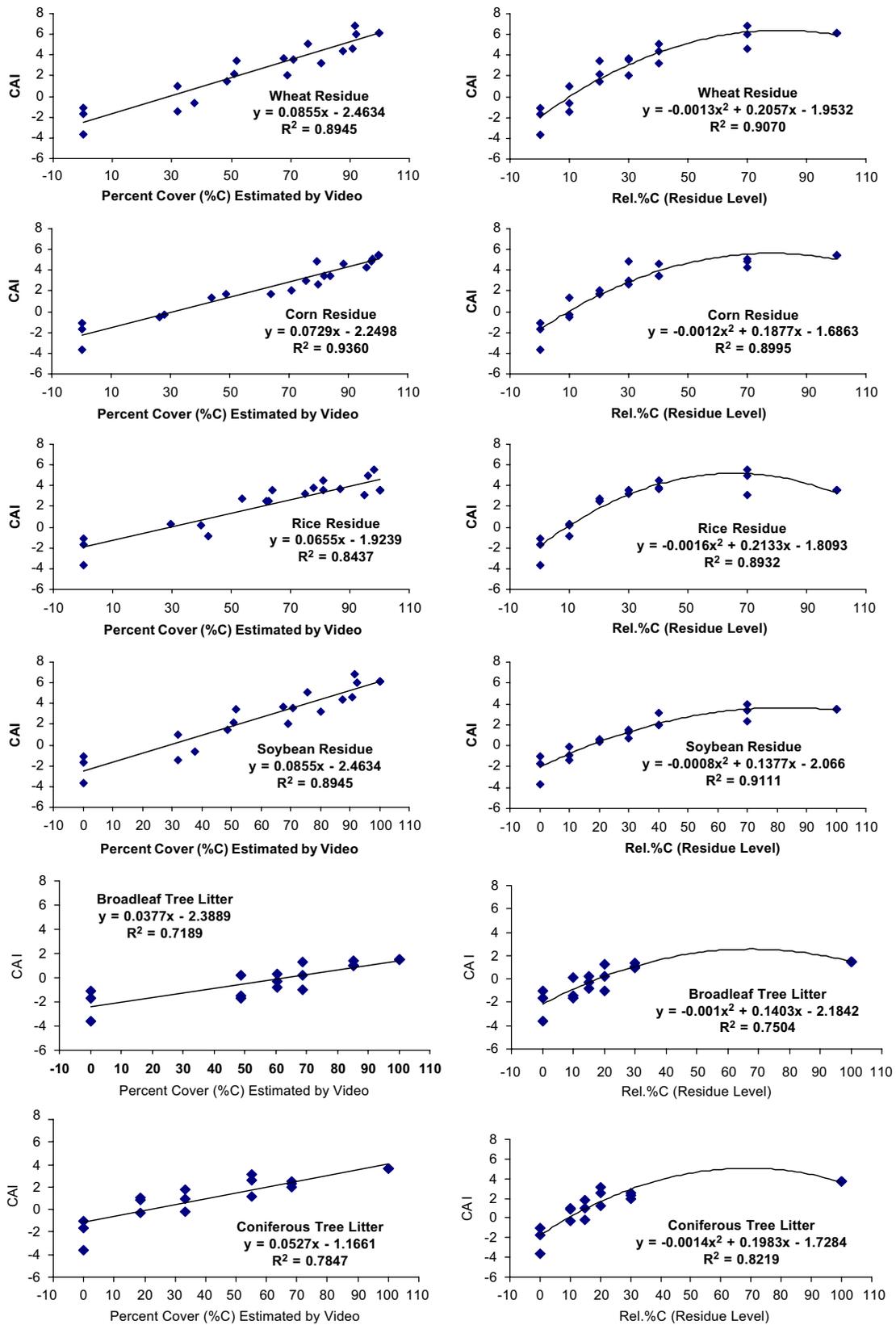


Fig. 7. Percent cover (%C) estimated for mixed scenes of four crop residues and two tree litters over soils by video (left-side figures) and level (Rel.%C) (right-side figures). By image analysis (%C video), a linear function describes the relationship between cellulose absorption index (CAI) and level (left), and a polynomial function describes the relationship between CAI and level estimated from its weight (Rel.%C) (right).

