

# ASSESSING THE SPATIAL DISTRIBUTION OF PLANT LITTER

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## 1. INTRODUCTION

Quantifying crop residue cover on the soil surface is important for improving estimates of surface energy balance, net primary productivity, nutrient cycling, and carbon sequestration. Quantifying crop residue cover is also an important factor in controlling soil erosion and evaluating the effectiveness of conservation tillage practices. By reducing the movement of eroded soil into streams and rivers, the movement of nutrients and pesticides is reduced. The overall result is less soil erosion and improved water quality.

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

Attempts to replace the human visual judgment present 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 residue lack the unique spectral signature of green vegetation in the 400 to 1000 nm wavelength region (Aase and Tanaka, 1991; Daughtry et al., 1995). Crop residues and soils are often spectrally similar and differ only in amplitude at a given wavelength (Baird and Baret, 1997). This makes discrimination between crop residues and soil difficult or nearly impossible using reflectance techniques in the visible and near infrared wavelengths. Two promising approaches have been identified for discriminating crop residues from soil -- one based on blue fluorescence emissions and another based on shortwave infrared reflectance.

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

The shortwave infrared approach utilizes a broad absorption band near 2100 nm that appears in all compounds possessing alcoholic -OH groups, such as sugars, starch, and cellulose (Murray and Williams, 1988). This strong absorption at 2100 nm was clearly evident in the reflectance spectra of the dry crop residues (Daughtry et al., 1996) and dry, intact plant materials (Elvidge, 1990). The cellulose absorption feature was absent in the spectra of the soils. Daughtry et al. (1996) defined a new spectral variable, cellulose absorption index (CAI) that quantifies the relative depth of this absorption feature and can discriminate between crop residues and soils. Additional work is needed to determine the effects of moisture, residue age, and mixed pixels (soil + residue) on discrimination of crop residues from soils. The CAI algorithm has yet to be tested with hyperspectral images for fields and watersheds for assessing crop residue cover.

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The objectives of this research were to (1) determine the spectral reflectance of green plants, plant litters, and soils as a function of water content, (2) assess the limits of discrimination that can be expected, and (3) evaluate hyperspectral imaging data for providing information on the spatial distribution of plant litter. This research provides the scientific foundation required for sensor development and field testing.

## 2. MATERIALS AND METHODS

### 2.1 Reflectance Spectra

Reflectance spectra were acquired with a spectroradiometer (FieldSpec Pro, Analytical Spectral Devices, Boulder, CO) over the 400-2500 nm wavelength region at 1 nm intervals. The samples were illuminated by two 300 W quartz-halogen lamps mounted on the arms of a camera copy stand at 50 cm over the sample at a 45° illumination zenith angle. The spectroradiometer was positioned 90 cm from the sample surface at a 0° view zenith angle. With the 18° optics on the spectroradiometer, the diameter of the field of view at the sample was 28 cm. The illumination and view angles were chosen to minimize shadowing and to emphasize the fundamental spectral properties of the soils and crop residues. Four spectra were acquired of each samples by rotating the sample tray 90° after each spectrum. A 76-cm square Spectralon reference panel (Labsphere, Inc., 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). Mean reflectance spectra ( $n=4$ ) were plotted as a function of wavelength and moisture condition. In addition, the reflectance spectra were integrated over 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 cellulose absorption index (CAI) was calculated as:  $CAI = 0.5(R_{2.0} + R_{2.2}) - R_{2.1}$ ; where  $R_{2.0}$ ,  $R_{2.1}$ , and  $R_{2.2}$  are the reflectance factors in 10 nm bands centered at 2015, 2106, and 2195 nm, respectively. In previous work, 30 to 50-nm wide bands were used (e.g., Daughtry et al., 1996; Nagler et al., 2000).

Broad absorption features centered near 1730, 2100, and 2300 nm in the reflectance spectra of the dry crop residues were selected for continuum analysis (Kokaly and Clark, 1999). The continuum is an estimate of the reflectance spectrum without the absorption due to the compound of interest. Linear segments were used to approximate the continuum. The end points of each continuum segment used are given in Table 1. The continuum-removed spectra were calculated by dividing the original reflectance values by the corresponding values of the continuum line (Kokaly and Clark, 1999). Band depths within each absorption feature were normalized by dividing by the band depth at the center of the feature.

