SOURCES OF VARIABILITY IN PLANT CANOPY HYPERSPECTRAL DATA IN A SAVANNA ECOSYSTEM

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1. INTRODUCTION

The relative importance of the plant structural, biophysical, and biochemical attributes of vegetation that determine a hyperspectral reflectance signal have not been well quantified. Vegetation reflectance is primarily a function of tissue optical properties (leaf, woody stem, standing litter), canopy structural attributes (e.g. leaf and stem area), soil reflectance, illumination conditions, and viewing geometry. Foliage and non-photosynthetic vegetation (NPV) affect the radiation field through their reflectance and transmittance characteristics (Ross 1981, Asner et al. 1998). Leaf optical properties are a function of leaf structure, water content, and the concentration of biochemicals (e.g. lignin, cellulose, nitrogen) (Gates et al. 1965, Wooley 1971, Fourty et al. 1996). However, several studies have demonstrated that leaf-level variability in carbon and nitrogen chemistry plays a small role in determining canopy reflectance characteristics in comparison to leaf water content and leaf area index (LAI) (Jacquemoud 1993, Baret et al. 1994, Jacquemoud et al. 1995).

In this paper, we use a combination of field and modeling techniques to quantify the relative contribution of leaf, stem, and litter optical properties, and canopy and landscape structural attributes, to the hyperspectral reflectance characteristics of a spatially complex savanna ecosystem. In contrast to recent studies focused on scaling within-leaf biochemical characteristics to leaf and canopy scales (Jacquemoud et al. 1995), this study approaches the scaling problem from the observed variability in tissue optical properties, then examines the importance of this tissue-level variability in comparison to canopy structural variability at landscape scales using a plant canopy radiative transfer model.

2. METHODS

2.1 Study Site

The Texas A&M La Copita Research Area is located on the Rio Grande Plains of southern Texas (27°40'N, 98°12'W), roughly 80km west of Corpus Christi. Like many regions of the western United States, the area has endured over a century of heavy grazing and fire suppression, leading to the encroachment of woody plant species into ecosystems once dominated by grasses. Woody plant canopies are dominated by the leguminous tree *Prosopis glandulosa* var. *glandulosa*, with many secondary shrubs, all imbedded in a relatively continuous herbaceous cover dominated by C_4 grasses. Among woody species at La Copita, leaf area index (LAI) ranges from roughly 2.0-5.0. Among grass species, LAI ranges from approximately 0.5-2.5 (Wessman et al. 1998).

2.2 Tissue Optical Properties

A comprehensive analysis of the characteristics and variability in leaf, woody stem, and standing litter optical properties across a 900 km Texas climate gradient was recently reported (Asner et al. 1998). A goal of the present study was to focus on the portion of the data set representing the variability in foliar, litter, and woody stem optical properties at the ecosystem level. At La Copita, we collected 400 samples (200 foliar, 200 litter+woody stem) representing the dominant woody plant and herbaceous species.

Leaves of woody plant species (trees, shrubs, sub-shrubs) were sampled by clipping five to ten branches from individual plants. Grass and standing litter samples were collected by placing whole grass clumps (including some roots and soil) into bags to maintain leaf moisture conditions. All measurements were subsequently conducted within 15 minutes of sample collection. Hemispherical reflectance and transmittance spectra (400-2500 nm) were obtained using a full-range spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO), a $BaSO_4$ integrating sphere (LI-1800, Licor Inc., Lincoln, NE), and a light source modified for full-range spectral measurements (Asner et al. 1998). The ASD spectrometer acquires measurements in 1.4 nm intervals in the visible/NIR (full-width at half-maximum = 3-4 nm) and 2.2 nm (FWHM = 10-12 nm) in the shortwave IR (SWIR) region. Each reflectance and transmittance measurement was comprised of a 200 spectrum average. A modified version of the Daughtry et al. (1989) method for spectral analyses of needle leaves was used for the leaflets of species not completely covering the sample port on the integrating sphere (e.g. *Acacia*, *Prosopis*, green and senescent grass leaves).

