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Assessing the relationship between spectral vegetation indices and shrub cover in the Jornada Basin, New Mexico

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Abstract. We assessed the statistical relations between spectral vegetation indices (SVIs) derived from SPOT multi-spectral data and semi-arid shrub cover at the Jornada LTER site in New Mexico. Despite a limited range of shrub cover in the sample the analyses resulted in r^2 values as high as 0·77. Greenness SVIs (e.g., Simple Ratio, NDVI, SAVI, PVI and an orthogonal Greenness index) were shown to be more sensitive to shrub type and phenology than brightness SVIs (e.g., green, red and near-infrared reflectances and a Brightness index). The results varied substantially with small-scale changes in plot size (60 m by 60 m to 100 m by 100 m) as a consequence of landscape heterogeneity. The results also indicated the potential for the spectral differentiation of shrub types, and shrubs from grass, using multi-temporal, multi-spectral analysis.

1. Introduction

In the Jornada Basin of southern New Mexico landscape degradation has occurred as a result of drought and overgrazing (Schlesinger *et al.* 1990). Perennial grasslands have been replaced by xerophytic shrub communities dominated by mesquite (*Prosopis glandulosa*), creosotebush (*Larrea tridentata*) and tarbush (*Florensia cernua*) (Buffington and Herbel 1965, York and Dick-Peddie 1969, Schlesinger *et al.* 1990). Invasive shrub cover in the Jornada Basin has been correlated with degradational effects including increased erosion, changes in soil texture and decreases in soil nutrient status and water-holding capacity (Schlesinger *et al.* 1990). Scientists working within the framework of the National Science Foundation's Long Term Ecological Research (LTER) (Franklin *et al.* 1990) project at the Jornada are attempting to model this vegetation change in the Basin.

One of the goals of the Jornada LTER project is to couple ground-based ecological studies with the large area, high temporal resolution monitoring capabilities offered by satellite remote sensing. An approach towards achieving this goal is to investigate the relationship of spectral vegetation indices (SVI) derived from satellite data to surface vegetation parameters using correlation or regression analysis (Richardson and Weigand 1977, Tucker *et al.* 1985, Tucker and Sellers 1986, and others). This type of study can lead to the development of site-specific methods for estimating vegetation parameters and enable long-term monitoring (Graetz *et al.* 1988). However, the research to date has concentrated on large-area estimates of vegetation parameters (Musick 1984, Foran 1987, Graetz *et al.* 1988). In the Jornada Basin, net primary production, soil moisture and nutrients and other properties are being monitored within fifteen 70 m by 70 m permanent plots. Therefore, it would be useful to develop predictive relationships between satellite data and surface parameters at a finer spatial scale than has been attempted in previous studies.

Our objective was to assess the relationship between spectral vegetation indices (SVIs) derived from high spatial resolution satellite data and the shrub cover fraction of the three dominant invasive shrub types of the Jornada study area. Data were acquired in the multi-spectral mode by the High Resolution Visible (HRV) sensor of the Système Pour l'Observation de la Terre (SPOT) satellite. The SPOT satellite acquires spectral radiance data in three wavebands (green, red and near-infrared) at 20 m resolution, and has pointable viewing optics allowing for increased temporal resolution and a greater likelihood of obtaining cloud-free coverage (which can be problematic even in semi-arid areas). The relationship between SPOT spectral radiance data and shrub cover proportions was examined using SVIs.

