Green Vegetation, Nonphotosynthetic Vegetation, and Soils in AVIRIS Data

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An Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) image collected over the Jasper Ridge Biological Preserve, California on 20 September 1989 was analyzed using spectral mixture analysis. The scene was calibrated to reflectance assuming a homogeneous atmosphere. The image was modeled initially as linear mixtures of the minimum number of reference endmember spectra that accounted for the maximum spectral variability. Over 98% of the spectral variation was explained by linear mixtures of three endmembers: green vegetation, shade, and soil. Additional spectral variation appeared as residuals. Nonlinear mixing was expressed as variations in the fraction of each endmember when a linear mixing model was applied to spectral subsets of the entire spectrum. After the fractions of the endmember spectra were calculated for each pixel, different types of soil were discriminated by the residual spectra. Nonphotosynthetic vegetation (NPV) (e.g., dry grass, leaf litter, and woody material), which could not be distinguished from soil when included as an endmember, was discriminated by residual spectra that contained cellulose and lignin absorptions. Distinct communities of green vegetation were distinguished by 1) nonlinear mixing effects caused by transmission and scattering by green leaves, 2) variations in a derived canopy-shade spectrum, and 3) the fraction of NPV. The results of the image analysis, supported by field observations in 1990 and 1991, indicate that the multiple bands of AVIRIS enhance discrimination of NPV from soil, and the separation of different types of green vegetation. The ability of the system to measure narrow absorption bands is one important factor; however, also important is the variation in continuum spectra expressed by the endmembers, and characteristic nonlinear mixing effects associated with green leaves.

INTRODUCTION

With the development of advanced imaging spectrometers, such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Vane et al., 1993), it is now possible to identify many terrestrial materials based on reflected visible and near-infrared (NIR) radiation. Two fundamental objectives when interpreting these remotely measured spectra are a qualitative determination of the physical nature of the materials within the field of view and a quantitative estimate of their abundances. Previous research on imaging spectrometer data has emphasized the direct identification of minerals in semiarid and arid regions (e.g., Clark et al., 1990). Where vegetation cover is dense, the emphasis has been on characterizing the vegetation, while neglecting the background substrate (e.g., Collins et al., 1983; Price and Westman, 1987). This study begins with the assumption that many terrestrial surfaces consist of various proportions of green vegetation, nonphotosynthetic plant parts/can-
opy components, and rocks and soils, and that remotely measured spectra typically are mixtures.

Methods for describing spectral mixtures of green vegetation and soils using endmembers have been discussed by several workers (e.g., Graetz and Gentle, 1982; Huete, 1986; Smith et al., 1990a,b). Adams et al. (1986) and Smith et al. (1990a,b) introduced an endmember defined as "shade" to model decreased solar illumination and shadowing, and a method to allow image endmembers to be described in terms of "pure" laboratory or field reference spectra. This approach has been used to derive quantitative estimates of the abundances of vegetation and soil (e.g., Smith et al., 1990b).

Many vegetation components lack significant quantities of chlorophyll, and thus lack the high NIR to red spectral contrast that distinguishes vegetation from soils. In this article, plant material lacking chlorophyll will be referred to as nonphotosynthetic vegetation (NPV). This category includes materials such as dry leaf matter (e.g., dry grass and litter), bark, wood, and stems. Depending on the sensor and the spectra of the soils, the NPV component may be spectrally indistinguishable from soil.

The presence of NPV, and nonlinear spectral mixing associated with NIR transmission and scattering by green vegetation, complicate the interpretation of remote sensing data as spectral mixtures. Spectral mixtures that include green vegetation have the potential of being nonlinear due to transmission and scattering of NIR light by green leaves and the high spectral contrast between red and NIR of leaves (Roberts et al., 1990a) (Linear mixing occurs when light interacts only with one material. Transmission by leaves leads to multiple scattering and nonlinear mixing.) For example, a linear model applied to spectral mixtures of vegetation and soils and shade overestimates the fraction of green vegetation and underestimates shade. The error in the estimate of the soil fraction is smaller, depending on the spectral shape of the soil (Roberts, 1991). The degree of nonlinearity varies depending on soil reflectance and leaf transmittance (Roberts, 1991); nonlinearity increases with an increase in leaf transmittance and/or an increase in background reflectance.