Woody stem material was collected from trees and shrubs by removing thin, opaque slices of the outer bark. Flat areas on the stems were chosen to ensure that the sample port of the integrating sphere would close properly. Reflectance spectra were collected from 5-10 individuals of each species, with each sample consisting of a 200 spectrum average.

2.3 Soil Reflectance

Full spectral range (400-2500 nm) soil reflectance measurements were collected at La Copita. A variety of soil types were sampled within one hour of solar noon. The fiber optic of the spectrometer was held 1m above ground level in a nadir position, and care was taken to ensure that only bare soil was sampled. Soil reflectance measurements were also collected after rainfall events to capture the variability caused by soil wetting.

2.4 Radiative Transfer Modeling

We used a discrete ordinates plant canopy radiative transfer model in which single scattering is solved exactly while multiple scattering is simplified to a single-angle problem (zenith). Iaquinta and Pinty (1994) first introduced this simplification in the multiple scattering component which sharply improved computation time while still producing top-of-canopy reflectance values with reasonable accuracy. We restructured the model to include both leaf and non-photosynthetic vegetation (NPV) in the radiative transfer equation formulation (Wenhan 1993, Asner and Wessman 1997), but maintained the Iaquinta and Pinty (1994) multiple scattering calculation. The revised model is designed explicitly for use with hyperspectral data, as wavelength-independent calculations (e.g. leaf angle distribution) are made only once per simulation, while those calculations requiring the leaf and stem optical properties (e.g. multiple scattering) are iterated by wavelength.

Leaf, woody stem, litter, and soil spectra were convolved to AVIRIS spectral response curves to produce 220 optical channels ranging from 400-2450 nm. All canopy and landscape reflectance analyses were subsequently based on the AVIRIS channels. The model produces top-of-canopy reflectance values from the following parameters: leaf and stem area index (LAI, SAI), leaf and stem angle distributions (LAD, SAD), leaf and stem hemispherical reflectance and transmittance properties and soil reflectance ($\rho_{leaf}(\lambda)$, $\tau_{leaf}(\lambda)$, $\rho_{stem}(\lambda)$, $\tau_{stem}(\lambda)$, $\rho_{soil}(\lambda)$), sun and view zenith and azimuth angles (θ_{sun}, ϕ_{sun}, θ_{view}, ϕ_{view}), and a hot-spot parameter for each vegetation component (H_{stem}, H_{leaf}):

$$\begin{aligned} R(\lambda) &= f\,(\text{GEOMETRY, STRUCTURE, TISSUES}, \rho_{soil}(\lambda)) \\ \text{where GEOMETRY} &= (\theta_{sun}, \phi_{sun}, \theta_{view}, \phi_{view}, H_{stem}, H_{leaf}) \\ \text{STRUCTURE} &= (\text{LAI, SAI, LAD, SAD}) \\ \text{TISSUES} &= (\rho_{leaf}(\lambda), \tau_{leaf}(\lambda), \rho_{stem}(\lambda), \tau_{stem}(\lambda)) \end{aligned} \tag{1}$$

Scattering characteristics at the tissue and soil level are modeled as isotropic. LAI and SAI are given on a m^2m^{-2} basis, and LAD and SAD can be modeled as erectophile, planophile, plagiophile, or uniform (deWit 1965). For analyses here, tree and grass LAD were set to plagiophile and erectophile, respectively. Tree stem angle distribution and grass litter angle distribution were also set at erectophile. Viewing and solar geometry as well as a hot-spot parameterization are used in simulating the canopy-level anisotropy. For all analyses in this paper, solar zenith and azimuth angles (θ_{sun}, ϕ_{sun}) were set at 30° and 0°, respectively. View zenith and azimuth angles (θ_{view}, ϕ_{view}) were both set to 0°.