2. Background

Two types of SVIs, greenness and brightness, have been investigated for their utility in estimating vegetation parameters in semi-arid areas. Greenness-type SVIs that are commonly correlated with vegetation cover or amount are derived from mathematical combinations of red and NIR (near-infrared) waveband radiances (Tucker 1979, Curran 1980, Jackson 1983, Ustin *et al.* 1986, and others). Green vegetation absorbs radiant energy for photosynthesis in the visible wavelengths (particularly in the red band) and reflects highly in the NIR as a function of plant structure and moisture content (Sellers 1985). Greenness SVIs include the Simple Ratio (NIR/RED), the Normalized Difference Vegetation Index ($NDVI = (NIR - RED)/NIR + RED$), where RED and NIR are spectral radiance or reflectance values), and othogonal-type indices such as the Kauth–Thomas Greenness Index (Kauth and Thomas 1976) and the Perpendicular Vegetation Index (PVI) (Richardson and Weigand 1977). McDaniel and Hass (1982) found that the Simple Ratio, and the Kauth–Thomas Greenness Index derived from Landsat-MSS data were highly correlated with green vegetation cover in a mesquite-grassland landscape ($r = 0{\cdot}945$ and $0{\cdot}933$, respectively; $n = 96$, 24 sites sampled on four dates). Foran (1987) utilized mean values from 23 large sites (with a minimum size of 2000 79 m by 57 m Landsat pixels) dominated by xerophytic shrubs and annual grasses, and found that the Simple Ratio was highly correlated ($r^2 = 0{\cdot}9$, $p < 0{\cdot}01$) with total plant cover. Both these studies cited the homogeneity in the soil background of their study sites as contributing to the high correlation coefficients (i.e., the variance in vegetation cover was the dominating influence on the radiative response of the sample plots).

Other studies have found the use of greenness SVIs to be problematic in semi-arid regions due to low vegetation cover and highly reflective and variable soils (Curran 1980, Graetz and Gentle 1982, Heilman and Boyd 1986, Williamson 1989). Huete (1988) found neither the NDVI nor the PVI to yield consistent estimations of vegetation amount under conditions of incomplete canopy cover and variable soil background. Incomplete canopies scatter a portion of the incoming NIR radiation towards the soil, which is subsequently reflected back to the sensor and is thus dependent on soil optical properties (Huete 1987). Huete (1988) found that the Soil Adjusted Vegetaion Index (SAVI) accounted for first-order soil–vegetation interactions better than the NDVI or PVI. The SAVI incorporates a correction factor into the NDVI equation that varies with the density of the vegetation ($SAVI = [(NIR - red)/(NIR + red + L)] \times (L + 1)$, where L is a correction factor varying from $0{\cdot}0$ to $1{\cdot}0$).

Brightness-type SVIs exploit the fact that even low levels of vegetation cover can result in a significant darkening of the typically bright soils in semi-arid areas due to shadowing and absorption by leaves and stems (Ringrose *et al.* 1989, Tueller and Oleson 1989). Brightness SVIs are therefore related to surface albedo and include single waveband radiances or reflectance factors, or band combinations that are weighted to emphasize soil reflectance (e.g., the Kauth–Thomas Brightness Index). Graetz and Gentle (1982), Pech *et al.* (1986) and Graetz *et al.* (1988) found that spectral radiance in the Landsat-MSS red waveband was an effective estimator of vegetation cover for a saltbush region of southern Australia. Ringrose *et al.* (1989) came to a similar conclusion when assessing a drought-impacted semi-arid savanna woodland environment in Botswana.

Musick (1984) correlated both greenness and brightness SVIs with vegetation parameters in the Jornado Basin using Landsat-MSS data. The results indicated that the strength of the correlations varied according to SVI type, particular SVI within the two types (NDVI versus PVI within the greenness SVIs, for example), time of year (phenological stage) and the tested vegetation parameter. For example, red band correlations (a brightness-type index) with total cover were significant and inverse for both the June and September test dates ($r = -0{\cdot}78$ and $-0{\cdot}84$, respectively). However, NDVI correlations (a greenness-type index) with the same parameter were significant and positive only in September when both grasses and shrubs were green ($r = 0{\cdot}69$). Correlations of the two SVI types with grass cover were similar to those for total cover with respect to date and the magnitude of the correlations. However, correlations with mesquite and snakeweed cover (the only shrub variables explicitly tested) were significant only in June and only with greenness-type SVIs.