This study addresses the problem of how to distinguish green vegetation, NPV, and soils in imaging-spectrometer data. Specific objectives of the study were: 1) to determine the minimum number of endmembers that accounted for the greatest amount of spectral variability in the AVIRIS image (see Sabol et al., 1992), 2) to identify and map materials in the scene that are not explicitly modeled as endmembers by the use of residuals, 3) to test predictions of nonlinear spectral mixing between green vegetation and other materials, and 4) to devise a means for improving estimates of green vegetation and shade fractions.

**MATERIALS AND STUDY SITE**

Image analysis was performed on data acquired by AVIRIS. The AVIRIS sensor is carried on a modified ER2 aircraft at an altitude of 20 km. At this altitude, the field of view of the instrument is nominally 12.25 km, and the instantaneous field of view of individual detectors is 20 m at the ground. AVIRIS measures a continuous spectrum between 400 nm and 2450 nm, dividing the spectrum into 224 spectral bands, each with a nominal 10-nm spectral response function (Green et al., 1990).

The image used in this study consisted of the unprocessed encoded radiance (DN) data supplied by the Jet Propulsion Laboratory (JPL). Established, undesirable data characteristics, such as a detector readout delay and vignetting (Chrien et al., 1990), were left uncorrected. Corrections applied by JPL, particularly for the detector readout delay, were considered undesirable at this stage, because of the potential effect of the corrections (especially interpolation) on spectral mixtures measured by the sensor. Prior to image analysis, each of the 224 bands was displayed, and the data quality was assessed. Based on a visual assessment of each band, a spectral subset consisting of 165 bands, primarily located outside of major atmospheric scattering or absorption regions, was chosen for further analysis.

The data were collected on 20 September 1989 along a southeast trending flight line centered over the Jasper Ridge Biological Preserve, located in the foothills along the northeastern margin of the Santa Cruz Mountains, approximately 7 km west of Palo Alto, California (Fig. 1). Elevations within the scene ranged from near sea level in the northeast to over 670 m in the
southwest, in the Santa Cruz Mountains. The data were collected at 13:48, Pacific Daylight Time. At this time the solar elevation was 45° and the solar azimuth was approximately 225°.

Field observations to map and verify vegetation-community types were made in September 1990 and November 1991. Soil samples and samples of green leaves and litter were collected at those times. Green-leaf samples were stored in moist plastic bags and kept cool. Reflectance and transmittance measurements from both surfaces of leaves and litter were collected using a modified Beckman DK2A spectrophotometer. Spectra were measured of green leaves within 1 day of their collection. Soil samples and litter were measured later. All reflectance and transmittance spectra measured using the Beckman were standardized with halon and then corrected to absolute reflectance using a national Bureau of Standards spectrum of halon. For all soil samples collected and measured in the field in 1991, bidirectional reflectance was measured using a Collins Mark IV spectroradiometer and barium sulfate as a standard.

The study site is located in an area with a Mediterranean climate characterized by mild summer and winter temperatures. Annual precipitation averages 76 cm, falling primarily in the winter. Natural vegetation in the area consists predominantly of undisturbed grasslands, deciduous oak woodland savannah dispersed among the grasslands, chaparral on south-facing slopes, broadleaf evergreen woodlands on north-facing slopes, and riparian vegetation along streams and in lowlands. Locally distributed serpentine in the area is associated with two communities that are adapted to survival on serpentine soils: one a grassland populated with a variety of serpentine-endemic plants, the other a chaparral community dominated by the serpentine-endemic leather oak (Quercus durata). Disturbance, in the form of overgrazing east of the reserve, urban and suburban sprawl throughout the surrounding area, and the development of recreational sites such as golf courses and horse ranches has produced a variety of unnatural vegetation types, and, in many locations, exposed areas of bare soil.

