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Reflectance of Vegetation and Soil in Chihuahuan Desert Plant Communities from Ground Radiometry Using SPOT Wavebands

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The spatially averaged reflectance of a partially vegetated land surface can be modeled as an area-weighted mixture of the reflectances of different components or classes of objects (plants, shadow) on a background (soil, grass). We sampled the spectral reflectance of the shaded and unshaded components of Chihuahuan desert plant communities (shrubs, soil, subshrubs, and perennial grasses) in the SPOT wavebands using a hand-held radiometer. We examined the mean reflectance differences between components to evaluate their spectral separability. Shrub canopy and shaded components have similar reflectance in the visible wavebands. However, in the near-infrared band, which is strongly scattered by green plant canopies, the shaded canopy and shaded background components were similar to each other and lower than either sunlit background or sunlit canopy. When reflectance measurements were transformed to normalized ratio (NDVI, SAVI) and orthogonal green vegetation indices, the shaded and sunlit portions of each component (canopy and soil) were similar, but the shaded components were intermediate between their sunlit counterparts. Different soil types and plant species with different life forms (e.g., shrubs, grasses) and phenologies exhibited different reflectance characteristics. However, the broadband reflectances of the three dominant shrub species were similar at the end of the growing season, in spite of their differences in morphology.

INTRODUCTION

In semiarid grasslands and shrublands that are grazed by domestic livestock, the relative cover of vegetation (woody versus grass) and exposed bare soil is often indicative of the condition of the soil and vegetation. Remote sensing methods for estimating the cover of vegetation and soil, including spectral mixture modeling, have been developed for arid lands (see, e.g., Marsh et al., 1980; Graetz and Gentle, 1982; Graetz et al., 1986; Pech et al., 1986; Smith et al., 1990). Because green vegetation cover is not continuous (horizontally homogeneous) in arid lands, the cover or canopy area of vegetation, estimated using remote sensing, may be directly related to biomass (Ludwig et al., 1975; McDaniel and Haas, 1982; Graetz et al., 1986; Franklin and Hiernaux, 1991). A geometric-optical canopy reflectance model (Li and Strahler, 1985) has been used to estimate plant size and density in semiarid environments (Franklin and Strahler, 1988; Franklin and Turner, 1992).

The objective of our study was to test one of the assumptions of the Li-Strahler model, that the landscape can be characterized by components that have reflectance characteristics that are distinct and different from each other. This modeling approach is based on a *discrete-object* treatment of surface reflectance (Strahler and Jupp, 1990), which states that the spatially averaged reflectance of an area of vegetated land surface is a function of 1) the reflectance of the *components* (major classes of objects, plants with discrete canopies) that cover that surface, their geometry, and the shadows they cast, 2) the reflectance of the *background* (e.g., soil, herbaceous understory, rock, treated as spatially and spectrally homogeneous), and 3) interaction between components and background due to transmission and scattering.

The Li–Strahler model treats canopy reflectance "as the area-weighted average of four fixed reflectance components—sunlit leaf or canopy, shaded leaf or canopy, sunlit background and shaded background—whereas radiative transfer theory shows that all of these components are variable" (Li and Strahler, 1992, p. 278). The components are variable due to nonuniformity of the

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Table 1. Studies of Vegetation and Soil Reflectance in Temperate and Tropical Semiarid Grasslands, Shrublands, and Woodlands

Study, Location	*Wave Band*	*Calibrated / Output*[a]	*FOV, Height, Area*[b]	*Dates Per Year*	*Components, Samples, Observations*[d]	*Indices*
Graetz and Gentle (1982), semiarid shrub, AUSTRALIA	MSS	Hemispher. irrad. / reflect.	15°, 1 m, 25 cm	1	Comp 1–6, 1–4 samples, 3–95 observ.	Cover Greenness
Warren and Hutchinson (1984), Chihuahuan shrub, grassland, NEW MEXICO	MSS	Grey card / reflect.	15°, 0.9–1.2 m, 30 cm	2	Comp 1–3, 5–14 samples, 2–18 observ.	MSS 5 / 7
Wilson and Tueller (1987), Great Basin shrub, NEVADA	MSS	Sun elev. correct. / radiance	15°, 1 m, 25 cm	1	Comp 1, 2, 16–25 samples, 10–116 observ.	–
Satterwhite and Henley (1987), Great Basin shrub, grassland, NEVADA	TM 1–4	Halon panel, irrad. / reflect.	15°, 0.5–1 m, 14–26 cm	1	Comp 1, 2, 1–21 samples, 2–62 observ.	All ratios NDVI orthogonal
Tueller and Oleson (1989), Great Basin shrub, NEVADA	MSS	Sun elev. correct. / radiance	15°, 0.3–1 m, 8–26 cm	2	Comp 1, 2, 6, ?, ?	Seven indices
Ringrose et al. (1989), semiarid tree savanna, BOTSWANA	MSS SPOT	?	?	1[c]	Comp 1, 3, 6–8, 1–12 samples, 60–94 observ.	–
Williamson (1990), semiarid shrub, AUSTRALIA	MSS	Grey card / reflect.	15°, 1.5 m, 39 cm	1	Comp 1, 2, 9 samples, 4–30 observ.	NDVI, PVI
Franklin et al. (1991), semiarid tree savanna, MALI	TM 3, 4	Hemispher. irrad. or grey card / reflect.	15°, 0.5–1.5 m, 14–39 cm	1[c]	Comp 1, 2, 6, 24 samples, 2–27 observ.	NDVI
This study	SPOT	$BaSO_4$ or halon panel / reflect.	1°, 0.5–1 m, 0.5–1 cm	2[c]	Comp 1–3, 6, 2–11 samples, 10–40 observ.	NDVI, SAVI, Greenness, Brightness

[a] Measurements were calibrated using hemispherical irradiance, reference panel ($BaSO_4$ or halon), or grey card (sometimes only a sun angle correction was made); output values were either radiances or reflectance factors.
[b] FOV is the angular field of view of the instrument, height is the height the radiometer was held above the target, and area is the footprint or diameter of the area of target measured.
[c] Sampling carried out on two successive years.
[d] Components: 1) soil, 2) shrub or tree crown, 3) grass and/or forbs, 4) litter, 5) ephemerals, 6) shadow, 7) foliage, 8) branches; samples are the number of samples per component (per date); observations are the number of observations per sample.

canopy and multiple scattering. However, Strahler and his colleagues maintain that for real plant canopies, especially those with low cover, variation between the four components is usually much greater than variation within them (Li and Strahler, 1992). They are often distinctly separable in multispectral measurement space (Strahler and Jupp, 1990), especially in the visible portion of the spectrum where vegetation is strongly absorbing and multiple scattering is not important (Li and Strahler, 1992). In the present study we test the assumption of separability of the four components, defined above, in semiarid grassland and shrubland.