3. Research questions

The following research questions were addressed in an effort to develop methods for quantifying semi-arid shrub cover from SPOT-derived SVIs:

1. Which SVIs correlate significantly with shrub cover in the study area?
2. What effect does shrub type and shrub phenology have on the relationship between shrub cover and SVIs, i.e., is prior stratification by shrub type a necessary step?
3. What effect does the size of the sampling units have on the correlations, i.e., what is an appropriate plot size to develop correlations between SVIs and proportional cover?
4. What is the effect of varying grass cover proportions on the shrub cover relationships?

4. Study area

The study area was located within the U.S. Department of Agriculture Jornada Experimental Range and the New Mexico State University College Ranch, approximately 40 miles north of Las Cruces in south-central New Mexico (figure 1). The Range is part of the Jornada Basin, considered to represent the northernmost extent of the Chihauhaun Desert. The basin is defined by the San Andres Mountains to the east, the Dona Ana Mountains to the south-west and Point of Rocks to the north-west. A string of small playas and drainageways with silty-clay texture mark the northwest–southeast axis of the basin (Warren and Hutchinson 1984). Mean annual

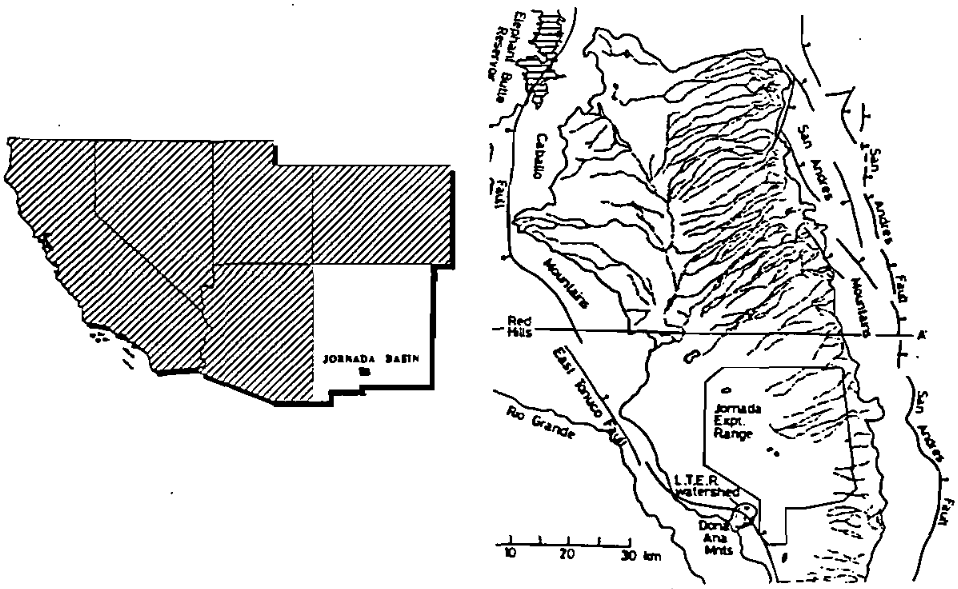

Figure 1. Location map of Jornada Basin. The Jornada Basin is located in southern New Mexico. The figure on the right outlines the Jornada Basin with the Jornada Experimental Range delineated in the lower portion of the figure. Study plots were located within and immediately adjacent to the Experimental Range.

temperature is 15·6°C and mean precipitation is 21 cm per year, with more than 50 per cent of the precipitation occurring from July to September (Schlesinger *et al.* 1990).

The timing of vegetation (shrubs, grasses and forbs) leaf-out and green-up in the region is quite variable while the distribution of shrub species is somewhat dependent on substrate. For example, the evergreen creosotebush grows predominantly on gravelly uplands. Both mesquite and tarbush are deciduous shrubs which drop their leaves with the first frost in November–December. Mesquite, the dominant shrub on sandy soils begins leafing out in March–April, reaching peak green biomass in June. Tarbush, growing on the silty bottomlands begins leaf growth later in March, reaching its peak in September. Perennial and annual grasses and forbs follow a cycle of growth and senescence tied to the winter and late summer rainfall which is highly variable both temporally and spatially (Kemp 1983, Warren and Hutchinson 1984).