*Table 1. Continuum end points and band centers for three absorption features in reflectance spectra of dried crop residues.*

| Spectroradiometer Data |                     |                   | AVIRIS Data     |                     |                   |
|------------------------|---------------------|-------------------|-----------------|---------------------|-------------------|
| Band Center, nm        | Continuum Start, nm | Continuum End, nm | Band Center, nm | Continuum Start, nm | Continuum End, nm |
| 1728                   | 1652                | 1800              | 1733            | 1653                | 1802              |
| 2106                   | 2010                | 2200              | 2111            | 2011                | 2201              |
| 2304                   | 2238                | 2366              | 2300            | 2241                | 2370              |

### 2.2 Soil and Crop Residue Reflectance

Three topsoil samples were acquired for this study and provided a wide range of colors and textures (Table 2). Each soil was oven-dried at 105° C, crushed to pass 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. 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).

*Table 2. Soil names and sources of the top soils used in this study.*

| Soil Series | Location       | Classification                                      |
|-------------|----------------|---|
| Barnes      | Morris, MN     | coarse-loamy, mixed Udic Haploboroll                |
| Codorus     | Beltsville, MD | fine-loamy, mixed, mesic, Fluvaquentic Dystrochrept |
| Othello     | Salisbury, MD  | fine-silty, mixed mesic Typic Ochraquult            |

Crop residues of corn (*Zea mays* L.) and soybean (*Glycine max* Merr.) were collected from agricultural fields near Beltsville, Maryland at 1 week and 8 months after harvest. The crop residues were dried at 70° C and then stored at room temperature. 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 the trays then were placed in mesh bags, immersed in water for 2 h, allowed to drain freely for 2 h, and weighed before spectral reflectance was remeasured. Water content was expressed as relative water content (RWC).

In practice, reflectance spectra often represent mixed scenes with varying proportions of crops residues and soils. Reflectance factors of these mixed scenes ( $R_{(M, \lambda)}$ ) were simulated 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 ( $RWC = 0$ ) and wet ( $RWC = 1.0$ ) mixtures of each residue and soil were simulated.

### 2.3 AVIRIS Data

High-altitude AVIRIS radiance data (f000511t01p03\_r02) were acquired by the Jet Propulsion Laboratory (JPL) on May 11, 2000 at 15:34 GMT (11:34 EDT) over the Beltsville Agricultural Research Center (BARC), Beltsville, Maryland. The flight line was south to north (38.13° to 38.65° latitude at -76.85° longitude). A cold-front went through the area without showers, so the visibility was excellent, with little haze, except for fog and clouds over the Goddard Space Flight Center in Greenbelt, MD. Five scenes were obtained over the flight line, scenes 2 and 3 were combined and the BARC area was subsetting for all analyses, the data were not georectified.

On May 11, spectral radiances of a number of surface features were acquired with spectroradiometers (FieldSpec Pro, Analytical Spectral Devices, Boulder, CO) over the 400-2500 nm wavelength region at 1 nm intervals. Apparent reflectance factors were calculated using Spectralon panels (Labsphere Inc., North Sutton, NH) without correction for the reflectance spectrum of the Spectralon. The primary calibration target was a large asphalt tarmac (approximately 100 m x 400 m) within the scene. The year 2000 wavelength calibration file provided by JPL was used to convert the ASD FieldSpec Pro data into the 224 AVIRIS bands by averaging the ASD reflectance factors from the center wavelength  $\pm 0.5$  of the Full Width at Half Maximum.

The Atmospheric Removal Program (ATREM 3.1) was obtained from the Center for the Study of Earth From Space (CSSES), Cooperative Institute for Research in Environmental Studies (CIRES), University of Colorado. First, ATREM was used to estimate pixel reflectances from the radiance data. Second, the mean ATREM reflectance spectrum of the tarmac region of interest (ROI) and the mean ASD FieldSpec reflectance spectrum were used for a one-point empirical line calibration using Research Systems, Inc. Environment for Visualizing Images (ENVI) version 3.2. Finally, two major atmospheric water vapor absorption bands (108-118 and 155-172; 1364-1664 nm and 1832-1991 nm) were removed from the AVIRIS data.

End-members for linear spectral unmixing were selected from the corrected AVIRIS scene. The regions of interest (ROI) included: tarmac for asphalt, recently plowed fields with no residue for soil, several ponds for water, several roof tops, and fields of winter wheat and hairy vetch for bright green vegetation. Furthermore, we added the reflectance spectrum of a shaded Spectralon panel for the shade end-member, and the laboratory reflectance of corn residue for the residue end-member. The linear spectral unmixing routine in ENVI 3.2 was used with the seven end-

members without a unit sum constraint (i.e., the sum of the individual end-member fractions do not have to equal unity) to classify the AVIRIS image over BARC.