Jasper Ridge was considered ideal for this study because of the wide variety of vegetation types in the area, the presence of significant amounts of senescent materials in September and the extent to which vegetation within the area has been mapped (Roberts, 1984).

METHODS

Calibration

The AVIRIS data were calibrated to reflectance using an empirical-line calibration from two sites (e.g., Roberts et al., 1985; Conel, 1990; Elvidge and Portigal, 1990). The two-point calibration utilized water and soil J9009181 (W and B in Fig. 1). The water was assumed to have 1% reflectance at all AVIRIS wavelengths. The soil spectrum was convolved to AVIRIS wavelengths using band centers and spectral-response curves provided by JPL. Image areas corresponding to this soil and water were used to develop a linear equation for each of the 165 bands. Encoded radiance from the two calibration sites was compared to laboratory reflectance, and used to generate a multiplicative and additive term for each AVIRIS band relating encoded radiance to reflectance:

\[ p_i = g_i \times DN_i + o_o \]  

(1)

where \( p_i \) is reflectance at band \( i \), \( DN_i \) is encoded radiance, \( g_i \) includes wavelength-dependent varia-
tion in atmospheric transmittance, solar irradiance, and detector sensitivities, and \( o_i \) includes instrumental dark currents and atmospheric backscattering. Calibration was assessed independently by spectral mixture analysis (Smith et al., 1990a). The results of the two methods were comparable as long as green vegetation (which mixes nonlinearly with shade and soil) was not used as one of the calibration sites (Roberts et al., 1991).

**Linear Mixture Analysis**

Once the calibration terms were derived, the image was modeled as linear spectral mixtures of laboratory reference spectra:

\[
DN_i = \sum_{j=1}^{N} f_j (r_j - o_j) / g_i + e_i
\]  

(2)

\( DN_i \) is modeled as the sum of \( N \) reference spectra multiplied by the fraction, \( f_j \), of reference spectrum \( r_j \). The calibration terms, \( g_i \) and \( o_i \), have already been discussed. \( e_i \) is a residual, which will be discussed later.

Reference endmembers were selected using the two-stage technique described by Smith et al. (1987; 1990a). In the first step, the image was modeled as mixtures of image endmembers (e.g., spectra selected from the image). Image endmembers were added until an average residual \( (E_k) \) decreased below a threshold for the average of all pixels [Eq. (3)]. The image endmembers were selected in order of decreasing spectral contrast:

\[
E_k = (\sum_{i=1}^{M} \sum_{j=1}^{N} f_j (r_j - o_j) - DN_{ki}) / M.
\]  

(3)

\( E_k \) at pixel \( k \) is calculated as the sum of the absolute difference between encoded radiance, \( DN_{ki} \), and a model spectrum consisting of \( N \) image endmembers, \( r_{ij} \), weighted by the fractions \( f_{ij} \). This sum is divided by the number of bands, \( M \), used in the analysis. The threshold used in this study for the whole image was below 4 DN (±2% reflectance for this data set).

In the second step, the image endmembers were modeled as mixtures of laboratory spectra (called reference endmembers). Reference endmembers, as well as the calibration terms can be determined at this stage (Smith et al., 1990a), although in this study the calibration terms were derived using the empirical line technique. Reference spectra are selected primarily based on the shape of the continuum and on albedo. For a more detailed description of image and reference endmember selection, see Smith et al. (1990a). In this study the reference endmembers were selected from a library consisting of 36 green-leaf spectra, 78 soil and rock spectra, and 51 spectra of bark, dry grass, wood, and leaf litter. Fraction images were made for each reference endmember.