2.5 Leaf Optical Variability versus Canopy Structure

The importance of leaf optical variability was tested at the canopy level. Two standard deviations about the mean of measured leaf reflectance and transmittance spectra (total range = 4 s.d.) were used as the criteria to determine the role of leaf-level variation at canopy scales. Tree canopy simulations also used the mean woody stem reflectance spectrum from field measurements, and herbaceous canopies used the mean of the standing litter optical properties. The importance of LAI variation on canopy reflectance was tested using the LAI range from measurements made at La Copita. These changes were evaluated by calculating first derivatives along each canopy reflectance spectrum (Wessman et al. 1989).

3. RESULTS AND DISCUSSION

3.1 Tissue and Soil Optical Variability

Here, we will not discuss the similarities and differences in tissue optical characteristics by species, genera, growthforms, lifeforms, or functional groups, as much of this discussion took place in Asner et al. (*in press, in review*). Instead, we will simply define the total variance in the optical properties of leaves, woody stems, and standing litter material at La Copita to facilitate an analysis of their importance at canopy and landscape scales.

Mean (±1 s.d.) reflectance and transmittance properties of woody plant and grass leaves from La Copita are shown in Figure 1. Grasses had consistently higher reflectance values than woody plant species throughout the visible spectral range (t-tests at each wavelength, $p < 0.05$), whereas woody species had higher values throughout the NIR region (t-tests, $p < 0.05$). There were no significant reflectance differences between woody plant and grass vegetation types in the shortwave-IR (SWIR) spectral region. In comparing transmittance spectra, the grass group was consistently lower than the woody plant group in the NIR. No other differences were found in the visible or SWIR spectral regions. Standing litter and woody stem optical properties were generally more variable in comparison to fresh leaves (Figure 2).

Mean (±1 s.d.) soil reflectance is shown in Figure 3. Strong absorption features centered near 1400 and 1900 nm are due to atmospheric water, preventing measurements and subsequent modeling of these spectral regions.

3.2 Leaf Optical Variability at Canopy Scales

Figure 4 shows the effect of varying the leaf optical properties by ±2 s.d. from their mean in canopies with low and high LAI (1.5, 5.0). The former is a common LAI scenario for grass cover at La Copita, and the latter represents the highest values for the woody plant canopies found there. Leaf optical variability played a small role in driving canopy reflectance changes in the low LAI scenario. Under low LAI conditions, the total range in canopy reflectance induced by leaf optical variability ranged in magnitude from <1% in the visible region to a maximum of 4% in the NIR, then decreased again in the SWIR range (2-3%). At high canopy LAI, the effects of leaf optical variability were more pronounced, with maximum effects in the NIR (10-12%). In the visible spectral region and along the "red edge" (~ 700 nm), effects of leaf-level variation were still extremely small. Leaf effects at canopy scales were greater in the 1600-1800 nm spectral range than in the 2000-2500 nm range because the single scattering albedo (= reflectance+transmittance/2) of fresh green leaves is higher in the 1700 nm than in the 2200 nm region (Figure 1).

3.3 Canopy Reflectance Sensitivity to LAI

Changes in canopy LAI strongly influenced canopy reflectance signatures (Figure 5a), with the most pronounced effect in the NIR and the smallest effect on the visible spectral region. Large increases in NIR reflectance with increasing LAI result from multiple scattering of photons, while small decreases in visible reflectance (increased absorption) are due to the presence of more chlorophyll in the higher LAI canopies. In general, structure enhances canopy reflectance in spectral regions where the scatterers are "bright" (e.g. NIR for green leaves), and enhances canopy absorption in "dark" regions (e.g. 680 nm for green leaves). The effect of adding LAI diminished as total canopy LAI increased, thus a small leaf area increase in a low LAI canopy had a much greater impact than did a similar increase in a high LAI canopy. Deepening of the two water absorption features within the NIR (~ 1000 and 1200 nm) was also apparent. While the overall NIR trend was toward increased scattering with increased LAI, these NIR plateau water absorption features "lagged" behind the rest of the plateau due to enhanced water absorption as canopy biomass (e.g. LAI) increased. Analysis of first derivatives supports this conclusion, as the slope of the reflectance continuum in these regions increased as LAI increased (Figure 5b). Other derivative results indicate the following regions to be highly sensitive to changes in canopy LAI: (1) the 695-700 nm region (the red edge), (2) the 1275-1375 nm region of the NIR plateau, and (3) the SWIR region between 1500-1800 nm. When LAI > 0.5, first derivative spectra in the visible and SWIR (2000-2500 nm) regions contain little to no information on changing LAI.