NDVI was calculated using bands 51 (827 nm) and 29 (646 nm). The Cellulose Absorption Index (CAI) was calculated using 176 (2031 nm), 183 (2101 nm) and 194 (2211 nm). Mean spectra, NDVI, and CAI were obtained from ROI for various fields at BARC.

### 3. RESULTS AND DISCUSSION

#### 3.1 Lab Spectra

Mean reflectance spectra of dry and wet corn and soybean residues are presented in Fig. 1. For each crop residue, the upper-most spectrum is the oven-dried residue and the lowest spectrum is for the water-saturated residue. The presence of water in the crop residue reduced reflectance across all wavelengths. Two major water absorption bands near 1450 and 1960 nm dominate the reflectance spectra at wavelengths >1300 nm. A broad absorption feature near 2100 nm is also evident in the reflectance spectra of all 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).

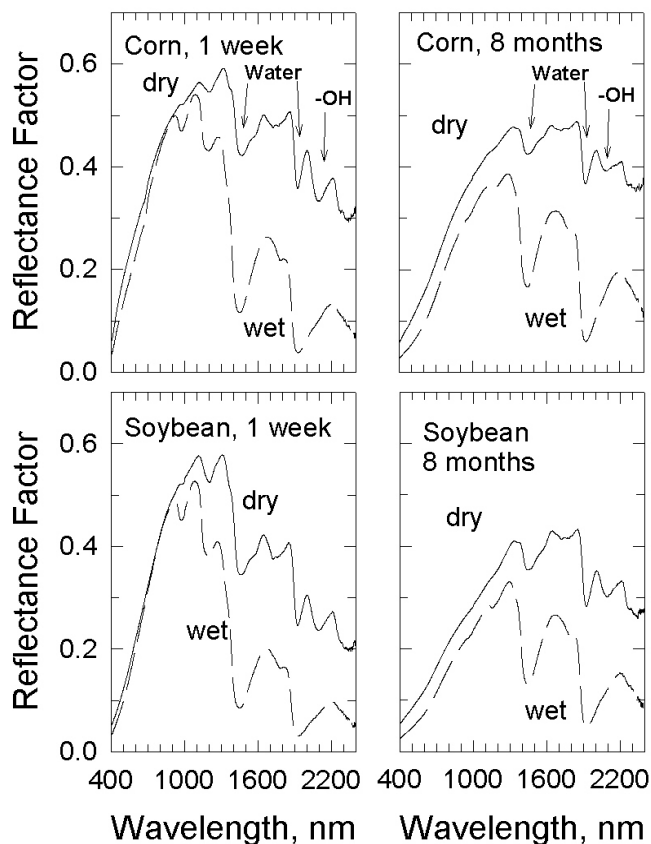


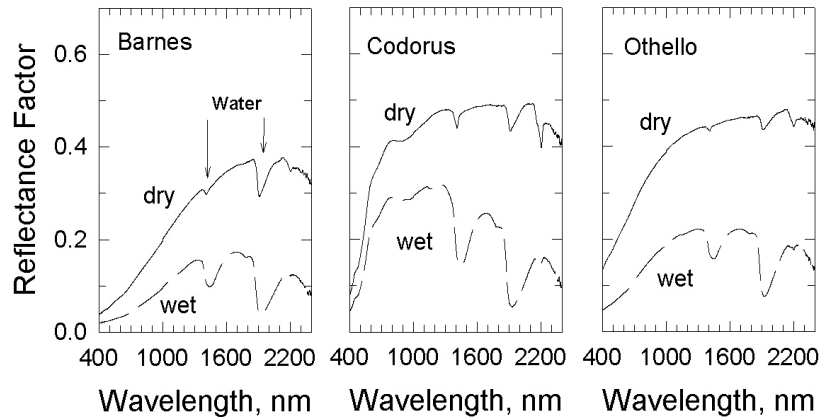
Figure 1. Reflectance spectra of dry and wet corn and soybean residues at 1 week and 8 months after harvest.

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 (Daughtry, 2001). Although the -OH absorption feature at 2100 nm was nearly obscured at high RWC, Gao and Goetz (1994) showed that cellulose and lignin absorption features can be identified in reflectance spectra dominated by water.