The term spectral separability is derived from the application of multivariate clustering techniques to multispectral image data; the "separability" of classes in the image is determined statistically from the means, variance / covariance, and sample sizes of the clusters defined using representative areas of an image (Thomas et al., 1987). We are using the term somewhat differently here in the context of modeling the spectral mixture of subpixel components. "How separate is separate enough" or "what is a biophysically significant difference in component reflectances" is related to both the spectral variance of the components and to the model being used (Strahler and Jupp, 1990), as well as to other factors (see Discussion).

The reflectances of the shaded and unshaded components and background of Chihuahuan desert plant communities (shrubs, perennial grasses, subshrubs, and soil) were measured in the field using a hand-held radiometer in SPOT wavebands. Spectral green vegetation indices were computed for the different components. Index values are intended to normalize for the effect of soil background color, shadowing, and illumination / viewing geometry, so that they are only sensitive to changes in the amount of photosynthetically active vegetation. The reflectance measurements and the spectral indices were examined to determine if the mean reflectances or index values of different components were significantly different. Results are discussed in light of the debate in the literature concerning significance testing in this type of study. Our goal was both to test the four-component separability assumption, and to determine the parameters (component reflectances) required for reflectance model inversion.

REFLECTANCE OF VEGETATION AND SOIL IN SEMIARID LANDSCAPES

Several studies in the last ten years have examined component reflectances *in situ* with broadband radiometry in temperate and tropical semiarid grasslands, shrublands, and woodlands. The sampling and analysis methods used in these studies are summarized in Table 1. The major conclusions of these studies are:

Visible and near-infrared reflectance characteristics of components:

Soil:

- Soils in arid lands are often bright, with near-infrared (NIR) reflectance greater than that of the vegetation present (Ringrose et al., 1989).
- Often when there are a variety of soils in an area, their brightness cannot be described by a single "soil brightness line" (Williamson, 1990).
- Background reflectance can be variable due to soil moisture content and the presence of litter, cryptogams, and deflation and salt crusts on the soil surface.

Vegetation:

- Plant canopies in arid lands have variable reflectance, partly due to variable canopy conditions (leaf area, leaf water content, spectral characteristics of leaves or other plant parts), but also due to low crown cover (e.g., low vertically projected cover of plant material within the perimeter of the crown), especially in shrubs and trees. This means that the soil, litter, other vegetation, and shadow beneath the canopy contribute significantly to the canopy reflectance (Williamson, 1990) and to its variance. This variance is greater in the NIR than in the visible wavebands due to multiple scattering by leaves.
- Because the NIR contrast between vegetation and soil is generally low, the relationship between green vegetation indices (based on red–infrared contrast) and vegetation cover or amount depends more on the reduced red reflectance of the canopy than its high NIR reflectance.
- It has been suggested that phenological differences between woody and herbaceous vegetation could be used to estimate their relative contributions to the reflectance of a site if reflectance data are available from different seasons and sun angle differences are taken into account (Warren and Hutchinson, 1984).

Spatially averaged reflectance:

- Spatially averaged reflectance for a site is often similar to soil reflectance because of generally low vegetation cover (Ringrose et al., 1989).
- Shadowing by vegetation contributes significantly to the main direction of reflectance variation, the "darkening" of a bright soil background by all components (vegetation, litter, shadow) (Graetz and Gentle, 1982; Wilson and Tueller, 1987; Tueller and Oleson, 1989; Ringrose et al., 1989).
- Because shadowing varies as a function of plant shape and cover, and illumination and viewing geometry, it has been considered both a source of noise, to be neutralized using spectral indices, and a source of information on canopy structure in spectral mixture (Smith et al., 1990) and geometric models (Strahler and Jupp, 1991).

Although many of these effects have also been noted in studies of other partially vegetated land surfaces, notably developing crop canopies (Richardson et al., 1975; Jackson et al., 1979; Huete, 1987), semiarid natural vegetation presents a complex reflectance surface due to the generally low plant cover, the high spatial variability of the exposed soil surface, the mixture of plant growth forms often occurring together, their variable phenology, and the spatial pattern of the vegetation.

STUDY AREA

The study took place on the Jornada LTER (Long Term Ecological Research) site, encompassing the Jornada Experimental Range and New Mexico State University Ranch, located in the Jornada del Muerto basin in southwestern New Mexico. During the past century, perennial grasslands on the Experimental Range have been replaced by shrublands (Buffington and Herbel, 1965; Gibbens and Beck, 1988). Similar changes in vegetation have occurred over large areas of southern New Mexico (York and Dick-Peddie, 1969; Grover and Musick, 1990; Schlesinger et al., 1990), southeastern Arizona (Bahre, 1991), and western Texas (Archer et al., 1988). Remote sensing research in the Jornada basin has been used to estimate and monitor the vegetation and soil parameters associated with the land surface changes described above from multispectral satellite imagery (Musick, 1984; Warren and Hutchinson, 1984; Franklin and Turner, 1992; Duncan et al., forthcoming).

Current ecological research in the Jornada LTER program examines the mechanisms underlying this vegetation transition, namely, changes in the distribution of water and nutrients between landform elements as a result of the loss of herbaceous cover (Schlesinger et al., 1990). The LTER research focuses on 15 large (70 m × 70 m) permanent plots in three biomass strata for each of five vegetation classes. Patterns of primary productivity (Muldavin and Huenneke, personal communication) and soil properties (R. Virginia, personal communication) are being monitored on these plots. The five vegetation types are dominated, respectively, by tarbush (*Flourensia cernua*), creosote bush (*Larrea tridentata*), mesquite (*Prosopis glandulosa*), black grama (*Bouteloua eriopoda*), and tabosa (*Hilaria mutica*). A complete description of the study area can be found in Buffington and Herbel (1965). In the present study, radiometric sampling was carried out adjacent to 13 of the permanent plots, but repeated measurements were only made in nine sites (Table 2).