3.4 Standing Litter Variability in Grass Canopies

The presence of standing litter has a significant impact on grass canopy reflectance. Figure 5c shows the result of increasing the relative proportion of standing litter (0-100%) in a grass canopy with total plant area index (PAI) = 1.4. As the relative abundance of litter increased, canopy reflectance increased significantly throughout the shortwave spectrum, with the largest changes in the NIR (18-25% absolute) and SWIR (12-21%) regions. The chlorophyll and pigment absorption features (~ 450 and 680 nm) and NIR plateau observed in green canopies deteriorated as litter increased. The visible-to-NIR transition (the red edge) flattened and became a nearly linear reflectance continuum characteristic. The features near 2075 and 2200 nm found in litter optical properties (Figure 2b) emerged at the canopy level as well.

There were several distinct changes in the reflectance continuum (as determined via first derivatives) that resulted from the presence of standing litter in a canopy (Figure 5d). First, the visible spectral region was highly sensitive to increases in canopy litter, particularly in the 550-700 nm range. This region was only mildly sensitive to changes in LAI (when LAI was low), thus the visible range is a good candidate for assessing canopy litter content via first derivative spectra. The far SWIR region from 2000-2100 nm and near 2250 nm was also sensitive to litter in comparison to LAI or leaf angle changes. First derivative spectra in these SWIR regions were more than three times as sensitive to litter content variation than to LAI or LAD variation.

3.5 Woody Stems in Tree and Shrub Canopies

Figure 6a depicts the radiative contribution of woody stems to a hypothetical tree canopy. We varied the proportion of stem area within the mean plant area index (PAI) value for tree canopies at La Copita (from Wessman et al. 1998). A range of stem area index (SAI) values were taken from a similar savanna tree canopy in North Texas (Asner et al. *in review*). The contribution of stem surfaces to canopy reflectance was significant. Increases in the percentage of stem material in a canopy had the following effects on canopy reflectance: (1) decreased the strength of the 680 nm absorption feature, (2) the strength of the entire NIR plateau decreased, (3) the entire SWIR region was elevated, and (4) the difference in magnitude of the NIR plateau and the local maxima centered at roughly 1680 and 2200 nm decreased.

The role of varying stem optical properties on canopy reflectance was much smaller than that of leaf optical variability (Figure 6b). For the hypothetical tree canopy (LAI = 3.5, SAI = 0.60), stem properties caused maximum canopy reflectance changes of 2-3% in the NIR. However, this result is largely dependent on the location of woody material within the canopy (van Leeuwen and Huete 1996). In this modeling scenario, the woody stems and foliage were assumed to be equally distributed (vertically) throughout the canopy. Stem optical variability will thus have a greater or lesser effect on canopy reflectance depending on the level of interaction that woody material has with photons that ultimately exit the canopy.

3.6 Variation in Vegetation Cover

Changing vegetation cover had the largest effect in the SWIR (2000-2500 nm) and visible spectral regions (Figure 7). When the percentage vegetation cover decreased, spectral features associated with bare soil emerged at the pixel level (e.g. 2150 and 2350 nm). This analysis emphasizes the difficulty in estimating vegetation characteristics (e.g. LAI, foliar biochemistry) in non-continuous vegetation covers.