Mean reflectance spectra of the soils are shown in Fig. 2. As for the crop residue, water content reduced reflectance across all wavelengths. In addition to the two major water absorption features, a clay mineral absorption feature near 2200 nm (Baumgardner, et al., 1985) is evident in all three soils, but is especially strong in the Codorus spectra. The broad cellulose-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 (Figs 1 and 2). Crop residues may be brighter or darker than a particular soil depending on moisture content. Thus, discrimination of crop residues from soils using reflectance in any single wavelength band in the 400-2400 nm wavelength region would be difficult and would require frequent adjustments of the discrimination thresholds for consistent results.

Figure 2. Reflectance spectra of dry and wet Barnes, Codorus, and Othello soils.



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 differences in scene reflectance for the mixtures of dry ( $RWC = 0$ ) crop residues and soils (Fig. 3). The wide range in reflectance factors for the spectra of mixtures of dry Barnes soil and dry corn residue made discrimination relatively easy at most wavelengths. However, for the Codorus and Othello soils, the addition of corn residue generally decreased reflectance across the spectrum. A closer examination of the 1600–2400 nm portion of the spectra (Fig. 4) shows the gradual shifts from the soil spectrum ( $f_R = 0$ ) to the corn residue spectrum ( $f_R = 1.0$ ) for each soil-residue mix. Although not shown, the narrow range of reflectance values for the mixtures of wet soil and wet residues ( $RWC = 1.0$ ) increased the uncertainty of crop residue cover estimates (Daughtry, 2001). Clearly, moisture conditions are important for determining crop residue cover in mixed scenes.

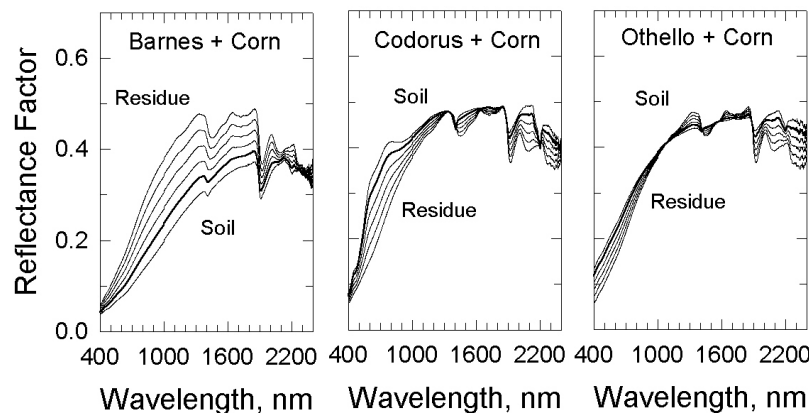


Figure 3. Reflectance spectra of mixed scenes of dry corn residue (8 months) and three dry soils. The six spectra for each soil represent 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of corn residue in the scene.

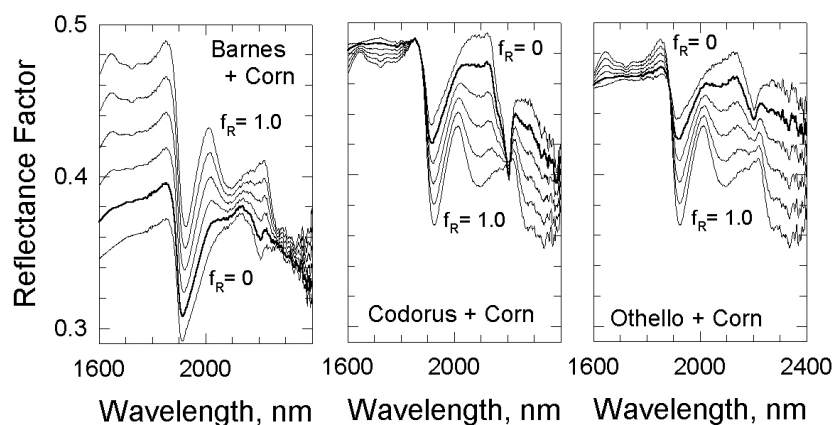


Figure 4. Expanded scale of mixed scenes of dry corn residue and dry soils. The six spectra for each soil represent 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of corn residue in the scene.

Many chemical bonds in plants have vibrational absorptions in the 1500 nm to 2500 nm wavelength region (Curran, 1989). Broad absorption features in the dry corn residue spectra centered near 1730 nm, 2100 nm, and 2300 nm were identified for continuum analysis. The end points of the continua of these three absorption features are given in Table 2 and are illustrated in Figure 5 for corn residues and two soils.