**Residual Analysis**

Other materials in the scene that could not be modeled by reference endmembers were identified by analysis of residual spectra (Smith et al., 1987; Gillespie et al., 1990; Roberts et al., 1990b). Residual spectra were calculated by rearranging the standard linear model, and solving for the residual term:

\[
e_i = DN_i - \sum_{j=1}^{N} f_j (r_j - o_j) / g_i.
\]  

(4)

A negative residual results where there are absorptions in the AVIRIS spectra that are not present in the endmember spectra. Where absorptions are present in the endmember spectra, but absent in the measured spectra, positive residuals result. The depths and wavelengths of residuals may be characteristic of surface materials; however, residuals also may be produced by illumination, atmospheric, and instrumental effects. The residual spectra consisted of 165 bands, equal to the number of bands used in the analysis. However, because many bands are at wavelengths that are devoid of diagnostic absorptions, residuals were examined from only four spectral regions (Table 1).

**Spectral Subsets**

Mixture models were applied to subsets of the 165 spectral bands, to test for nonlinear spectral mixing (Roberts et al., 1990a; Roberts, 1991). The spectral subsets were: the visible (476–673 nm), the NIR (752–1788 nm), and the SWIR (2028–2356 nm). Fraction images were generated for each subset. Nonlinear mixing was indicated by changes in the fraction of the same endmember in different spectral subsets.
### Table 1. Band Residuals

<table>
<thead>
<tr>
<th>Residual</th>
<th>Spectral Range (nm)</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>752-1158</td>
<td>Fe$^{2+}$, Fe$^{3+}$ crystal field in minerals (Hunt et al., 1971; Hunt, 1977)</td>
</tr>
<tr>
<td>B</td>
<td>1511-1788</td>
<td>Leaf spectral properties, tannic acid (1650), lignin (1700, 1740), xylan (1700, 1720, 1780), cellulose (1700, 1770) (from Elvidge, 1987)</td>
</tr>
<tr>
<td>C</td>
<td>2028-2207</td>
<td>Xylan, cellulose (2090), lignin (2130) (from Elvidge, 1987)</td>
</tr>
<tr>
<td>D</td>
<td>2207-2355</td>
<td>OH in minerals (Hunt, 1977): lignin (2270), xylan, cellulose (2270, 2340) (from Elvidge, 1987)</td>
</tr>
</tbody>
</table>

**Figure 2.** Canopy field spectrum of a clump of grass collected using a Spectron SE590. Residuals generated from a linear mixture of shade, and laboratory measured grass and soil spectra (collected with the same instrument, illuminated using a quartz-halogen bulb and standardized with spectrolon) show negative residuals along the red edge.
Canopy Shade

Because the shade in a canopy of green vegetation includes a significant component of NIR light that has been transmitted and scattered by leaves, a canopy typically does not fit as a linear mixture of photometric shade and a leaf spectrum. The residual is expressed as a “spike” at the wavelength transition between linear and nonlinear spectral mixing at the red edge (Fig. 2).

One way to derive improved endmember fractions from a nonlinear spectral mixture of green vegetation and shade is to modify the photometric shade endmember whenever there is a residual spike. Canopy shade can be calculated by rearranging the standard linear mixing equation and solving for shade:

\[ S_i = \left( R_i - \sum_{j=1}^{N-1} (f_j r_{ij}) \right) / f_s, \]

where \( S_i \) is the canopy-shade reflectance for band \( i \), \( R_i \) the calibrated reflectance for band \( i \), \( N \) the number of endmembers, \( f_j \) the fraction of endmember \( j \), \( r_{ij} \) the reflectance spectrum of endmember \( j \), and \( f_s \) the fraction of canopy shade. In essence, this equation is identical to Eq. (4), except that all of the terms have been converted to reflectance and the residual term is assumed equal to the canopy-shade spectrum for a given canopy type. Note that any source of residuals, such as instrumental noise, will contribute as well.

The canopy-shade spectrum was constrained in this study as having near zero red reflectance and positive NIR reflectance. A canopy-shade spectrum was produced for each pixel having a negative residual spike.