5. Methods

5.1. *Data acquisition and processing*

Three SPOT HRV XS digital images were acquired over the study area on 10 March, 12 June and 24 September 1989. Table 1 lists the view geometry and solar elevation for each image. Vertical true colour aerial photography was acquired for the study area on 29 September 1989, within two hours of solar noon. The nominal scale of the photography was 1:2500. The aerial photographs were acquired along transects that included the LTER shrub primary productivity plots and near-by roads useful for plot location.

Table 1. View and illumination parameters for the three SPOT images acquired in 1989. View incidence is the angle from normal to the look angle at scene centre in degrees. View orientation is the complement of the angle between the centre scene line of the raw scene and the meridian through the centre of the raw scene in degrees clockwise. Solar azimuth is listed in degrees East from North. Solar elevation is the angle from the surface of the Earth to the solar position in degrees.

	View (°)		Solar (°)	
Date	Incidence	Orientation	Azimuth	Elevation
10 March	6·6 West	10·8	+150·7	48·8
12 June	7·0 East	9·9	+116·4	71·6
24 September	7·0 East	9·9	+152·2	53·9

The SPOT-XS multi-temporal data were normalized for atmospheric variations using an improved dark object subtraction technique that models atmospheric scattering as a wavelength-dependent process (Chavez 1988). The image data were corrected for variations in solar elevation, converted to spectral reflectance factor values based on calibration data provided by SPOT Image Corporation (Chavez 1989) and geographically referenced to the Universal Transversé Mercator (UTM) grid system.

5.2. *Sample plot location*

Sample plots were chosen based on three criteria: (1) our ability to accurately locate the plot on both the satellite imagery and the aerial photography, (2) to maximize spatial homogeneity of vegetation and soil and (3) to include a range of shrub cover proportions in the sample. The aim was to achieve a sample of at least 30 plots in each type that would be adequate for regression analysis. However, the choice of sample plots was limited because it was difficult to locate sites that fit the first two criteria within the limited extent of the air photo coverage. In an attempt to include a range of shrub cover amounts, sample plots were selected by using a stratified random design near the nine LTER biomass plots located in shrub-dominant areas. The LTER plots are located in areas of high, medium and low biomass within each shrub type (L. Huenneke, unpublished data). A total of 74 plots were chosen: 18 in tarbush, 25 in creosotebush and 31 in mesquite (figure 2). The LTER shrub plots were included in our sample.

Plot locations were recorded by their UTM coordinates derived from the georeferenced September SPOT image and were outlined on clear mylar overlays affixed to the photographs. Sample plots covered an area equivalent to a 5 by 5 SPOT pixel group or 100 m by 100 m (1 ha). They were subdivided into 25, 20 m by 20 m quadrats (pixels) which were also marked on the mylar overlays.

5.3. *Estimating shrub and background cover*

Shrub cover proportions were estimated from the colour aerial photographs using a dot grid method (Edinger 1983, Warren and Dunford 1986). With the aid of a zoom transfer scope, each 20 m by 20 m pixel within each sample plot was magnified and optically overlayed on gridded paper so that a regular pattern of 49 grid intersections was visible within each pixel-size area. Edinger (1983) found that