Table 2. Description of Field Sample Sites, Component Samples, and Sample Dates

Site Name	*Vegetation Type Description*
1. Tarbush East	*Florensia cernua* shrubland on silty bottomland with some *Hilaria mutica* and *Scleropogon brevifolius*
2. Tarbush West	As above, grass cover denser
3. Tarbush Taylor	As above, grass cover locally dense
4. Creosote Caliche	Stunted *Larrea tridentata* shrubland on gravelly upper bajada with caliche at or near surface
5. Creosote Sand	*Larrea tridentata* shrubland on gravelly or sandy bajada with *Muhlenbergia porteri* and *Xanthocephalum sarothrae*
6. Mesquite West	*Prosopis glandulosa* on sandy uplands with *X. sarothrae* and *Sporobolis flexuosus*
7. Mesquite Rabbit	As above, *Prosopis* forming large coppice dunes
8. Grama Basin	*Bouteloua eriopoda* grassland on lower bajada with *Yucca elata* and *Ephedra spp.*
9. Grama IBP	*Bouteloua eriopoda* grassland on sandy upland with *Yucca elata* and *Ephedra spp.*

Components	*Sites*	*Description*
SOTR soil transect	All	20–30 observations along a linear transect
SOIL bare soil	1–7	Soil sampled near shrubs
SHSO shaded soil	1–7	Soil shaded by dominant shrub
SHCA shaded canopy	1–7	Self-shaded portion of dominant shrub canopy
CANO shrub canopy	1–3	Tarbush, *Florensia cernua*
	4, 5	Creosote bush, *Larrea tridentata*
	6, 7	Mesquite, *Prosopis glandulosa*
SNKW snakeweed	1, 4–7	*Xanthocephalum sarothrae*
GRAS grass	3	*Scleropogon brevifolius* and *Hilaria mutica*
	6	*Sporobolis flexuosus*
MUHL grass	4, 5	*Muhlenbergia porteri*
GRAM grass	8, 9	*Bouteloua eriopoda*
SHGR shaded grass	2	*S. brevifolius* and *H. mutica* shaded by tarbush
EPHE Ephedra	8, 9	*Ephedra spp.*
YUCC Yucca	8, 9	*Yucca elata*

Sampling Dates	*Sites*
1. 4–7 June 1989	All sites listed above
2. 26–29 September 1989	All sites listed above
3. 4–9 June 1990	Tarbush East, Creosote Caliche, and Creosote Sand
4. 3–5 October 1990	Creosote Sand, Mesquite West, Grama IBP, and Tarbush West
3–7 October 1991	Tarbush East, Creosote Sand, and Tarbush West, field of view comparison

HYPOTHESES

The research objectives described above can be stated as the following hypotheses:

1. Within a given site on a sampling date, the broadband reflectances and spectral index values for plant and soil components (shaded and unshaded) will be significantly different. Greater reflectance differences will be found in visible bands and a spectral brightness index than in the NIR band and spectral greenness indices.
2. The reflectances of different soil types and plant species, and of the same species found on different soil backgrounds, will be different.

Another important question concerns whether plant canopies have significantly different reflectance in different parts of the growing season because of the timing of leaf-out. The temporal dynamics of component signatures must be characterized prior to geometric-optical modeling.

METHODS

Sample Design

Radiance was sampled in seven shrub sites and two grass sites (Table 2). The components sampled were

Plants: the dominant species or functional groups of species (grouped by growth form—shrubs, subshrubs, grasses).

Soil: bare soil was sampled in the shrub sites, and soil transects (incorporating more soil variability, including litter) were sampled in all sites.

Shadow: the canopy and soil shaded by the dominant shrubs were measured in the shrub sites (shadows from grasses and subshrubs were not measured).

Not all components occurred in all sites (Table 2). Sampling was carried out in 1989 and 1990 at the beginning of the summer growing season (June), and

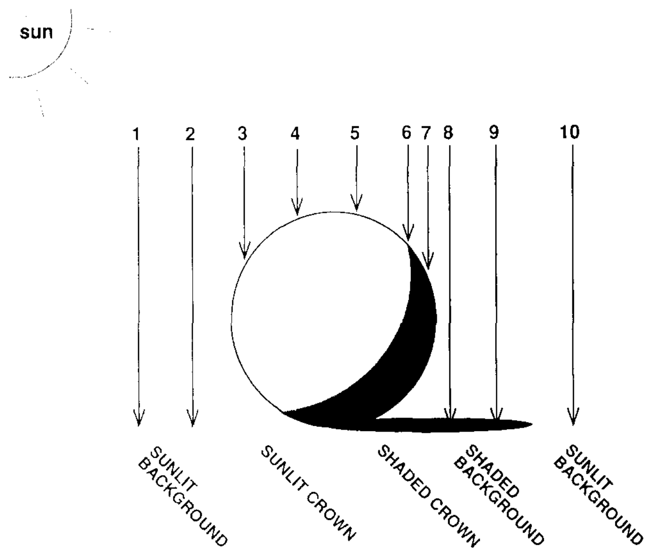

Figure 1. Side view of idealized shrub canopy showing four spectral components and the location of 10 radiometric samples taken along a transect in the principal plane of the sun. Measurements 1, 2, and 10 were averaged to represent sunlit background, 4 and 5 for sunlit crown, 7 for shaded crown, and 8 and 9 for shaded background.

again at the end of the growing season (late September / early October; Table 2).

Our goal was to collect 20–30 observations per sample, where a sample includes all the measurements of a component in a site. In fact, our sample size varied from 10 to 40, but 60% of the samples had at least 20 observations. Samples were located in the following ways. In the shrub-dominated sites, sunlit and shaded shrub canopy and background (bare soil) were measured along transects oriented in the principal plane of the sun (Fig. 1) (Franklin et al., 1991; Turner, 1991). Shrubs of average size and leaf density for the site were subjectively chosen for sampling. In all sites, additional soil transects, roughly 50–75 m long, were usually oriented parallel to one edge of the LTER site and at least 20 m from it. Radiance was measured at each meter (measured by pacing) that had unshaded soil exposed (no vegetation), including points covered by litter and cryptogams. All other vegetation (subshrubs, grasses, rarer shrubs) was sampled by choosing a random bearing within the site and measuring the first 20–30 plants encountered.

Radiometric Sampling Methods

Measurements of radiance of the ground targets were made using an Exotech radiometer with SPOT Bands 1–3 filters and 1° field of view (FOV) lenses. The height of instrument above the target was 0.5–1.0 m, yielding a footprint roughly 0.5–1.0 cm in diameter. In order to compare the results of our study to those listed in Table 1, and to adequately characterize components with a small number of samples, a 15° FOV might have been a better choice. Therefore, we performed an additional experiment in October 1991, sampling the same targets with both the 1° and 15° lenses, to determine if there were systematic differences in the means or variances (Table 2).

All sampling was carried out between 9:30 a.m. and 3:30 p.m., but avoiding solar noon. Measurements were taken when the solar zenith angle was no greater than 59° and no less than 10°. This was to correspond approximately to the Sun angle at the time of the SPOT overpass, to avoid strong non-Lambertian effects of low illumination angles, and to avoid very small zenith angles when shadowed components are difficult to sample and shading of the target by the operator is a problem.