4. CONCLUSIONS

This study used an approach to combine field observations with mechanistic modeling to uncover which factors influence hyperspectral reflectance in a spatially complex savanna ecosystem. Evidence from the analyses presented in this paper indicates:

- Variation in canopy LAI is the dominant control on canopy reflectance data (with the exception of soil reflectance in sparse canopies such as shrublands).
- Variability in leaf optical properties plays a very small role in determining canopy reflectance variability in this savanna ecosystem. We predict that these results would apply to other canopies with LAI < 5.0, but the degree to which this is true also depends on variability in leaf angle distribution.
- Stem material plays a small but significant role in determining canopy reflectance in woody plant canopies with LAI < 5.0.
- Standing litter significantly affects the reflectance characteristics of grassland canopies. Small increases in the percentage of standing litter lead to disproportionately large changes in canopy reflectance.
- Vegetation cover variation has the potential to dominate the reflectance spectrum because soils tend to be much brighter in the visible and SWIR and darker in the NIR than vegetation canopies. Therefore, quantitative analyses of vegetation structure and biochemistry must account for horizontal discontinuities in the canopy which significantly affect AVIRIS data.

The results presented here are idealistic in that only canopy-level reflectance was simulated without the added complexity of the atmosphere. If the influence of the atmosphere can be adequately removed, then the trends found here remain pertinent to the interpretation of hyperspectral remote sensing data. One important advantage of imaging spectrometry is that the calibration to reflectance (e.g. atmospheric removal) is approached in a physically robust manner (Gao et al. 1993). Nonetheless, our ability to quantitatively employ remote sensing data relies on improving the ways in which radiometric and atmospheric errors can be minimized.

5. ACKNOWLEDGMENTS

This work was supported by NASA Innovative Research Grant NAGW-4689, NASA Interdisciplinary Science Grant NAGW-2662, and a NASA Earth System Science Fellowship to G.P.A.

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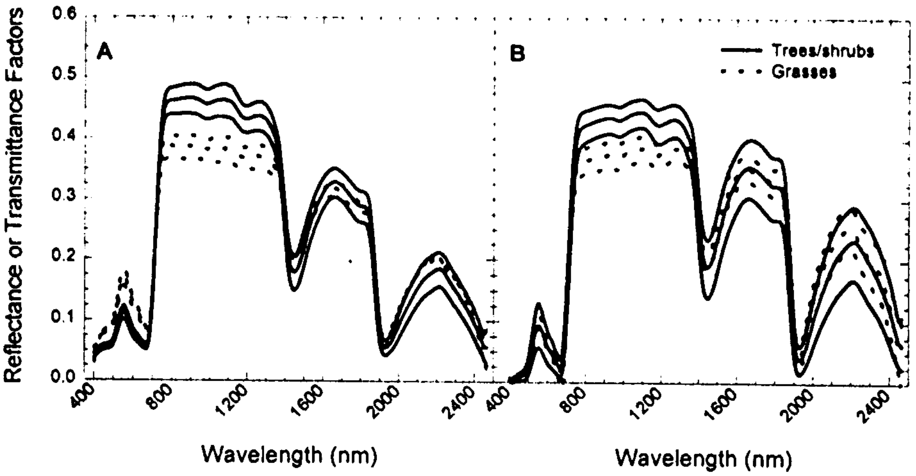

Figure 1. (A) Mean (+/-1 s.d.) hemispherical reflectance spectra for woody plant and grass leaves. (B) Mean (+/-1 s.d.) hemispherical transmittance spectra for woody plant and grass leaves.