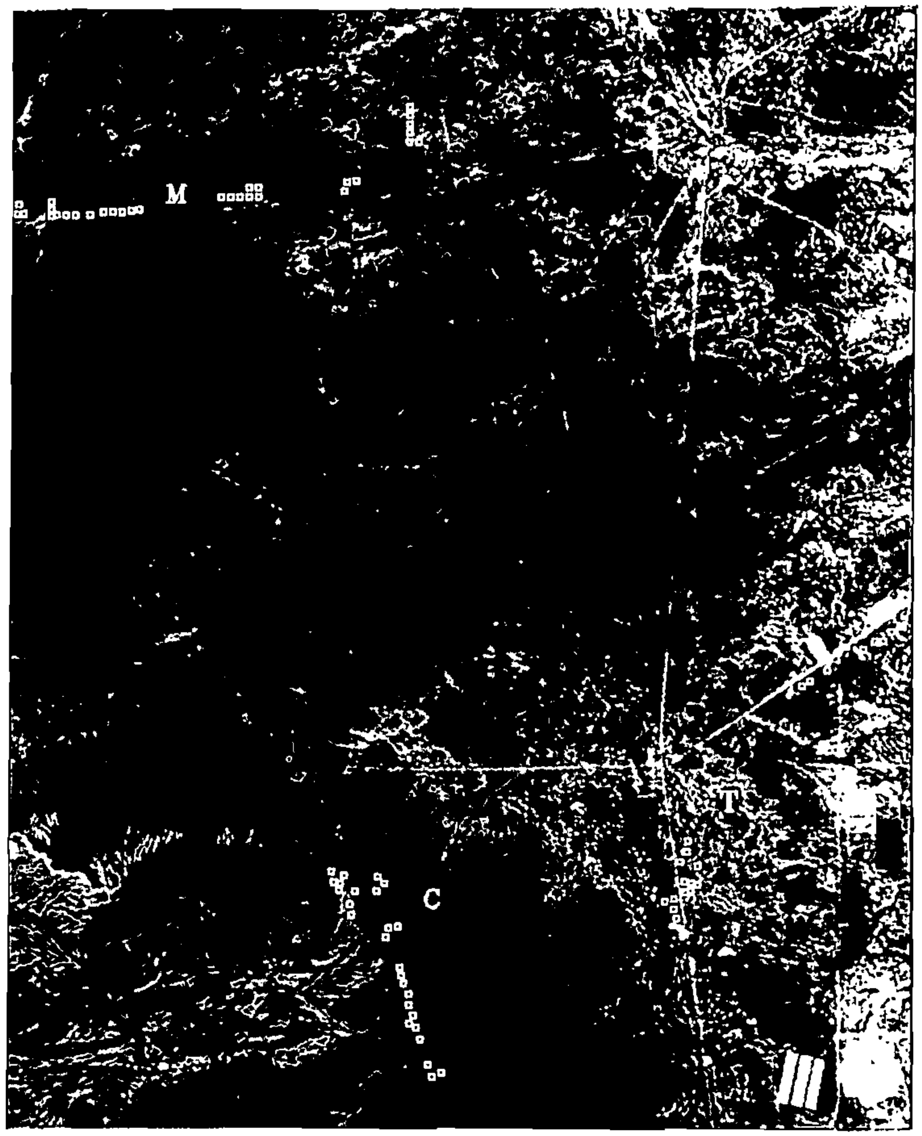

Figure 2. September SPOT XS subimage of study area with study plots outlined. The figure represents a portion of a SPOT XS false colour composite image of the Jornada Basin acquired 24 September 1989. Portions of the study area are labelled by dominant shrub type: M = mesquite, C = creosotebush, T = tarbush.

this grid density and configuration were operationally more efficient than other designs and did not result in a significant increase in the variance of cover estimates for a similar semi-arid landscape. Each pixel-size area was visually interpreted and grid intersections scored as shrub or not shrub. Shrub cover was calculated as the ratio of shrub scores to the total number of grid intersections (49). Shrub cover is thus expressed as the proportion (0–1) of the plot covered by shrub canopy, or the vertically projected canopy area not accounting for canopy overlap.

Visual examination of the aerial photography indicated that the background in the tarbush area was less homogeneous than in the creosotebush or mesquite areas. Bright, bare soil contrasted strongly with a darker soil covering. Field observations showed these dark areas were comprised of a combination of grass and dark lichen crust on the soil surface. Therefore, in the tarbush area a light or dark background category was scored when a grid intersection did not fall on a shrub. The cover of dark background was calculated in the same manner as proportional shrub cover.