broadleaf, deciduous tree litter on gray soil ( $r^2=0.89$ ). The  $r^2$  was higher than 0.90 for all other combinations examined. These monotonically increasing curves show the relationship between CAI and percent cover (%C) of nongreen landscape components (soils and litter) and may be considered analogous to the hyperbolic curves of NDVI shown as a function of leaf area index (LAI) in numerous studies of green vegetation and spatial and temporal landscape dynamics. The number of leaves, stems, or stalks bears some similarity to the leaf area index in terms of plant matter per unit area. Since, in most studies, a spectral variable, such as NDVI, gives an approximation of percent cover and is shown as a function of the biophysical component, such as LAI for green plants, it does not seem unusual to relate this relationship for green vegetation to one for nongreen landscape components, although it may be

overreaching the scope of this study. An assumption is being made that there is a strong correlation between CAI and NDVI, as has been found with percent cover and LAI. Thus, just as NDVI gives an approximation of percent cover, so may CAI. Furthermore, the curvilinear regressions in Fig. 6 do not saturate at high levels of percent residue cover and thus show that soil background contamination is not as likely to affect CAI (or the scene reflectance) or to distort the interpretation of the spectral variable, as is often a problem with the NDVI–LAI relationship at LAI levels greater than 3.0 (Gao, Huete, Ni, & Miura, 2000; Huete et al., 1985).

As shown in Fig. 6, a polynomial function with high  $r^2$  values describes the relationship between CAI and residue level by relative residue weight (Rel.%C) for each of the three underlying soil types. Fig. 7 shows the same poly-