RESULTS AND DISCUSSION

Endmember Analysis

Most (98.3%) of the spectral variability in the scene could be explained by three reference end-

Figure 3. Reference spectra. Spectra of the three endmembers, corresponding to green leaf (Sasp7stack), soil (J9009181), and shade. A fourth material, dry plant material (Hw186c), is also shown.

Figure 4. Three-endmember fraction images. Fraction images of green vegetation, shade and soil for the central strip. Light areas correspond to high fractions.
members: photometric shade, a green leaf stack (Sasp7stack), and soil (J9009181) (Fig. 3). The average residual for this model was 3.2 DN (<2% reflectance). The three-endmember model was applied to a 112-pixel-wide subset centered over the Jasper Ridge Biological Preserve (Fig. 4). Green vegetation abundance was highest in the extreme southeast of the image located at the Palo Alto Country Club on a well-watered golf course, and in a forested wetland located at the western edge of the Preserve (L and S in Fig. 1). Shade fractions were highest at Searsville Lake (W in Fig. 1), at several flooded quarries southeast of Jasper Ridge, and on the northeast-facing slopes covered by evergreen forest. Soil fractions were highest in the Horse Ranch, north of the Preserve, in a series of open fields southeast of the ridge, and along the central crest of the ridge. Many of the sites having high soil fractions were found to consist almost entirely of NPV in September 1990 and November 1991. Some negative soil fractions were estimated in a number of canopies using the

Figure 5. Measured reflectance spectrum of the Drygrass Site compared to the modeled spectrum for that area. A residual spectrum is plotted below.
photometric shade endmember, probably resulting from the presence of "canopy shade."

Residual Analysis

The NPV continuum spectrum mimics that of the soil. When NPV is present in a pixel, but is not included as an endmember, its spectrum is partitioned as a mixture of soil with minor quantities of green vegetation and shade. When NPV and soil are both included as endmembers, $E_i$ is not significantly reduced; however, there is an increase in the uncertainty (noise) in the endmember fractions as expressed by high frequency spatial variability (Sabol et al., 1992).

An alternative to including NPV as an endmember was to determine the NPV abundance by analysis of residual spectra. Residual spectra were generated in four spectral regions using the three-endmember mixing model. NPV was distinguished from soils based on the presence of lignin (2130 nm and 2270 nm) and cellulose (2090 nm and 2270 nm) absorptions in the SWIR.

The residual spectra also were useful for mapping ferric-oxide-rich soils, which were distinguished by residuals centered at 900 nm. A good example is at the Drygrass Site along the central spine of Jasper Ridge Preserve (Figs. 1 and 5). Comparison between a model spectrum for the area, consisting of a mixture of 0.57 soil and 0.43 shade, and the measured spectrum, showed negative residuals in the SWIR that were attributed to lignin and cellulose in dry grass, and negative residuals at wavelengths shorter than 1000 nm, attributed to iron oxides in the soil. The residuals also responded to atmospheric variation across the scene. Positive residuals at 940 nm, 1130 nm, and 1400 nm were attributed to reduced atmospheric water vapor at higher elevations (Green et al., 1989): The Drygrass site is at 200 m compared to 103 m and 122 m for Searsville Lake and the Bright Soil calibration sites. Spatial variability in atmospheric backscattering affected residuals in the visible portion of the spectrum as well.

NPV was mapped (Fig. 6), based on the presence of a negative 2267 nm band residual (lignin and cellulose). Decreased atmospheric attenuation modified the magnitude of the residual by producing more negative residuals at higher elevations. The effect of the atmosphere was partially removed by subtracting the 2267 nm band residual from the 2207 nm band residual, assuming that decreased atmospheric attenuation affected both of these residuals equally. Subtraction of the 2267 nm residual from the 2207 nm residual should produce positive values in dry grass areas due to 2267 nm absorption by lignin and cellulose. In Figure 6 the dry grass areas corresponding to moderate (1.3–4.9 DN) and large (5–9.9 DN) differences are displayed as reddish-brown and red, respectively. The intensity of Figure 6 is modulated by the negative of the shade fraction image.