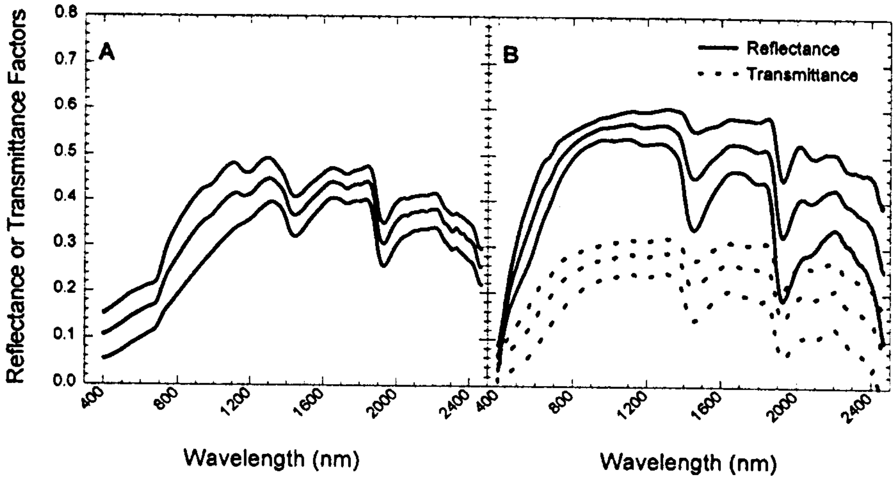

Figure 2. (A) Mean (+/-1 s.d.) hemispherical reflectance spectra for woody plants stems. (B) Mean (+/-1 s.d.) hemispherical reflectance and transmittance spectra for standing grass litter material.

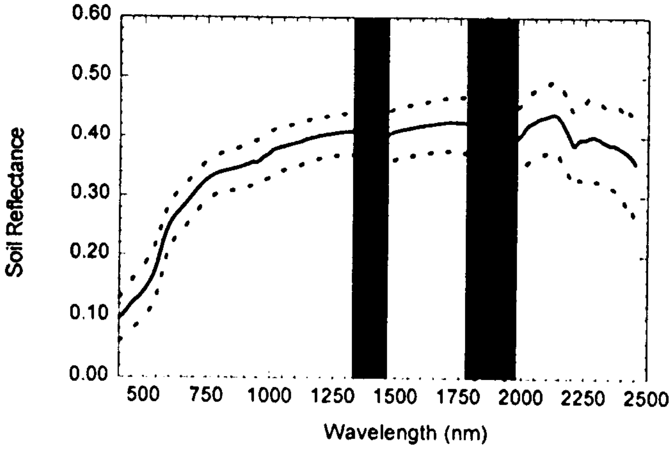

Figure 3. Mean (+/-1 s.d.) of nadir soil reflectance spectra

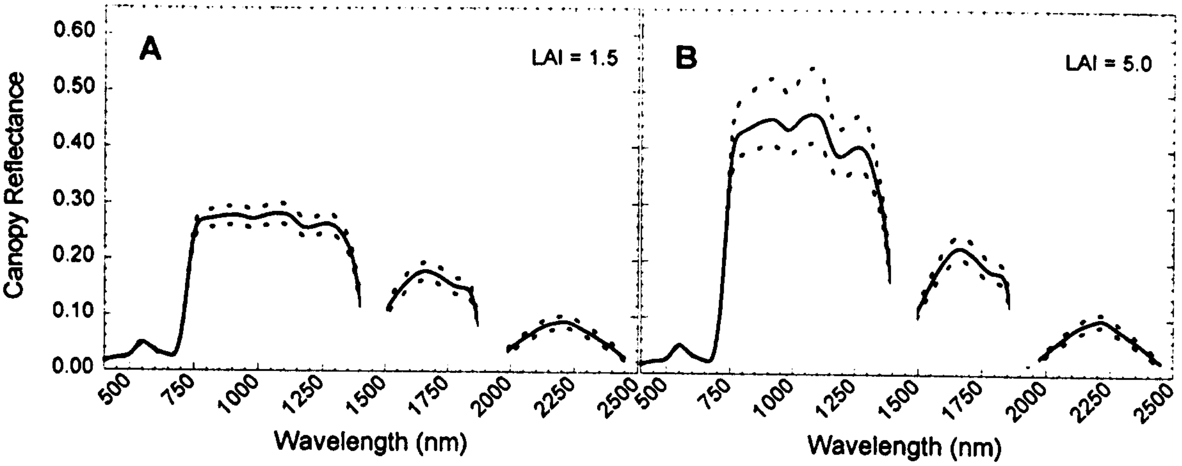

Figure 4. Range (dotted lines) in canopy reflectance resulting from measured variation in leaf optical properties (4 standard deviations). (A) Canopy LAI = 1.5 (B) Canopy LAI = 5.0