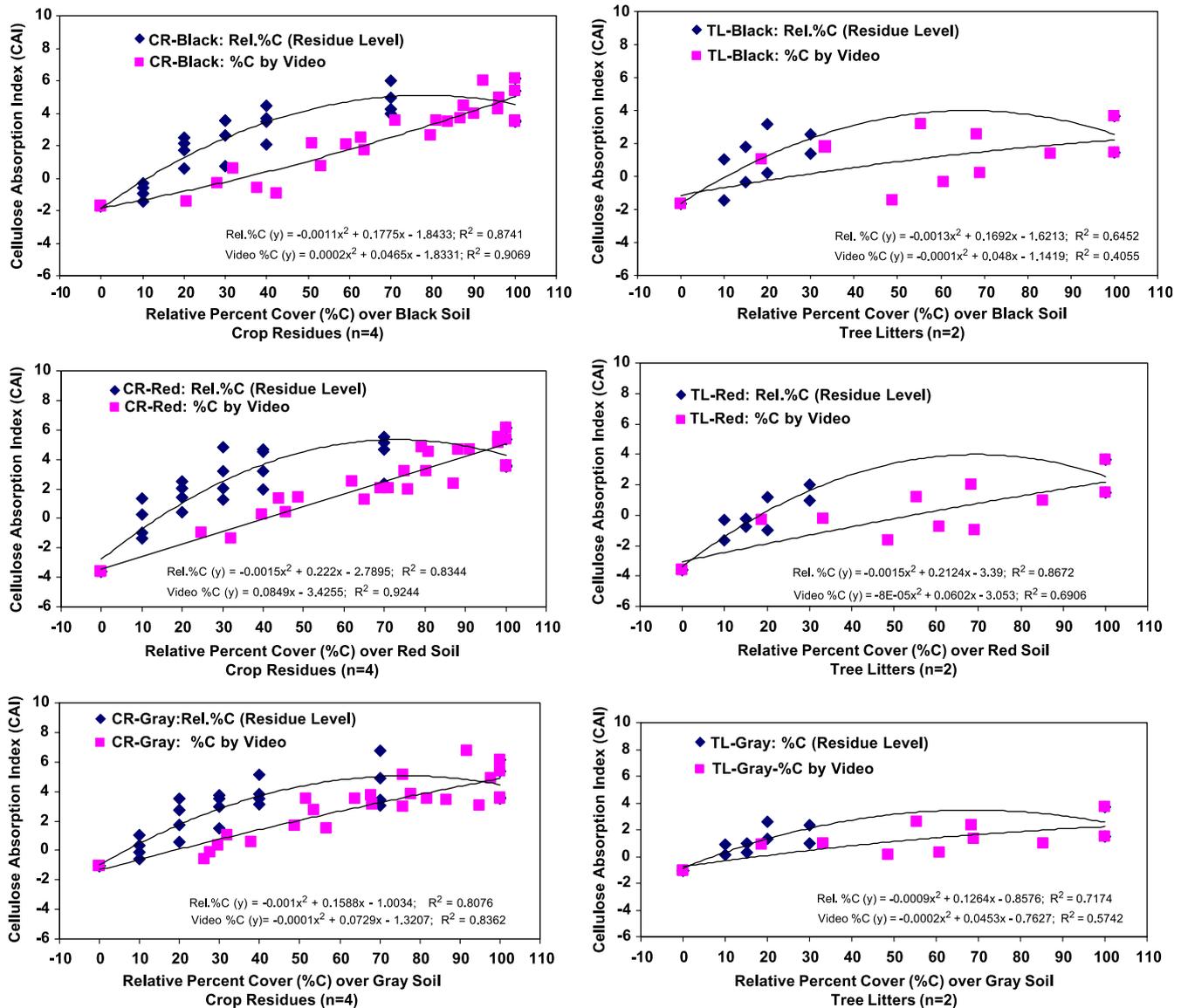


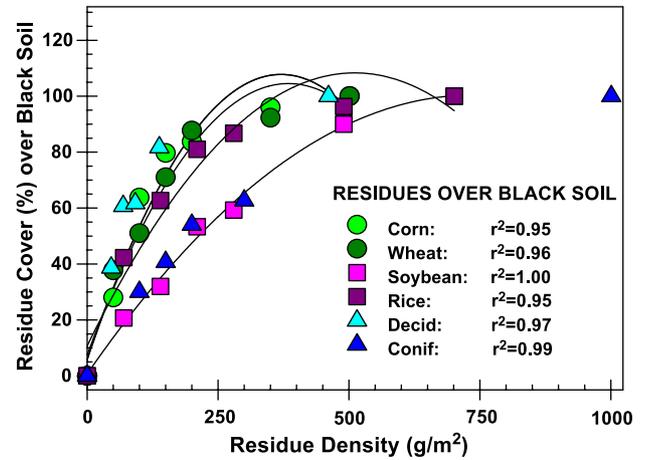
Fig. 8. Cellulose absorption index (CAI) as polynomial functions ( $n=2$ ) of level (Rel.%C) and %C by video for each soil (black, red, and gray) for mean crop residues ( $n=4$ ) (left-side figures) and tree litters ( $n=2$ ) (right-side figures).

nomial relationship between CAI and residue level, but averaged across the soils. Percent cover (%C) estimated for mixed scenes of four crop residues and two tree litters over soils (i) by video (left-side figures) and by (ii) relative residue weight (right-side figures) can be compared (Fig. 7). By image analysis (%C by video), a linear function described the relationship between CAI and residue amount (left), and a polynomial function described the relationship between CAI and residue level by relative residue weight.

CAI was also shown as a function of the average percent cover by image analysis (%C by video) and residue level (%C by weight) by soil type for each experiment, crop residues and tree litters (Fig. 8). These polynomial functions, CAI by image analysis (%C by video) and residue level, showed that the crop residues had more robust coefficients of determination ( $r^2$ ) values than the tree litter, regardless of soil type. In fact, the regressions of CAI and %C by video were more robust than the regressions of CAI and residue level for only the crop residues and were the inverse for the tree litters, i.e., CAI and %C by video had much lower  $r^2$  values than residue level. From these relationships, it appears that %C by video (image analysis) was a more effective method of discriminating crop residues, while %C by weight (residue level) was a more effective method of discriminating tree litters. For this experiment, the CAI–%C relationship is not statistically influenced by soil background, with the exception of tree litter with underlying red soil, but for both the %C by video and level, the polynomial relationships for litter over red soil were greater than those over either the black or gray soil, regardless of litter cover. The polynomial function for CAI versus %C by video or level showed that crop residue over red soil had the overall highest  $r^2$  for any soil (the relationship is averaged across crop residues and across tree litters), although the red soil may remain confounded by the cellulose or lignin features of plant materials in the short-wave infrared wavelength range. Because the red soil was significantly different from the other soils, pigments in the visible wavelength range may make this soil a more visible one to discern from residues covering it, and perhaps, bands in the visible wavelength range could be considered in combination with CAI when trying to discriminate plant material from certain soils.