In September 1990 and November 1991, field inspections were made at the Jasper Ridge Biological Preserve, including the Horse Ranch, Felt Lake and vicinity, Windy Hill, and the entire region between SLAC and the Preserve. In general, Figure 6 depicted well the distribution and abundance of NPV. The only exception was in the serpentine grassland located north to northwest of the Drygrass Site, where the fraction of NPV in the field appeared to be higher than on the image (<0.5). At this site the NPV consisted primarily of upright stems of Calycadenia multiglandulosa. Spectral measurements revealed that the Calycad...
denia had weak lignocellulose absorptions in the SWIR relative to other types of NPV in the area (Fig. 7). Thus, the anomalously low fractions at this site appear to have been caused by weak lignin-cellulose absorptions that were used as the main criterion for discriminating NPV. In other areas such as the Horse Ranch, the fraction of dry grass was low, which, coupled with the instrumental noise, resulted in a speckled appearance in Figure 6.

Soil maps were produced from the soil fractions and from band residuals at 868 nm, 1042 nm, and 2207 nm (Table 1). Good correspondence was obtained between these residuals and soils in the field. However, when the lignin and cellulose absorptions were not used to discriminate the NPV, soil types without the characteristic residuals were attributed incorrectly to pixels that actually consisted of over 95% cover of NPV. These results illustrate that the soils and the NPV must be considered together when analyzing the image. For example, an NPV map derived from the lignocellulose residuals can be used as a mask when mapping the soils.

Residuals also were useful for distinguishing types of green vegetation. The only significant residual affected by green vegetation was negative, occurring at the transition between 678 nm

Figure 7. Reflectance spectra of the soil endmember compared to three types of nongreen vegetation collected in the vicinity of Jasper Ridge. Residuals calculated from mixtures of shade and the soil endmember are plotted below.
and 750 nm, in the region commonly referred to as the red-edge. This residual will be discussed in the context of canopy shade.

**Spectral Subsets**

Fractions of each endmember in each of the four spectral subsets were compared (Table 2). Linear mixing was indicated where the fractions were similar in each subset. For example, soil fractions for all four subsets were nearly identical for the Golf Course site. Nonlinear mixing was indicated where fractions differed between subsets. For example, at the same site shade had higher fractions in the visible than in the NIR and over the full spectrum. The NIR and the full-spectrum fractions were similar, suggesting that the NIR was the dominant factor controlling the full-spectrum fractions.

Other anomalous fractions among the spectral subsets were caused by mimicking or by missing endmembers. For example, in the SWIR the Drygrass site had 0.36 green vegetation. The SWIR spectra of green vegetation and NPV were nearly identical (Fig. 3), except that the NPV had higher integral reflectivity. Thus, the NPV mimicked a combination of high fractions of green vegetation and low fractions of shade. In the visible the Drygrass site had < 0 vegetation fraction, because NPV was not included as an endmember, and the soil in this area was different from the soil used in the model.

The best estimates of shade were produced in the visible subset. The results were consistent with theory and laboratory experiments (Roberts et al., 1990c). However, when the analysis was extended to the whole scene, it was found that the fractions of shade were influenced by atmospheric backscattering at the shorter wavelengths. In Figure 8, green-vegetation fractions in the visible (displayed in red) were highest in the east, in Palo Alto and Menlo Park in the direction of increasing atmospheric backscattering. The scattering produces a short-wavelength rise in DNs that roughly matches the spectral shape of green vegetation for most of the spectral range covered by the visible model, producing higher green-vegetation fractions. For the visible model to be useful, it would be necessary to remove these atmospheric effects as part of the calibration.