Voltages from the Exotech were recorded along with time of day on a data logger. Three replicates of each observation were made and the median was used. The reflectance factor of the target was computed based on measurements taken 0.5 m over a reference panel (45 cm × 45 cm) used to estimate irradiance. Because radiance $L = C*V$ (where V is the voltage measured by the instrument and C is the calibration relating voltage to radiance for an instrument in a particular waveband) and because C is the same for both the panel and target, the target reflectance factor can be calculated from

$$R_t = (V_t / V_p)R_p,$$

where V_t and V_p are the voltages recorded for the target and the panel and R_p is the reflectance factor of the panel (Jackson et al., 1980; Pinter et al., 1990). Note that the reflectance factor is a dimensionless ratio.

Measurements of the panel were taken with the same radiometer at the beginning and end of each series of target measurements (or when different radiometers were used, they were cross-calibrated), and the voltage measurement from the panel (V_p) corresponding to each target measurement was calculated from linear interpolation or from polynomial regression of V_p with time. Note that these computations were relative, not absolute, due to the unknown reflectance factor of the "home made" barium sulfate ($BaSO_4$) panel used on the first three sampling dates (R_p was assumed to be 1). The hemispherical reflectance factor of $BaSO_4$ panels typically ranges from 0.90 to 0.95 in the visible and near-infrared wavebands for solar zenith angles between 0° and 60° (Duggin, 1980; Jackson et al., 1980). The non-Lambertian behavior of these panels has been shown to be significant, especially at solar zenith angles greater than 60°, reducing the reflectance factor of the panel to 0.85 or less (Jackson et al., 1992). Sampling was not carried out when the solar zenith angle was greater than 60°, as noted above. However, the values used in the analysis should not be compared directly to other studies where reflectances were calculated from the known bidirectional reflectance of a reference panel.

During the fourth sampling period, October 1990, a calibrated, commercially available halon panel was used [hemispherical reflectance factors in the SPOT wavebands were about 0.99 (R. Jackson, personal communication)]. In principle, this panel could have been used to calibrate the $BaSO_4$ panel and recalculate the reflectance factors for the first three dates. However, the reflectance properties of $BaSO_4$ panels change with use (Jackson et al., 1987), and there was some evidence that the reflectance of the first panel had changed over the course of the study (see Results). Therefore, we did not attempt to back-calibrate the panel because of the possibility of introducing more error than we would correct.

Several spectral indices were derived for each observation including the normalized difference vegetation index (Rouse et al., 1974),

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red}) / (\mathrm{NIR} + \mathrm{Red}),$$

where NIR and Red are the reflectance factors in those wavebands, and the soil-adjusted vegetation index (Huete 1988),

$$\mathrm{SAVI} = [(\mathrm{NIR} - \mathrm{red}) / (\mathrm{NIR} + \mathrm{red} + L)] * (1 + L).$$

The constant (L) is used in SAVI to normalize for the effect of the soil background on canopy reflectance. A value of 0.5 has been suggested by Huete (1988) for intermediate vegetation cover, and used in other rangeland studies (M. S. Moran, personal communication). We used a value of 1.0 because of the low plant cover in our sites and because as L approached 0.0, SAVI approaches NDVI. Therefore, values of SAVI for $L = 0.5$ would be intermediate between the SAVI and NDVI values calculated in this study. Orthogonal greenness and brightness indices were calculated from the reflectance factors in the three SPOT wavebands according to the method described in Jackson (1983). In this study

$$\mathrm{Greenness} = (-0.2839 * \mathrm{Green}) + (-0.6943 * \mathrm{Red}) + (0.6614 * \mathrm{NIR}),$$

$$\mathrm{Brightness} = (0.2186 * \mathrm{Green}) + (0.6247 * \mathrm{Red}) + (0.7496 * \mathrm{NIR}).$$

Statistical Analysis Methods

Our objective of evaluating component spectral separability calls for an analysis of variance (ANOVA) to determine the significance of the differences between sample means of component reflectance (Sokal and Rohlf, 1981). Furthermore, because our sample design required us to use some samples repeatedly in different comparisons, tests for multiple comparisons using a fixed "experimentwise" error rate are appropriate. However, there is considerable debate in the literature about the use of multiple comparison tests and about significance testing in general in biological studies. Although some (Day and Quinn, 1989; Schultz, 1989) maintain that an experimentwise error rate must be used when multiple comparisons are made, others argue that a comparisonwise error rate is more logical (Jones, 1984; Soto and Hurlbert, 1991). Several writers have emphasized the importance of determining the biological significance of the magnitude of the treatment effect, and question the role of statistical significance testing in biological experiments (Perry, 1986; Yoccoz, 1991). Some of the studies listed in Table 1 used ANOVA (Ringrose et al., 1989), or ANOVA followed by pairwise comparison of means tests (Williamson, 1990; Tueller and Oleson, 1989), while another study used a subset of the data from Franklin et al. (1991) and multiple comparison tests of the significance of differences in component reflectances (Hanan et al., 1993).

In the present study, we hypothesized that the components we defined have different reflectance properties based on the spectra of pure components (green leaves, soil) and models of canopy radiative transfer. We tested this hypothesis with *in situ* measurements because we expected that the openness of plant canopies and the heterogeneity of the soil surface in the study area would reduce the difference between components. We needed to determine which differences a) were significant (low P value), b) were of a large magnitude, and c) would be expected based on spectral curves of the materials making up the components and principles of radiative transfer. Differences in reflectance properties among components that met these criteria could be termed "biophysically significant."

In light of these issues, we chose the following procedure: An ANOVA was performed to test for the effect of the different treatments (components, sites, dates) and interactions on each variable (SPOT bands and spectral indices). The samples were tested for normality and for equality of variances. The mean differences were calculated and tested for significance by t-test and Bonferroni test for each pairwise comparison addressing hypotheses 1 (comparisons of components within sites) and 2 (comparisons of a component across sites). The Bonferroni test is simply a t-test with a comparisonwise error rate adjusted to a proportion of experimentwise error rate for the total number of comparisons to be made, decided *a priori* (Day and Quinn, 1989). This test is robust when variances are unequal. It is also a less powerful test than a t-test (is less likely to detect differences in means when they are actually different), but was included for the reasons discussed above. The magnitudes of the differences in spectral values were also examined graphically. All statistical analyses were carried out using BMDP and Statview software.