### 3.8. Curvilinear relationships between litter level and density

Residue cover over black soil is shown as a function of residue density ( $\text{g}/\text{m}^2$ ) (Fig. 9). The litter type, regression equation, and coefficients of determination ( $r^2$ ) for the mean of each residue and litter type over the black, red, and gray soil are also shown. Curvilinear relationships produced high correlation coefficients, regardless of soil color. The curvilinear relationships that exist between residue cover and density (Fig. 9) also exist for CAI as a function of percent



Black Soil		
Corn Residue	$y = -0.0007x^2 + 0.5508x + 5.7772$	$r^2 = 0.95$
Wheat Residue	$y = -0.0007x^2 + 0.5053x + 7.4017$	$r^2 = 0.96$
Soybean Residue	$y = -0.0002x^2 + 0.271x + 0.6507$	$r^2 = 1.00$
Rice Residue	$y = -0.0004x^2 + 0.3823x + 10.677$	$r^2 = 0.95$
Deciduous Tree Litter	$y = -0.0012x^2 + 0.7588x + 4.5000$	$r^2 = 0.97$
Coniferous Tree Litter	$y = -0.0002x^2 + 0.2671x - 2.9972$	$r^2 = 0.99$
Red Soil		
Corn Residue	$y = -0.0008x^2 + 0.5429x + 12.274$	$r^2 = 0.93$
Wheat Residue	$y = -0.0006x^2 + 0.4801x + 5.8063$	$r^2 = 0.99$
Soybean Residue	$y = -0.0003x^2 + 0.3243x + 3.6871$	$r^2 = 0.98$
Rice Residue	$y = -0.0003x^2 + 0.3653x + 9.7190$	$r^2 = 0.96$
Deciduous Tree Litter	$y = -0.0013x^2 + 0.7919x + 6.9943$	$r^2 = 0.97$
Coniferous Tree Litter	$y = -0.0002x^2 + 0.2983x - 3.3161$	$r^2 = 0.98$
Gray Soil		
Corn Residue	$y = -0.0007x^2 + 0.5369x + 2.2935$	$r^2 = 0.98$
Wheat Residue	$y = -0.0007x^2 + 0.5053x + 7.4017$	$r^2 = 0.96$
Soybean Residue	$y = -0.0002x^2 + 0.2824x + 4.1806$	$r^2 = 0.99$
Rice Residue	$y = -0.0003x^2 + 0.3425x + 5.2048$	$r^2 = 0.99$
Deciduous Tree Litter	$y = -0.0013x^2 + 0.8082x + 8.0226$	$r^2 = 0.96$
Coniferous Tree Litter	$y = -0.0002x^2 + 0.3126x + 3.5128$	$r^2 = 0.99$

Fig. 9. Residue cover over black soil as a function of residue density ( $\text{g}/\text{m}^2$ ) (top figure) and the litter type, regression equation, and coefficient of determination ( $r^2$ ) for the mean of each residue or litter type over the black, red, and gray soil (bottom figure).

residue cover (Figs. 5–8), because, generally, the spectral variable (CAI or NDVI) gives an approximation of percent cover.

Since the relationship is well correlated, differences in residue density are evident when comparing the residue at 100% coverage. Only 500 g of wheat and corn residue (compared to 700 g for soybean and rice or 1000 g for coniferous tree litter) was needed to cover the area. Lighter litters had greater percent cover while heavier litters had lesser percent cover, for example, corn residue stalks were heavier and could not cover the soil as well as soybean or rice residues. Coniferous tree litter and rice residue were the densest.

For densities less than  $350 \text{ g}/\text{m}^2$  (wheat, corn residues, and deciduous litter),  $490 \text{ g}/\text{m}^2$  (soybean and rice residue), or  $750 \text{ g}/\text{m}^2$  (coniferous litter), which is a level of 70% of the total residue by weight, residue density is a good predictor of residue cover (estimated by image analysis or by weight), but at higher densities, the relationship saturates and density is no longer a good predictor of residue cover. Overlapping pieces of plant litter contribute to density but

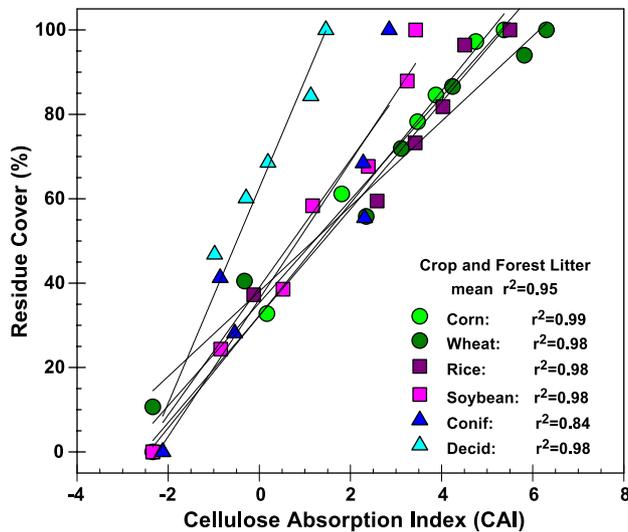


Fig. 10. Crop and forest litter levels estimated by their weight (Rel.%C) averaged over three soils shown as a function of cellulose absorption index (CAI).

do not contribute to percent cover, the horizontally projected residue area.