Cover was also estimated in the field using ground-based transects. Five parallel 100 m transects were placed 20 m apart in each of 14 plots, 6 tarbush plots, 5 creosotebush plots and 3 mesquite plots. The type of cover (shrub by species, grass, forb, lichen or soil) was observed and recorded at 1-m increments along each transect. The proportional cover of each of these categories was determined as a percentage of the total number of points sampled in each plot ($n = 500$).

Finally, in order to determine if the estimates of dark background cover from the air photos were an accurate representation of grass cover in the tarbush plots, dark background proportions were compared to the field transect estimates of grass cover through a regression analysis. In this way a predictive equation was calculated whereby grass cover was estimated for all 18 tarbush samples plots.

5.4. *Regression analyses*

Linear least squares regression analyses were performed with spectral indices as the dependent variables and proportional shrub cover as the independent variable (i.e., shrub reflectances determine, in part, the surface radiances recorded at the satellite, see Curran and Hay 1986). In order to test the effect of small-scale changes in plot size, one complete set of regressions was run using mean values of spectral variables and shrub cover from the entire 5 by 5 pixel area plot (100 m by 100 m) described previously. Another complete set of regressions was run using means derived from the centre 3 by 3 (60 m by 60 m) area located within each 5 by 5 plot. Therefore, the factors related to plot location and selection were held constant, and the only variation tested related to the size of the area over which data were averaged. Analyses were run for each pairwise combination of shrub cover and SVI for each plot size (3 by 3, and 5 by 5) using all plots together in a pooled data set, and using plots stratified by shrub type.

The Brightness SVIs that were tested included the SPOT-derived green, red and NIR reflectance factors, and a Brightness transform calculated according to the methods described in Jackson (1983). The Greenness SVIs that were tested included the Ratio, the NDVI, the SAVI, the PVI and the Jackson (1983) Greenness transform. Three SAVI correction factors were tested, 0·25, 0·50 and 1·0, in order to evaluate the sensitivity of the SAVI correction factor to the level of shrub cover in this landscape.

The PVI and Jackson Brightness and Greenness transforms were derived from soil and vegetation spectra of the study area acquired in the field during March, June and September of 1989. A hand-held radiometer fitted with filters emulating the three SPOT bands was used to sample soil radiance at representative sites for each of the shrub communities during at least one of the three field visits in 1989. Sample radiance was converted to reflectance using samples acquired over a reflectance panel painted with barium sulphate (Franklin *et al.* 1993). There was no systematic difference in soil reflectance among the three shrub areas, therefore all the soil data were used to derive the slope of the PVI soil line projected in NIR/red spectral space

(Richardson and Weigand 1977). The green, red and NIR reflectance spectra representing a bright and dark soil sample was used to derive the Jackson Brightness transform (Jackson 1983). Jackson (1983) found that the Greenness transform (which is orthogonal to Brightness) is insensitive to the choice of vegetation spectra used in its calculation. Therefore, the sampled spectra of creosotebush was used to derive the Greenness transform used in this study.

The Jackson (1983) Brightness and Greenness SVIs were also used in a multiple regression with proportional shrub cover as the dependent variable. It was hypothesized that this approach might better account for soil reflectance variations than would the use of a greenness index alone. However, in a preliminary test the R^2 values were not greater than those involving either single index. This may be explained by the lack of significant soil reflectance variations in the sample plots, or by the variance in subshrub, grass and forb cover unaccounted for by either index. Therefore, the results of this aspect of the study are not included.

In many areas of the Jornada Basin the shrubs are the dominant cover type but in areas where shrubs are actively encroaching into grasslands, shrubs and grasses are mixed. Therefore, the effect of grass cover was examined using multiple regressions of grass cover and shrub cover against the individual SVIs for tarbush area plots.