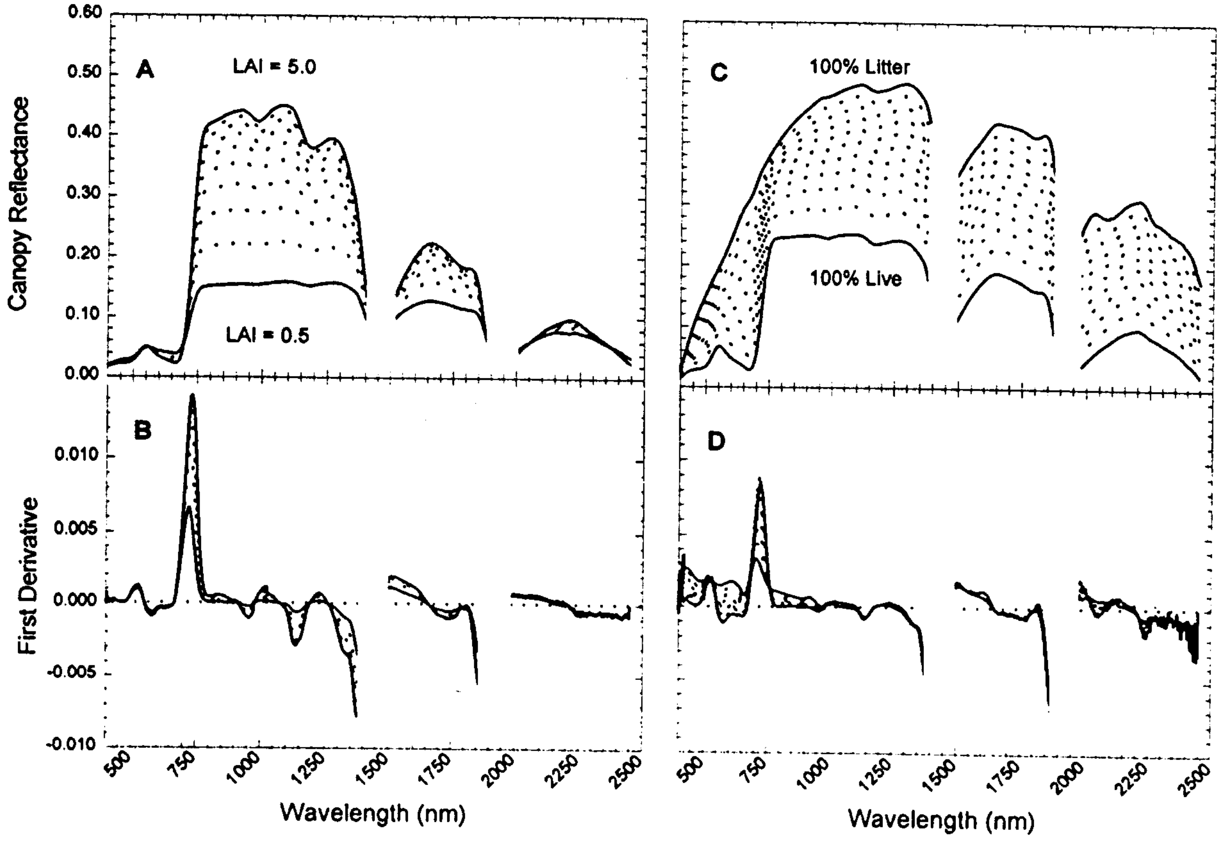

Figure 5. (A) Effect of increasing LAI on tree canopy reflectance. (B) Resulting first derivative spectra with increasing LAI. (C) Effect of increasing litter fraction on grass canopy reflectance. (D) Resulting first derivative spectra with increasing litter fraction.