Density is important in this study because it relates to the fractional cover as follows: (i) the weight of litter affects its percent cover and thus the underlying soil has a greater effect on the scene reflectance, and (ii) the number of residue layers (i.e., pieces of litter) overlapping may have an effect on the scene reflectance. Stacked litter layers, (similar to an LAI of litter), which was not tested in this study, could be compared with the green leaf biophysical parameter LAI; in addition, like the NDVI–LAI relationship, at low densities, more soil shows through in the scene and the background soil reflectance would affect the overall calculation of CAI. It would be worthwhile to measure the effect of different residue densities, all at 100% cover, on CAI.

### 3.9. Linear relationships between litter level and CAI

Residue level by relative weight (Rel.%C), averaged over three soils, is shown for crop and forest litter levels and is linearly related to CAI (Fig. 10). Coniferous tree litter had the most variability and lowest correlation ( $r^2=0.84$ ). Deciduous tree litter had the lowest CAI values and a high correlation ( $r^2=0.98$ ). Although the discrimination of background soils from litter at low densities or residue levels of less than 10% (crop residues) or less than 20% (tree litters) may be difficult based on these results, CAI is a very good predictor of the percent of plant litter cover in mixed scenes.

## 4. Conclusions

Reflectance spectra of pure and mixed scenes of six plant litter types and three soils were measured and the

cellulose absorption index (CAI) was calculated using the spectral feature at 2.1  $\mu\text{m}$ . The CAI values of pure plant litter were significantly larger than the CAI value of the pure soils. For the mixed scenes, as plant litter cover increased, CAI increased linearly. The results showed that CAI was successful in distinguishing fractions of litter from underlying soils in laboratory mixed samples. In some soil types, as in the red soil in this study, a complication arises with using the depth of the cellulose absorption feature at 2.1  $\mu\text{m}$ , because the width of the clay mineral absorption feature at 2.2  $\mu\text{m}$  matches the minor reflectance peak of cellulose at 2.2  $\mu\text{m}$  that has been induced by absorptions at 2.1 and 2.3  $\mu\text{m}$  in plant material, and thus leads to lower values of CAI than with either the black or gray soils in this study. Therefore, it is recommended that special attention be given to the shoulder of the absorption feature at 2.2  $\mu\text{m}$  before utilizing the countered absorbance and reflectance features to calculate CAI. Using a two-way ANOVA for crop residues, soils were found not to be significantly different from one another, although when the statistics were run for tree litters, the red soil was indeed found to be slightly significant. Thus, only one soil type in this study inhibited the detection of tree litter and/or the ability to quantify litter cover. Because the relationship between CAI and litter level did not saturate at low levels of cover in these experiments, this spectral variable was useful over nearly the whole range (>70% cover) of mixed soil–litter scenes and was generally not affected by soil type. Furthermore, the strong linear relationship between the crop residues/tree litters and CAI promotes the idea of extrapolating these findings to other residue and litter species, although new experimental data would first have to be obtained. The relationships between CAI and percent cover were also determined for each plant litter by image analysis of color slides (%C by video) and residue level by weight (Rel.%C); the polynomial relationship between CAI and the level by weight was more useful than %C by video for all litters, except corn residue. When CAI was regressed with the average percent cover by image analysis (%C by video) and average %C by weight (residue level) for each experiment, crop residues and tree litters, the crop residues had more robust coefficients of determination ( $r^2$ ) values than the tree litter across all three soil types. However, %C by video (image analysis) was a more effective method of discriminating crop residues, while %C by weight (residue level) was a more effective method of discriminating tree litters. The red soil showed a more promising polynomial relationship between CAI and percent cover than the other soils for both methods of estimating percent cover (video and residue level by weight); percent cover was averaged across crop residues and across tree litters. Residue density ( $\text{g}/\text{m}^2$ ) can be compared with stacked leaves (weight per unit area) similar to leaf area index; this may warrant a new study in which the effect of a range of residue densities, all at 100% cover, on CAI is determined. An

instrument based on measuring CAI could replace tedious, manual methods of quantifying plant litter cover.

## 5. Uncited reference

Huete & Jackson, 1987

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