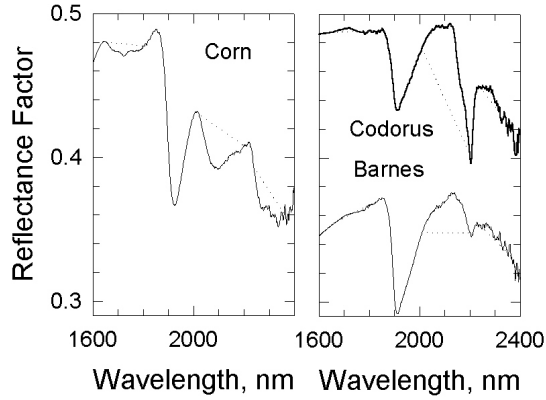


Figure 5 (Left). Linear continua for three major absorption features in corn residues. The same lines are also shown on the spectra of two soils.

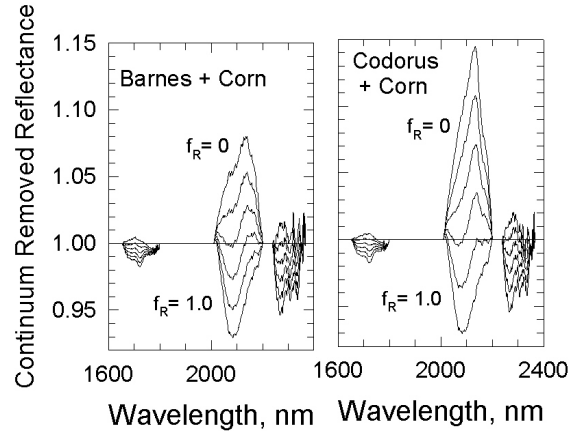


Figure 6 (Right). Continuum-removed reflectance spectra for Barnes and Codorus soils with 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of corn residue cover.

Once the continuum line was established, the continuum-removed spectra were calculated by dividing the original reflectance by the corresponding value from the continuum line (Kokaly and Clark, 1999). For the dry crop residues, the continuum line is greater than the original reflectance and the continuum-removed reflectance is less than 1.0 (Fig. 6). For the dry soils, the continuum-removed reflectance is greater than 1.0. The absorption feature near 2100 nm decreased rapidly as residue was added to the bare soils. The cellulose absorption index (CAI) is a adaptation of the continuum-removal method that uses reflectance in three bands -- two the shoulders and one in the center -- to estimate the depth of the absorption feature at 2100 nm. The continuum-removed reflectance (and CAI) provided better separation of crop residues from soils than reflectance factors because the crop residues could be darker or lighter than the soil.

### 3.2 AVIRIS Spectra

The AVIRIS scene (Fig. 7) covers most of the USDA Beltsville Agriculture Research Center, as well as portions of the Patuxent Wildlife Research Center (eastern 1/4 of image) and the commercial and residential corridor along US 1 (north western quarter of image). Mean reflectance spectra for six of the agricultural targets are shown in Figure 8. The conifer (Fig. 8A) and hairy vetch (Fig. 8B) targets have typical green vegetation spectra with low visible reflectance and high near infrared reflectance. The corn residue (Fig. 8D) and wheat residue (Fig. 8E) exhibit the absorption feature at 2100 nm that we observed in the reflectance spectra of dry corn and soybean residues (Fig 1). In Figure 8C, the cool season weeds (primarily wild mustards and cool season annual grasses), which had been recently sprayed with a contact herbicide, obscured much of the corn residue. Only a slight absorption at 2100 nm due the corn residue is evident in the mean reflectance spectrum. The bare soil field (Fig. 8F), which was rough from chiseled plowing several weeks earlier, showed a minor absorption (clay minerals) near 2200 nm.

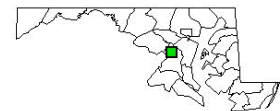
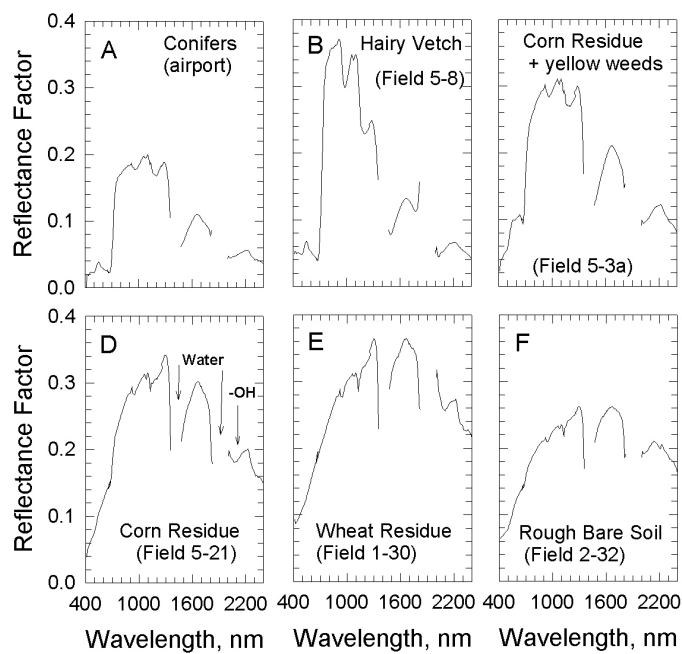