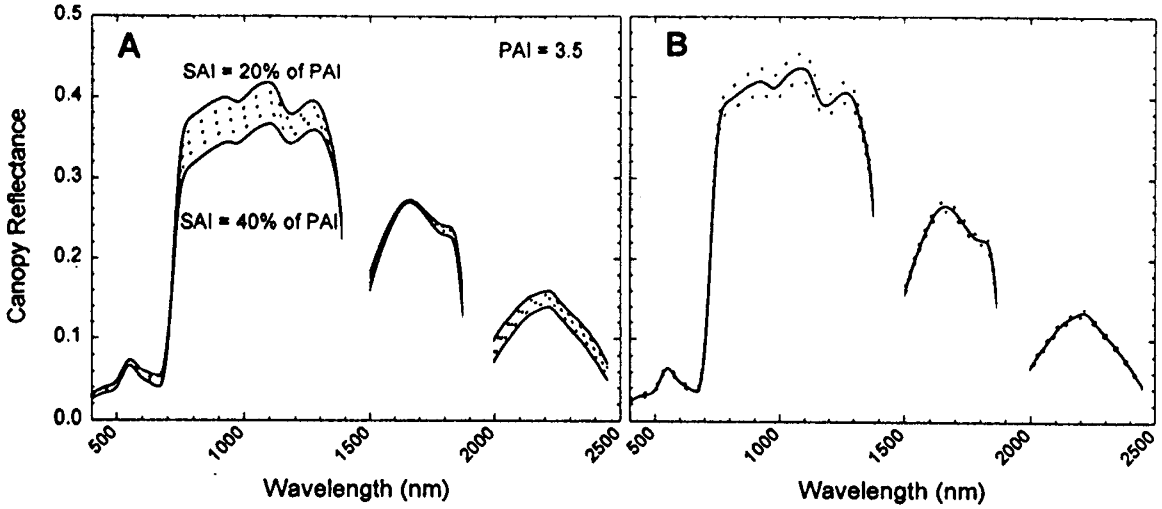

Figure 6. (A) Change in canopy reflectance with increasing percentage of woody stem material. Whole plant area index = 3.5, and stem fraction increased from 20-40%. (B) Variation in canopy reflectance due to measured stem optical variability. LAI = 3.5 and SAI = 0.65 (from Asner et al. in review).

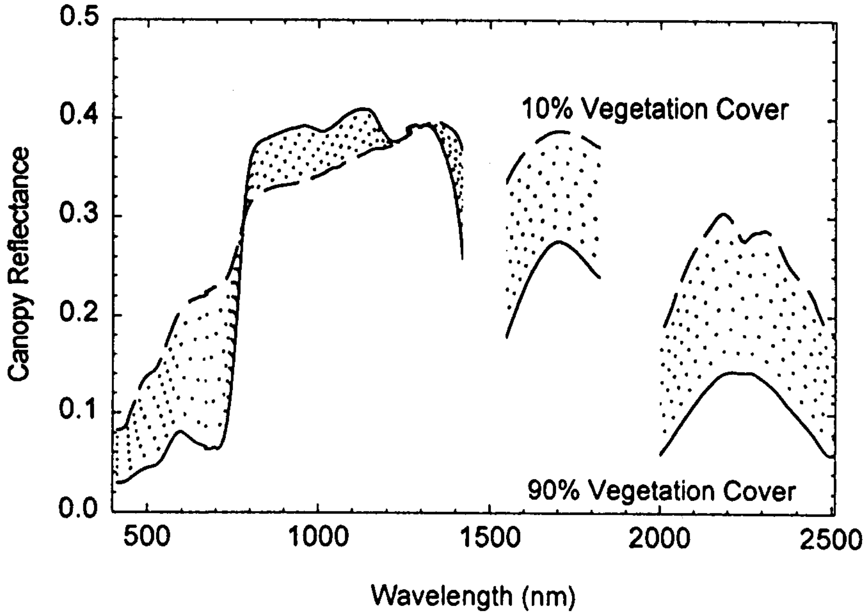

Figure 7. Changes in AVIRIS pixel reflectance due to changes in vegetation cover.