RESULTS

1° versus 15° Field of View Comparison

For the majority of the components sampled with both FOVs in October 1991, the mean single band reflectance or vegetation index was not significantly different at the 0.05 level. There were significant differences in single spectral bands in only two of 40 cases (the Creosote Sand site, shaded canopy, green, and NIR) and the magnitude of the mean difference was 0.011 in the green band and 0.051 in the NIR. There were significant differences in vegetation index values in two of 10 cases for NDVI (canopy, Creosote Sand and Tarbush West) and two of 10 cases for SAVI (canopy and shaded canopy, Creosote Sand), and the magnitude of these differences ranged from 0.047 to 0.103. None of the differences were significant at the 0.001 level. The Levene test for equality of variances of the samples taken using different FOVs showed that all sample variances in the Tarbush West and Tarbush East sites were different at the 0.05 level except for one. There were no significant differences between the variances for the Creosote Sand site. However, in all Tarbush East and Tarbush West samples and in 15 of 20 Creosote Sand samples, the sample taken with the 1° FOV had a greater standard error than the 15° FOV sample. Standard errors ranged from 0.001 to 0.028 for 15° and 0.002 to 0.038 for 1°. The reason for this is intuitive: An FOV that is an order of magnitude smaller will sample more variation in the subcomponents (leaves, stems, shadow, soil, litter) that make up the components we have defined. However, it appears that, in spite of the small sample size, the means of component spectral variables taken with the two FOVs are not significantly different. We conclude that our results using the 1° FOV can be compared to results from the other studies listed in Table 1. Further, the increased variance introduced by the 1° FOV has reduced the power of the statistical comparison of component means discussed below; therefore, it is especially important to examine the magnitude of the average differences in evaluating the biophysical significance.

Addressing the Hypotheses

The data consisted of 2701 observations in 127 samples (up to 11 components, in as many as 10 sites, on four dates). About 71% (531 out of 746) of the datasets (4–7 spectral variables per sample) were normally distributed according to the W statistic (Shapiro and Wilk, 1965). The percentage of normal samples varied by date from 67% in September 1989 to 86% in June 1990, and by band/index from 65% (red) to 90% (Brightness). The nonnormal red samples were usually right-skewed. Among sites, the percentage of normal samples varied from 60% (Mesquite West) to 80% (Grama Basin). The only distribution pattern of any consistency was that of the components. Soil and soil transect samples were normally distributed only 55% and 48% of the time, respectively. This was especially influenced by the mesquite sites, where only 25% of the samples were normal. In addition, nonnormal soil and soil transect samples were left-skewed much more often than right. Although nonnormal shaded soil samples were also left-skewed, nonnormal vegetation and shaded canopy samples were frequently right-skewed. This suggests that some darker measurements (litter, vegetation) may have caused the soil samples to be left-skewed while a few bright observations (possibly due to canopy openings) caused the vegetation measurements to be right-skewed.

Although Levene's F test indicated that some variances were unequal, no single transform was effective in equalizing the variances (there was not a systematic relationship between mean and variance). However, the Bonferroni test is robust to unequal sample variances. A three-way ANOVA showed that for each band all three treatments (component, site, and date) were highly significant ($P \ll 0.01$). Throughout the following sections, "significance" will refer to $P < 0.01$ unless otherwise indicated, because this value appeared to correspond better to differences that were biophysically significant (had a large magnitude) than the Bonferroni significance level (0.01 divided by 652 comparisons = 0.000015). However, the P value was examined for each comparison, and many of the differences were also significant at the Bonferroni level.

Differences among Components in a Site

The results are illustrated in scatterplots showing the mean red and infrared reflectance factors for all samples in all sites on a given date (Fig. 2), and box plots showing the mean and variance for selected bands and transforms arranged by site and date for Tarbush East, Creosote Sand, and Mesquite West (Figs. 3–5). The results will be discussed for the red spectral band which is highly correlated with the green band ($r = 0.848$) and orthogonal brightness transform ($r = 0.918$), the NIR band, and one vegetation index (NDVI) which is correlated with SAVI ($r = 0.92$) and Greenness ($r = 0.92$). The other spectral indices (SAVI, Greenness, and Brightness) will be discussed in cases where the magnitude of differences in components differs greatly from the bands that are discussed in detail. The shaded components measured in June 1989 will not be discussed because of problems with component definition on that first sample date.

In the red waveband (within the region of absorption of photosynthetically active radiation by green vegetation), sunlit shrub canopy, shaded canopy, and shaded soil were rarely significantly different from each other in any site and the magnitude of their differences ranged from 0.0 to 0.09 (reflectance factor). Sunlit soil was

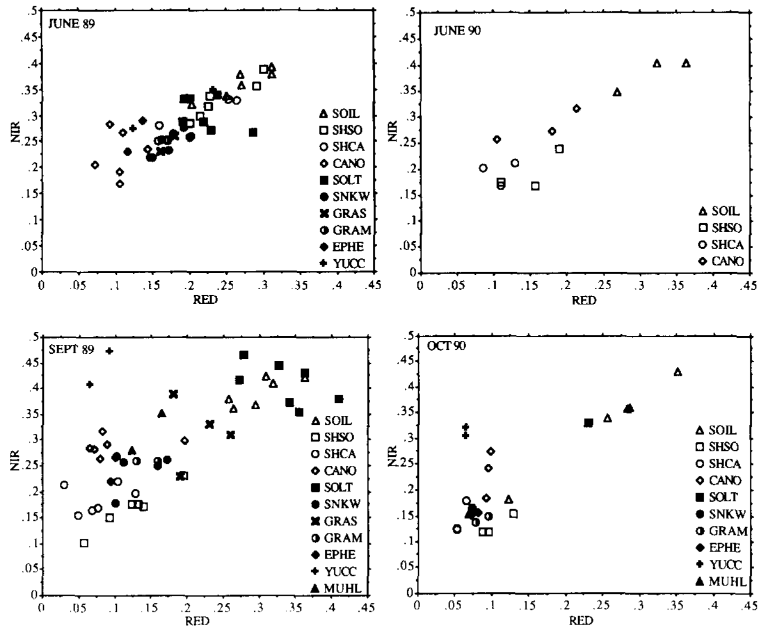

Figure 2. Mean component reflectances for two SPOT wavebands, red and NIR, in (top left) June 1989, (bottom left) September 1989, (top right) June 1990, and, (bottom right) October 1990. See Table 2 for definition of components.