An unanticipated benefit arose from separate linear mixture analyses of visible, NIR, and SWIR spectral subsets. Green-vegetation types were dis-

**Table 2. Fractional Estimates from Spectral Subsets**

<table>
<thead>
<tr>
<th>Target</th>
<th>Visible</th>
<th>NIR</th>
<th>SWIR</th>
<th>Full Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green leaf</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Golf Course</td>
<td>0.61</td>
<td>0.72</td>
<td>0.83</td>
<td>0.72</td>
</tr>
<tr>
<td>Forested Wetland</td>
<td>0.15</td>
<td>0.52</td>
<td>0.34</td>
<td>0.51</td>
</tr>
<tr>
<td>Evergreen</td>
<td>0.06</td>
<td>0.17</td>
<td>0.29</td>
<td>0.18</td>
</tr>
<tr>
<td>Drygrass</td>
<td>-0.32</td>
<td>-0.08</td>
<td>0.36</td>
<td>-0.01</td>
</tr>
<tr>
<td>Chaparral</td>
<td>-0.03</td>
<td>0.04</td>
<td>0.23</td>
<td>0.09</td>
</tr>
<tr>
<td>Shade</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Golf Course</td>
<td>0.26</td>
<td>0.17</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
<td>Forested Wetland</td>
<td>0.82</td>
<td>0.54</td>
<td>0.63</td>
<td>0.54</td>
</tr>
<tr>
<td>Evergreen</td>
<td>0.85</td>
<td>0.72</td>
<td>0.65</td>
<td>0.74</td>
</tr>
<tr>
<td>Drygrass</td>
<td>0.85</td>
<td>0.39</td>
<td>0.22</td>
<td>0.43</td>
</tr>
<tr>
<td>Chaparral</td>
<td>0.87</td>
<td>0.63</td>
<td>0.55</td>
<td>0.66</td>
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<tr>
<td>Soil</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Golf Course</td>
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<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>Forested Wetland</td>
<td>0.02</td>
<td>-0.07</td>
<td>0.01</td>
<td>-0.06</td>
</tr>
<tr>
<td>Evergreen</td>
<td>0.06</td>
<td>0.09</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Drygrass</td>
<td>0.45</td>
<td>0.68</td>
<td>0.40</td>
<td>0.57</td>
</tr>
<tr>
<td>Chaparral</td>
<td>0.14</td>
<td>0.31</td>
<td>0.20</td>
<td>0.24</td>
</tr>
</tbody>
</table>

*The Forested Wetland and Evergreen sites are from the same locations as in Figure 3. The Golf Course is from a 2 x 2 pixel box at sample 249, line 32. The Drygrass Site is from a 4 x 4 pixel box at sample 295, line 333. The Chaparral is from a 5 x 5 pixel box at sample 312, line 345.*
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Spectrally distinct vegetation types were expressed as different green-vegetation fractions in the three spectral subsets. For example, in a color-subset composite (Fig. 8), the Golf Course was white and the Forested Wetland was green. If the different green-vegetation fractions in each spectral subset were a consequence of reflectivity differences in each of the subsets, we would conclude that the Golf Course had vegetation with high visible, NIR, and SWIR reflectivity and that the Forested Wetland had vegetation with low visible, high NIR, and low SWIR reflectivity. These interpretations are consistent with the spectral properties of the vegetation types known to exist in these areas. The Golf Course is dominated by thin-leaved grasses and the Forested Wetland is dominated by a thicker-leaved deciduous broad-leaved species, such as willow (Salix).

Canopy Shade

Vegetation fractions also varied with canopy architecture and shade. Negative residuals between 700 nm and 750 nm were a consequence of the difference between the actual canopy shade spectrum and the modeled photometric shade. The difference resulted in overestimates of green leaf relative to shade (Fig. 9). The effect of canopy shade on the green-vegetation fractions was revealed by analysis of the spectral subsets. Shade estimates for the forested wetland using the visible model ranged from 0.8 to 0.9 compared to 0.56 for the full spectrum. Between 663 nm and 752 nm, an underestimate of shade in the full spectrum produced a model spectrum that had significantly higher radiance than the measured spectrum, generating a negative residual.