6. Results

6.1. *Radiometric normalization and georegistration*

The effectiveness of the radiometric normalization procedures used in this study was evaluated by comparing mean reflectance values of a stable target for the three dates, in this case a 20 pixel-sized portion of a dirt road, which had been graded within two weeks prior to each image acquisition. Table 2 lists the results including the NDVI values. While differences between the March and September single band and NDVI means were minimal, the June results were substantially different. The June image included scattered pixels with obviously incorrect brightness values in one or more of the three SPOT bands. In addition, the overall brightness values were significantly higher than the other two dates, a difference that was not corrected by the adjustment for solar zenith angle included in the reflectance factor alogrithm (Chavez 1989). Differences in the June data were apparently related to satellite data

Table 2. Comparison of reflectance values among the three SPOT images calculated using the Chavez (1989) method: single band mean values and the NDVI for a stable, bright target (graded dirt road).

	Reflectance values			
Image date	Green band	Red band	NIR band	NDVI
10 March	0·16	0·24	0·32	0·143
12 June	0·20	0·30	0·38	0·110
24 September	0·16	0·24	0·33	0·158

Note: Reflectance values are in fractional units. The NDVI is a normalized index scaled from $-1·0$ to $1·0$.

transmission problems (SPOT Corporation, personal communication). It is therefore important to note that quantitative comparisons of June SVI values with March and September may be inappropriate.

The majority of studies to date have utilized mean values derived from large sample plots (Graetz and Gentle 1982, Musick 1984, Foran 1987, Graetz *et al.* 1988). This research utilized study plots on the order of 1 ha or smaller in order to evaluate problems related to linking small-scale satellite data to large-scale ground-based ecological studies. As a consequence, the level of misregistration between the satellite and ground data becomes more critical (see, for example, Townshend *et al.* 1992). The three dates of SPOT data used in this study were georeferenced to the UTM grid using 40 evenly distributed ground control points (GCP). While the root mean square (rms) difference of the GCPs to the third-order polynomial surface used for the coordinate transform was $<1\cdot5$ pixels, the level of misregistration can vary across the image. The effects of spatial misregistration, plot size and landscape heterogeneity will be addressed in a later section.

6.2. *SVI/shrub cover relationships for pooled data*

Scatterplots of a brightness SVI (red band, figure 3), and a greenness SVI (the NDVI, figure 4) versus pooled shrub cover (plots for all three shrub types combined) are effective at illustrating the differing effects of index type, shrub type, phenology and background. While there is a good deal of scatter, red band reflectance was inversely correlated with proportional shrub cover for all dates (figure 3). The consistency of this relationship is notable given the phenological differences among the shrub types on these dates. The brightness of mesquite plot data decreases relative to creosotebush data from March to June, presumably because of increased absorption and shadowing caused by mesquite leaf-out. However, the overall effect of this on the relationship is relatively small.

The outliers evident in figure 3 (particularly in September) are circled and represent data from four tarbush sample plots. These plots were substantially darker than other plots in the aerial photographs because of high grass cover. Therefore, these points were excluded from the regression analyses at this point in order to evaluate the brightness index/shrub cover relationship without the extreme influence of grass cover. The effect of grass cover will be reported more fully in a later section. With these data excluded, the r^2 values for red band data ranged from 0·27 to 0·46 for the three dates (table 3; with the four outliers excluded, all brightness SVI results were significant at the 0·001 level). The other brightness SVIs yielded consistently lower r^2 values (with the exception of the Jackson Brightness Index in September), when compared for a given date and plot size. This result is in agreement with other studies that have indicated that the spectral response of vegetation in the green and NIR wavebands is less consistent than the red band, particularly where sparse canopies are contrasted with bright soils (Graetz and Gentle 1982, Ringrose *et al.* 1989).