Figure 7 (Above). Composite image of AVIRIS over the Beltsville Agricultural Research Center (BARC) near Beltsville, Maryland on May 11, 2000. Bands 33, 54, and 174 (655 nm, 866 nm, and 2011 nm, respectively) were assigned as green, blue, and red.

Figure 8 (Left). Mean AVIRIS spectra for selected regions of interest



Table 3. Mean NDVI, CAI, and end-member relative weights from the linear spectral unmixing analysis for regions of interest.

| Cover Type        | n  | NDVI  | CAI   | End Member Weights |             |             |        |       |
|-------------------|----|-------|-------|--------------------|-------------|-------------|--------|-------|
|                   |    |       |       | Corn Residue       | Hairy Vetch | Plowed Soil | Water  | Error |
| Crop Residue      | 6  | 0.158 | 1.78  | 0.150              | -0.071      | 1.111       | 0.033  | 0.013 |
| Soil              | 4  | 0.192 | -0.88 | 0.009              | 0.025       | 0.928       | -0.117 | 0.009 |
| Water             | 2  | 0.132 | -0.08 | 0.002              | 0.013       | -0.010      | 0.927  | 0.005 |
| Green Vegetation  | 9  | 0.763 | -0.31 | -0.046             | 0.925       | 0.430       | 0.252  | 0.011 |
| Yellow Vegetation | 11 | 0.364 | 0.39  | -0.033             | 0.387       | 0.948       | 0.475  | 0.014 |
| Mowed Alfalfa     | 2  | 0.215 | -0.68 | 0.060              | 0.114       | 0.813       | -0.452 | 0.010 |

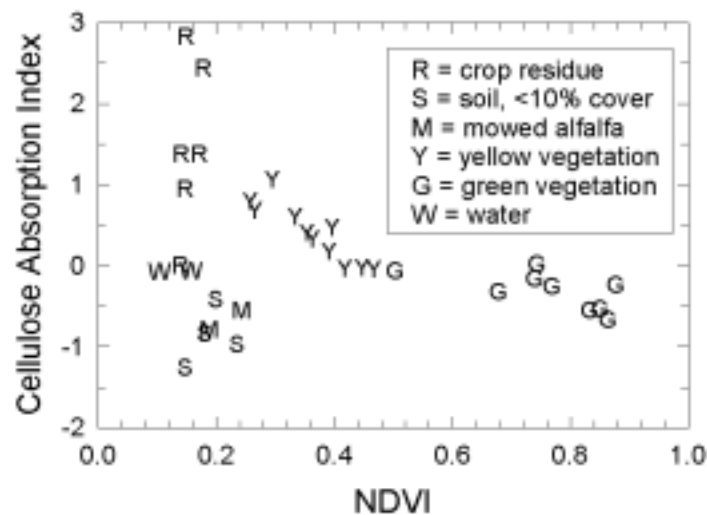


Figure 9. Scatter plot of the cellulose absorption index (CAI) as a function of NDVI.

For our initial analysis, we selected 34 regions of interest within the scene and grouped them into six cover types. The ‘Crop residue’ cover type consisted of fields with >80% cover of either corn or wheat residues. The ‘Soil’ class included fields that had been chiseled plowed or disked with <10% crop residue. The ‘Water’ class consisted of small lakes or ponds. The ‘Green Vegetation’ was broadly defined to include fields of hairy vetch, winter wheat, and orchardgrass and stands of conifers. The

‘Yellow Vegetation’ included fields that had been sprayed with foliar herbicides prior to no-till planting of summer crops and pastures with standing brown plant materials. The ‘Mowed Alfalfa’ fields had been harvested 1-2 days prior to the AVIRIS overflight and consisted of 5-10 cm alfalfa stems with very few leaves and bare soil.