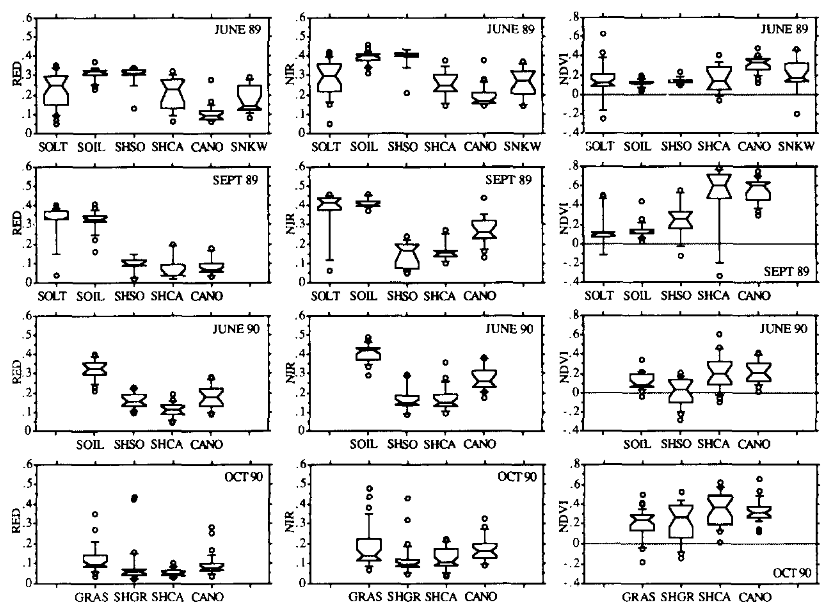

Figure 3. Box plots of component reflectance samples for Tarbush East site on four dates (rows) shown for three bands (columns): red, NIR, and NDVI. Boxes show the 25th and 75th percentiles, notches indicate the 95% confidence interval around the median, and whiskers show the 10th and 90th percentiles; outliers are indicated by circles. See Table 2 for definition of components.

always significantly different from canopy and shadows with mean differences ranging from 0.12 to 0.28.

In June 1989 the subshrub Snakeweed (*Xanthocephalum sarorthrae*) occurring in the shrub sites had red reflectance similar (0.01–0.12; ranges listed parenthetically refer to the magnitude of the mean differences between components unless otherwise indicated) to shaded shrub canopy and shaded soil, that is, intermediate between the darker (0.6–0.10) shrub canopy and brighter (0.07–0.14) soil (Figs. 4 and 5). In the Grama sites, all vegetation components had 0.04–0.08 lower red reflectance than soil, and Ephedra and Yucca had similar red reflectance; both were darker (0.03–0.07) than Grama and Snakeweed, which were similar to each other (Fig. 2). In September 1989 and October 1990, when most of the vegetation components were greener than they were in June, the grasses (*Muhlenbergia porteri* and *Scleropogon brevifolius*) and Snakeweed (Figs. 4 and 5) in the shrub sites had red reflectance intermediate between the darker (0.04–0.19) canopy and shadows (often significant) and the significantly brighter (0.08–0.25) soil. In the Grama sites, Snakeweed, Ephedra and Yucca all had similar (0.02–0.03) red reflectance that was significantly lower (0.03–0.09) than Grama (Fig. 2).

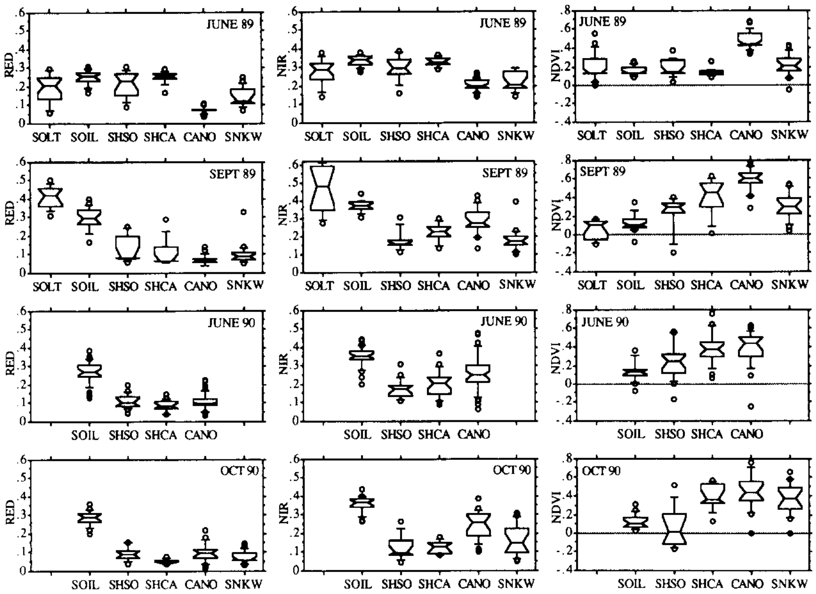

Figure 4. Box plots (as in Fig. 3) of component reflectance samples for Creosote Sand site on four dates (rows) shown for three bands (columns): red, NIR, and NDVI. See Table 2 for definition of components.

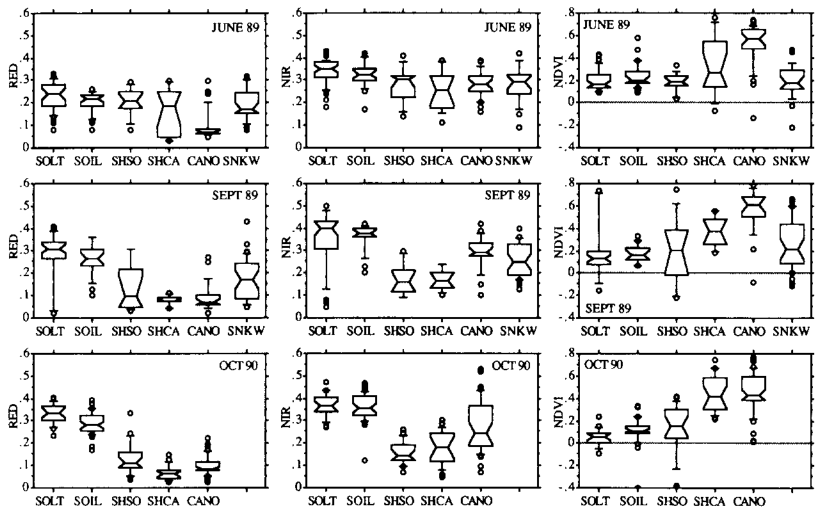

Figure 5. Box plots (as in Fig. 3) of component reflectance samples for Mesquite West Well site on three dates (rows) shown for three bands (columns): red, NIR, and NDVI. See Table 2 for definition of components.