As described in the methods section, canopy shade spectra were calculated for two canopy

Figure 9. Effect of transmission and scattering on residuals. Comparison of a modeled spectrum consisting of 56% shade and 44% green leaf to a measured spectrum. The residual is calculated by subtracting the modeled spectrum from the measured spectrum. Low shade estimates generate a prominent negative residual.
types: the “Forested Wetland” and the “Golf Course” grass. The analysis generated both a minimum estimate of canopy shade as well as a spectrum for canopy shade. The minimum fraction of canopy shade was calculated as 0.85 for the Forested Wetland (Fig. 10). The canopy shade spectrum had a relative reflectance value below 30% in the NIR. When applied to the Golf Course grass, the minimum shade abundance was calculated at over 0.65, associated with a canopy-shade spectrum that had relative reflectance close to 50% in the NIR (Fig. 11). Experiments with different green-leaf endmembers revealed no major change in estimates of canopy-shade abundance, only changes in the visible and NIR shape of the canopy shade.

The results (Figs. 10 and 11) were consistent with field observations of the vegetation types in the area. Leaves in the Forested Wetland had high reflectance and low transmittance relative to other canopies. The canopy itself had gaps and openings between branches that increased shadows at low sun angles. The Golf Course, on the other hand, was dominated by grasses that had lower NIR reflectance and considerably higher NIR transmittance. The low grass canopy had few gaps and few openings between plants, and the canopy shadows were expected to have a high NIR flux. The fraction of shade is expected to be lower than that of the Forested Wetland.

When the canopy was modeled by (photometric) shade and green vegetation, the residuals were a combination of the nonlinear canopy-shade effects and the spectra of other unmodeled components. Thus, areas with high fractions of NPV, in addition to green leaves and shade, produced unrealistic canopy-shade spectra unless the contribution of the NPV was first removed. An exam-

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Figure 10. Canopy shade in the Forested Wetland. Spectra are shown for shade fractions of 55%, 65%, 75%, 85%, and 95%.
ple was the Chaparral area (C in Fig. 1), which had high fractions of woody material.

SUMMARY

In the area studied, the spectra of soils and non-photosynthetic vegetation were too similar to include both as endmembers in spectral mixture analysis. When soil was included as an endmember, along with green vegetation and shade, much of the NPV was modeled as soil. However, NPV was distinguished from soil based on residuals in SWIR attributable to cellulose and lignin in the vegetation.

This study was an initial step toward integrating nonlinear mixing into an analysis of AVIRIS images of vegetated areas. Nonlinear mixing produced by NIR transmission and scattering by green leaves was expressed as variations in endmember fractions in spectral subsets, and as a residual spike at the chlorophyll red-edge. Linear mixing overestimated green-leaf fractions and underestimated shade when the full spectrum was used. Improved estimates of green vegetation and shade fractions, however, were calculated by deriving a canopy shade spectrum. Canopy shade, especially when coupled with an estimate of woody NPV, proved to be a reliable discriminator among green-vegetation communities.

The main results of this study were made possible by the high spectral resolution and multiple bands of AVIRIS. In particular, imaging spectrometer data were required for the analysis of spectral subsets and absorption-band residuals as well as the derivation of canopy shade. The same results could not have been obtained with the multispectral satellite data that is currently available.

Figure 11. Canopy shade at the Golf Course. Shade spectra for fractions of 15%, 25%, 35%, 45%, 55%, and 65% are shown.
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REFERENCES


Green, R. O., Conel, J. E., Margolis, J. S., et al. (1990), In-flight validation and calibration of the spectral radiometric characteristics of the Airborne Visible/Infrared Imaging Spectrometer, in Proc. SPIE, Imaging Spectroscopy of the Terrestrial Environment (G. Vane, Ed.). Orlando, FL, 16-17 April, pp. 18-36.