The scatter plot of CAI and NDVI showed the clustering of cover types (Fig. 9). Green vegetation and water had similar CAI values, but significantly differed in NDVI. Likewise, the crop residues, water, soil, and mowed alfalfa had similar NDVI values, but differed significantly in CAI. Mow alfalfa and bare soil were confounded. One corn residue field that was wet was also confounded with water in this scatterplot (Fig. 9). Thus, pairs of vegetation indices may be useful in discriminating most, but not all, cover types.

The relative weights assigned to each end-member spectrum by the linear spectral unmixing analysis are shown in Table 3. The cover types were generally represented by the appropriate end-members. For example, the crop residue cover type was represented by the corn residue and the plowed soil end-members. The relative abundance of the soil, crop residue, and green vegetation end-members are shown in Figure 10. Fields with high relative abundance values of soil and crop residue have low values for green vegetation. High relative abundance of green vegetation also corresponds to high NDVI values.



#### 4. CONCLUSIONS

Although reflectance spectra of crop residues and soils are similar in the 400-1000 nm wavelength region, three broad absorption features in the reflectance spectra of the crop residues are not evident in the soils spectra . Band-depth analysis of these absorption features using simulated mixed residue-soil scenes indicated that quantitative assessment of crop residue cover is possible. The CAI, which estimated the depth of the absorption at 2100 nm, separated crop residues from soils. In this preliminary study with early Spring AVIRIS data of the Beltsville Agriculture Research Center, NDVI and CAI provided better separation of fields with residue than the end-member analysis. A multiband radiometer with the two NDVI bands and the three CAI bands could be used as a replacement for the manual line-transect method of for measuring field crop residue cover. Regional surveys and maps of crop residue cover and conservation tillage practices may be feasible using hyperspectral imaging systems.