In the NIR band, where scattering by green vegetation is greater, the shaded components were not significantly different from each other in most sites and dates (0.0–0.06), but they were darker than both sunlit canopy (0.10–0.21) and soil (0.09–0.32). In June 1989, Snakeweed in shrub sites had NIR reflectance similar to shrub canopy (less than 0.07 different and not significantly) and 0.05–0.15 (significantly) darker than soil (Figs. 4 and 5). In the Grama sites, all vegetation components had similar NIR reflectance. In September 1989 and October 1990, grasses and Snakeweed had similar (0.0–0.13) NIR reflectance to shrub canopy and 0.06–0.19 lower NIR reflectance than soil. In the Grama sites, Ephedra, Snakeweed, and Grama had similar NIR reflectances which were 0.15–0.28 lower than the NIR reflectance of the succulent Yucca (Fig. 2).

When the NDVI was calculated for the samples, sunlit and shaded canopy were not significantly different (0.0–0.19), nor were sunlit and shaded soil (0.0–0.13). The vegetation index had, to some extent, normalized for the effect of illumination. Although the differences between the shaded and unshaded components were not great, the NDVI values for the shaded components were usually intermediate between the unshaded ones except that sometimes the NDVI for shaded soil was lower than for soil (Figs. 3–5). In June 1989, dormant grasses and Snakeweed had a low NDVI, more similar (0.04–0.09) to soil than to canopy (0.10–0.35 higher) in the Creosotebush and Mesquite sites (Figs. 4 and 5). Deciduous Tarbush canopies also had a low NDVI in June 1990 (Fig. 3). In the Grama sites, Ephedra and Yucca had 0.13–0.20 higher NDVI than dormant Grama

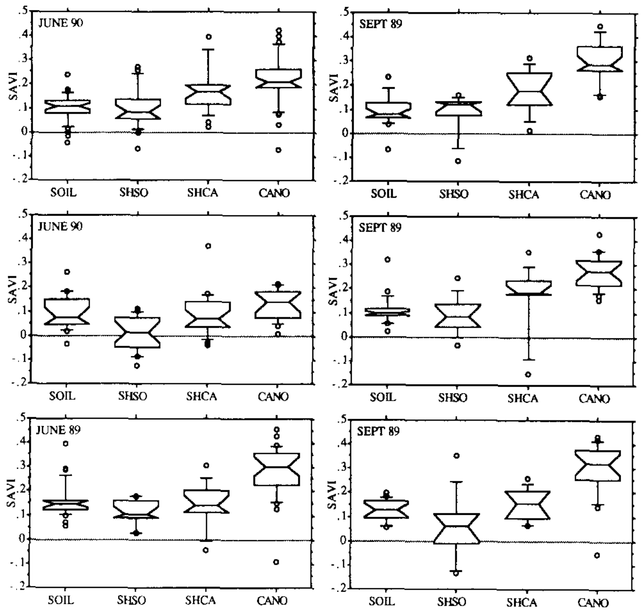

Figure 6. Box plots (as in Fig. 3) showing SAVI for component samples in Creosote Sand (first row), Tarbush East (second row), and Mesquite West Well (third row). See Table 2 for definition of components.

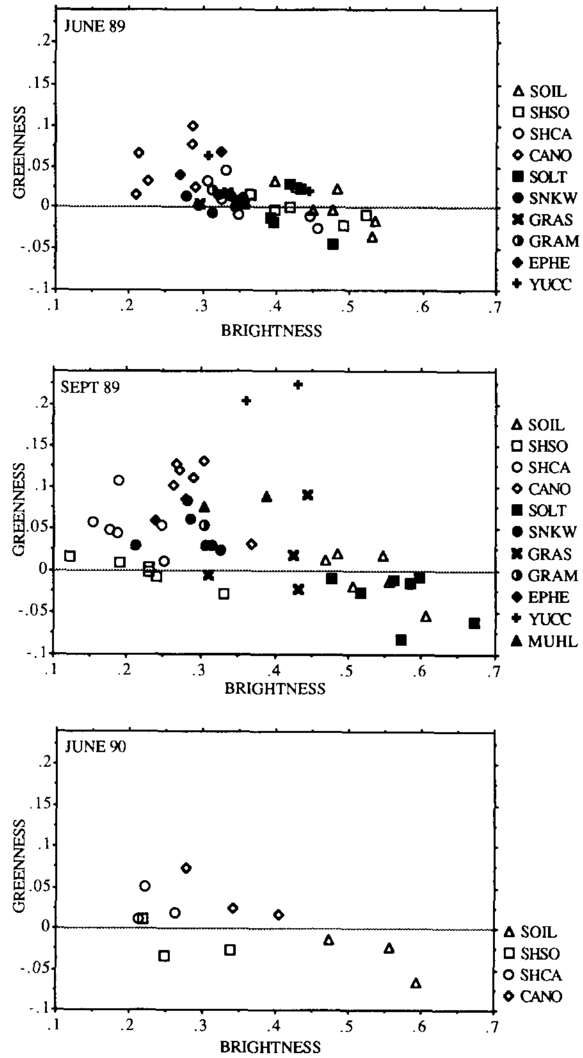

Figure 7. Mean component reflectances for orthogonal transforms, Brightness and Greenness, in (top) June 1989, (middle) September 1989, and (bottom) June 1990. See Table 2 for definition of components.

and Snakeweed. In September 1989 and October 1990, Snakeweed and Muhlenbergia found in the shrub sites had higher NDVI than in June but not as high as the shrub canopy (0.15–0.35 lower; Figs. 2, 4, and 5).

Comparing SAVI (Fig. 6) to NDVI (Figs. 3–5) for shrub sites, the SAVI for shaded soil was lower than the NDVI and more similar to sunlit soil than to shaded canopy. The SAVI was lower for green vegetation components such as shrub canopy (values of 0.2–0.3) than the NDVI (values of 0.4–0.7) while the value of both indices for bare soil is about the same (values of 0.1–0.2). Because of the compressed range of values for SAVI calculated with a constant (L) of 1, the contrast between sunlit and green vegetation was lower.

In September 1989, the orthogonal brightness index for shaded canopy and soil was lower than for sunlit canopy and sometimes significantly so, in contrast to the pattern for red reflectance (Figs. 2 and 7). This pattern was not consistent for June 1989 or 1990, but on those dates not all shrub species were in leaf. In general, the magnitude of the differences between components was greater in the brightness transform than in the red band.

Based on these comparisons, it appears that components that were significantly different also had differences ranging from 0.06 to 0.32 in single bands, and components that were not significantly different had differences of 0.0–0.09. NDVI had higher variance than single bands and significant differences between component means were larger, ranging from 0.10 to 0.55. SAVI had high variance, but the magnitude of the differences between components were less than for NDVI. SAVI and NDVI yielded fewer significant differences between components than individual bands and the brightness transform; therefore, hypothesis 1 is supported by the results.