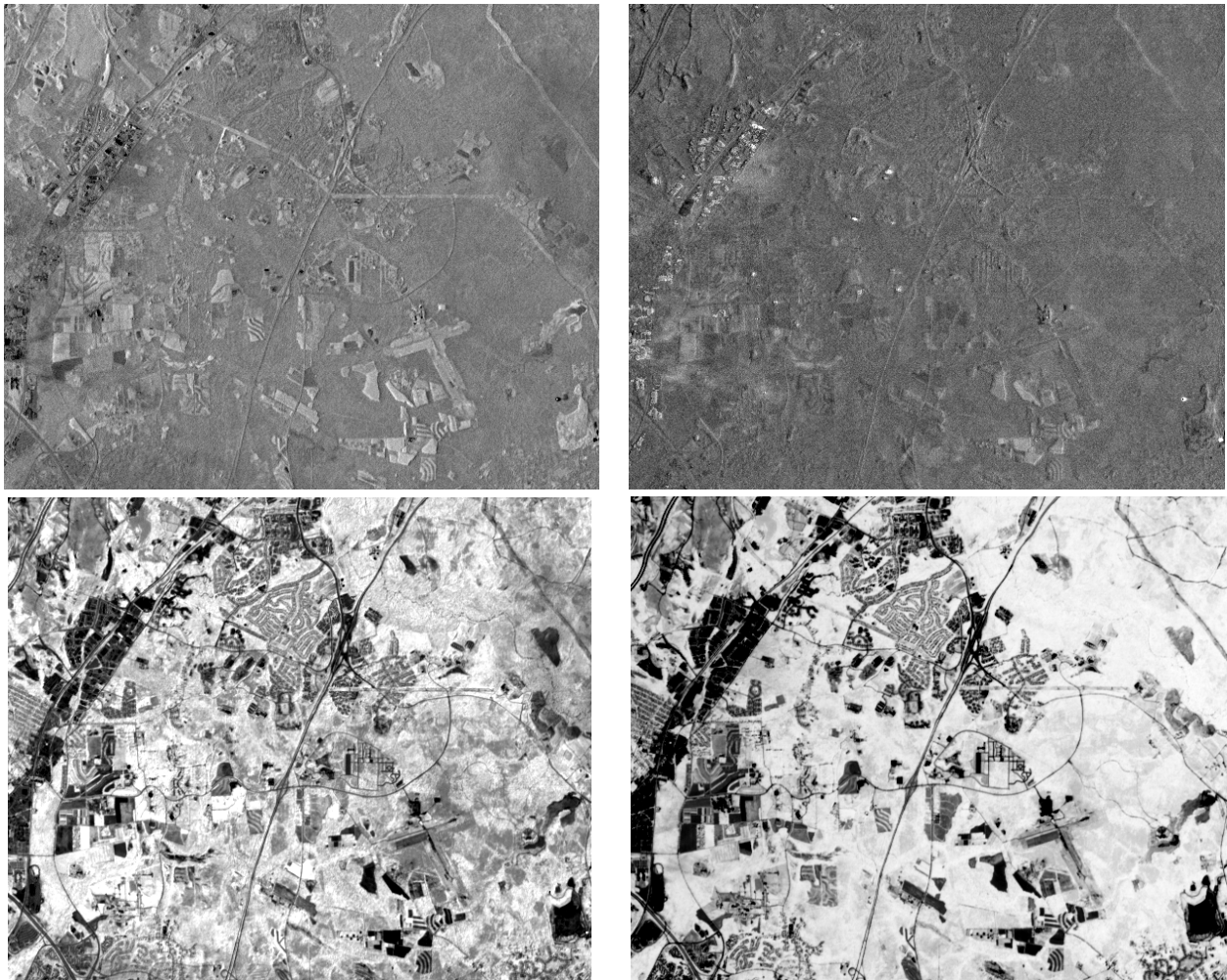


Figure 10. Relative abundance of soil (upper left), residue (upper right), and green vegetation (lower left) end-members. NDVI image (lower right). In each image, white represents high values and black represents low values.

## 5. REFERENCES

- Aase, J. K. and D. L. Tanaka. 1991. Reflectance from four wheat residue cover densities as influenced by three soil backgrounds. *Agronomy J.* 83:753-757.
- Baird, F. and Baret, F. 1997. Crop residue estimation using multiband reflectance. *Remote Sens. Environ.* 59:530-536.
- Baumgardner, M. F., Silva, L. F., Biehl, L. L., and Stoner, E. R. 1985. Reflectance properties of soils. *Advances in Agronomy* 38:1-44.
- Corak, S. J., Kaspar, T. C., and Meek, D. W. 1993. Evaluating methods for measuring residue cover. *J. Soil Water Conservation* 48:700-704.
- Curran, P. J. 1989. Remote sensing of foliar chemistry. *Remote Sens. Environ.* 30:271-278.
- Daughtry, C. S. T. 2001. Discriminating crop residues from soil by shortwave infrared reflectance. *Agronomy J.* 93:125-131.
- Daughtry, C. S. T., J. E. McMurtrey III, E. W. Chappelle, W. P. Dulaney, J. R. Irons, and M. B. Satterwhite. 1995. Potential for discriminating crop residues from soil by reflectance and fluorescence. *Agronomy J.* 87:165-171.
- Daughtry, C. S. T., P. L. Nagler, M. S. Kim, J. E. McMurtrey III, and E. W. Chappelle. 1996. Spectral reflectance of soils and crop residues. pp. 505-510. *In* A.M.C. Davies and Phil Williams (eds) *Near Infrared Spectroscopy: The Future Waves*. NIR Publications, Chichester, UK.
- Elvidge, C. D. 1990. Visible and near infrared reflectance characteristics of dry plant materials. *Int. J. Remote Sensing* 10:1775-1795.
- Gao, B. C. and Goetz, A. F. H. 1994. Extraction of dry leaf spectral features from reflectance spectra of green vegetation. *Remote Sens. Environ.* 47:369-374.
- Kokaly, R. F. and Clark, R. N. 1999. Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. *Remote Sens. Environ.* 67:267-287.
- McMurtrey III, J. E., E. W. Chappelle, C. S. T. Daughtry, and M. S. Kim. 1993. Fluorescence and reflectance of crop residue and soil. *J. Soil Water Conservation* 48:207-213.
- Morrison, J. E., Jr., C. Huang, D. T. Lightle, and C. S. T. Daughtry. 1993. Residue cover measurement techniques. *J. Soil Water Conservation* 48:479-483.
- Morrison Jr., J. E., Lemunyon, J., and Bogusch Jr., H. C. 1995. Sources of variation and performance of nine devices when measuring crop residue cover. *Trans. Amer. Soc. Agricultural Engineers* 38:521-529.
- Murray, I. and Williams, P. C. 1988. Chemical principles of near-infrared technology. pp.17-34. *In* Williams, Phil and Norris, Karl (eds) *Near-Infrared Technology in the Agricultural and Food Industries*. Amer. Assoc. Cereal Chemists, St. Paul, MN, USA.
- Nagler, P. L., Daughtry, C. S. T. and Goward, S. N. 2000. Plant litter and soil reflectance. *Remote Sens. Environ.* 71:207-215.
- Robinson, B. F. and Biehl, L. L. 1979. Calibration procedures for measurements of reflectance factor in remote sensing field research. *Proc. Soc. Photo-Opt. Instrumentation Engineers. SPIE* 196:16-26.