Differences in Components between Sites

Although sometimes statistically significant, the magnitude of the difference in the reflectance of a single component (such as sunlit soil or shaded canopy) between sites was generally less than the differences between components discussed above. Comparisons focus on June and September 1989, the dates when many of the sites were sampled (Table 2). The magnitude of the differences for this comparison ranged from 0.0 to 0.11

in the red band and 0.0 to 0.16 in the NIR (usually higher in September).

In the Creosote Caliche site, soil and canopy were brighter in the red band, but not in the NIR, than in all other sites. With its bright soil due to an exposed caliche layer, it also had a lower NDVI for sunlit canopy than any other site. This site and the partially leafed out Tarbush sites had lower (0.17–0.28) NDVI than the Mesquite and Creosote Sand sites in June, but Creosote Caliche was the only site whose shrub canopy component had a significantly different NDVI than the other sites in September (lower by 0.32–0.40) in spite of the species differences. Although the magnitude of this difference was less (0.13–0.19) for SAVI, it was significant. In September, canopy differences were smaller than soil differences among the sites in single bands. Again, the linear brightness transform tended to increase the contrast between sites for a component, especially for soil, while the linear greenness transform increased the separability of green vegetation components relative to the NIR band alone. Hypothesis 2 was only partly supported.

Temporal Patterns of Component Reflectances

The temporal patterns of any component must be evaluated cautiously because of the calibration problems described above. There were systematic differences between the June and September 1989 data even for components that should have been stable. Bare soil reflectance was lower in June (0.01–0.05 in the red and NIR) when it would be expected that September soils reflectance would be the same or lower due to larger solar zenith angles and greater shading by microrelief. We attribute those changes to changes in the panel surface. Soil reflectances showed no systematic difference between September 1989 and June 1990 in any band ($\pm$0.01–0.02) or transform. In the Tarbush East site, sampled on both of these dates, sunlit and shaded canopy had lower (0.04–0.10) red reflectance, higher, or unchanged NIR reflectance (0.0–0.02) and higher NDVI (0.23–0.34) in September when Tarbush is in leaf. In the Creosote Sand site, sunlit canopy had higher red (0.03), NIR (0.03), and NDVI (0.18) in September, but shaded canopy and soil were not different for this evergreen shrub site. The very sparse crowned Creosote Caliche site showed no difference in any components between these dates.

DISCUSSION

The general pattern of component reflectances can be summarized as follows. The four components described by Li and Strahler (1985) for woody vegetation, sunlit and shaded canopy and background, were separable based on these results when the background was primarily soil. Furthermore, the assumption that the model can be simplified to two components, sunlit background, and canopy plus associated shadow (Franklin and Strahler, 1988; Franklin and Turner, 1992) is supported for the individual SPOT wavebands. Differences between sunlit soil and canopy are always large in the red waveband and the vegetation indices except when the soil is very bright and the canopy very sparse (e.g., Creosote Caliche). Differences are not as great in the NIR both because the soils in this area have very high NIR reflectance and the open canopies have high NIR transmittance. The shaded components (canopy and soil) are not greatly different than the sunlit canopy in the absorptive bands, brightness transform, or SAVI, from each other in the NIR, or from their respective unshaded components in the NDVI. It appears that the NDVI and Greenness perform better than SAVI for normalizing the effects of shadowing (e.g., yielded index values for shaded canopy or soil that were similar to their respective sunlit counterparts).

Surprisingly, green vegetation index differences for the sunlit canopy in the dominant shrub types (tarbush, creosote bush, mesquite) were not great at the end of the growing season, and appeared to be more related to biomass or leaf area than to the obvious morphological differences between the species. This may be because the crowns are open and the canopy reflectance is strongly influenced by the background reflectance.

Herbaceous vegetation, subshrubs, and shrubs other than the dominant species often had different reflectance characteristics than the dominant shrub crowns, probably because of their differences in biomass, morphology, and phenology. Grasses and subshrubs often had green vegetation index values intermediate between low soil values and high shrub values even during the growing season. This may be related to the amount of standing brown biomass in their canopies (Tucker, 1979). The importance of these differences depends on the relative cover of the vegetation components in a site. For example, although Yucca has extremely high infrared reflectance, and consequently a high vegetation index value, its cover is less than 1% in most parts of the study area.

Regarding the sample size used in this and other similar studies, simple calculations based on the observed sample variances indicate that a much larger number of observations (perhaps 50–250) would be needed to reliably estimate the means of the samples (Curran and Williamson, 1986), as well as to increase the power of the differences in means test. In spite of the large variances, and the small sample sizes, many differences were detected that were statistically significant, even by the more conservative Bonferroni test. An evaluation of their magnitude revealed that a mean difference of at least 0.10 for spectral bands or SAVI when $L=1$ (higher for NDVI or Brightness) could be used as a criteria for biophysically significant differences.

For components that consistently have high variance, such as the soil background, this high variance is in itself useful information and may not be resolved by a greater number of observations. High variance could indicate that the assumption that the component is homogeneous is not valid, and its heterogeneity or spatial variance should be treated explicitly in a surface reflectance model (Strahler and Jupp, 1990; Jasinski, 1990). Alternatively, in the case of the shaded components, their lower variance may be treated more deterministically by modeling their reflectance as a function of the irradiance, path length, and attenuation by the canopy, and reflectivity of the subcanopy components (Franklin et al., forthcoming).

There are a number of limitations to the study. Broadband measurements were made of components that are actually mixtures themselves, and effects of illumination and shadowing, changing biomass and canopy geometry were not fully quantified, although they were controlled for, to some extent. Even in cases where the components were determined to be significantly different based on statistical analysis of field samples, it may not be possible to accurately retrieve the contribution of these components to a spatially averaged reflectance measurement via multiple regression, factor analysis, or some other spectral unmixing technique. Because there is variance in the component reflectances, and because reflectance and "contribution" (projected cover) are measured with error, it may be difficult to accurately resolve the contribution of two components with similar reflectance using a limited number of bands. Further, when a canopy model is inverted based on satellite radiometric measurements, the contrast between average component reflectances measured on the ground may be further reduced by atmospheric scattering.

Finally, absolute calibration of reflectance measurements would be necessary if reflectance values from the literature are to be directly compared, or if they are to be used for model parameterization. In spite of these limitations, this study is useful for examining a key assumption (separability of component reflectances) of, and estimating parameters for, a simple reflectance model that can be applied to broadband imaging sensors for the inventory of semiarid vegetation resources.

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