In contrast to the brightness SVIs, the results for the greenness SVIs varied substantially between dates (figure 4 shows the NDVI). In March, mesquite and creosotebush plots had similar NDVI values despite the fact that creosotebush is evergreen and mesquite was not in leaf. Tarbush plots, which had lower shrub cover than mesquite or creosotebush plots in the sample, were leafless and had low NDVI values in March yielding an overall r^2 value of 0·40 (table 4). Mesquite plots had

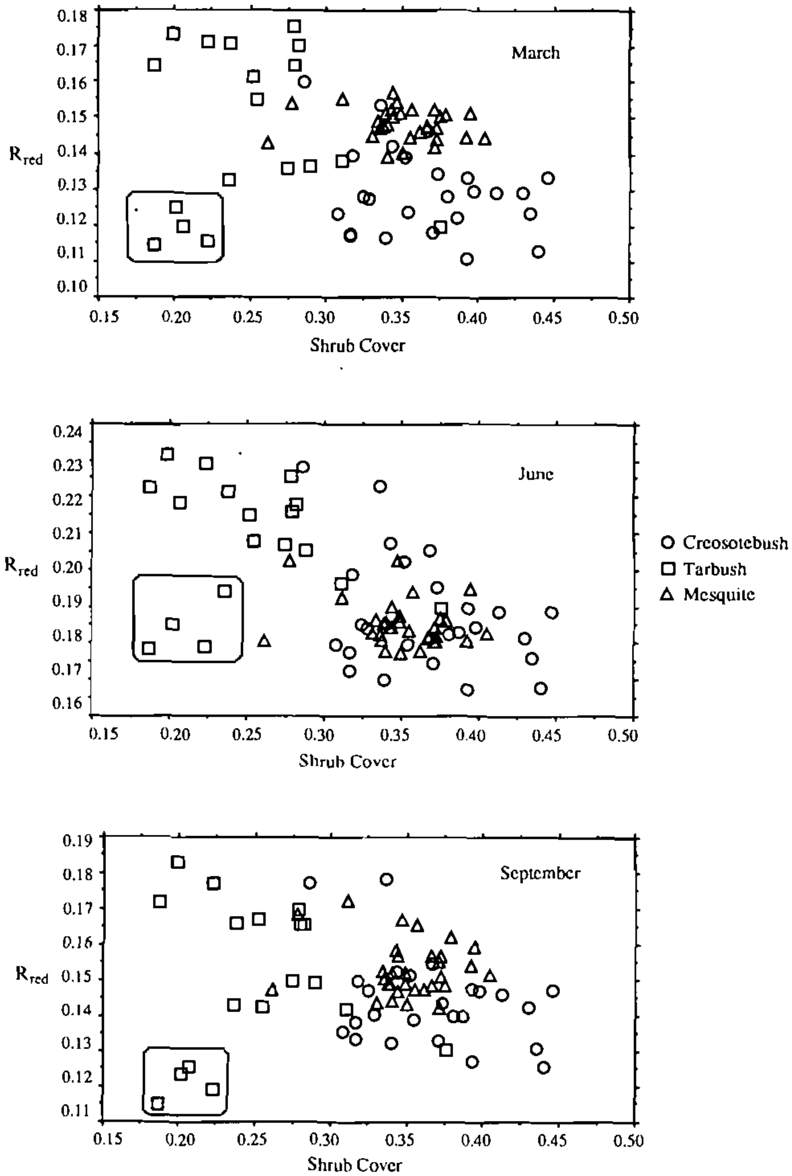

Figure 3. Red band reflectance (Rred) plotted against pooled shrub cover (creosotebush, tarbush and mesquite area data combined): March, June and September images, 100 m by 100 m plot size (5 by 5 pixels). Tarbush plots with high grass cover are outlined. Reflectance and shrub cover units are fractions of 1; $n = 74$.

significantly higher NDVI values than creosotebush plots in June. At this time of year new mesquite leaves are typically lime-green in colour and contrast strongly with the sclerophyllous creosotebush leaves. This added variance introduced by the spectral response of the mesquite plots reduced the r^2 value for the pooled data to 0·26. In September, when mesquite leaves are darker green in colour, NDVI values for mesquite and creosotebush plots were again of the same general magnitude while

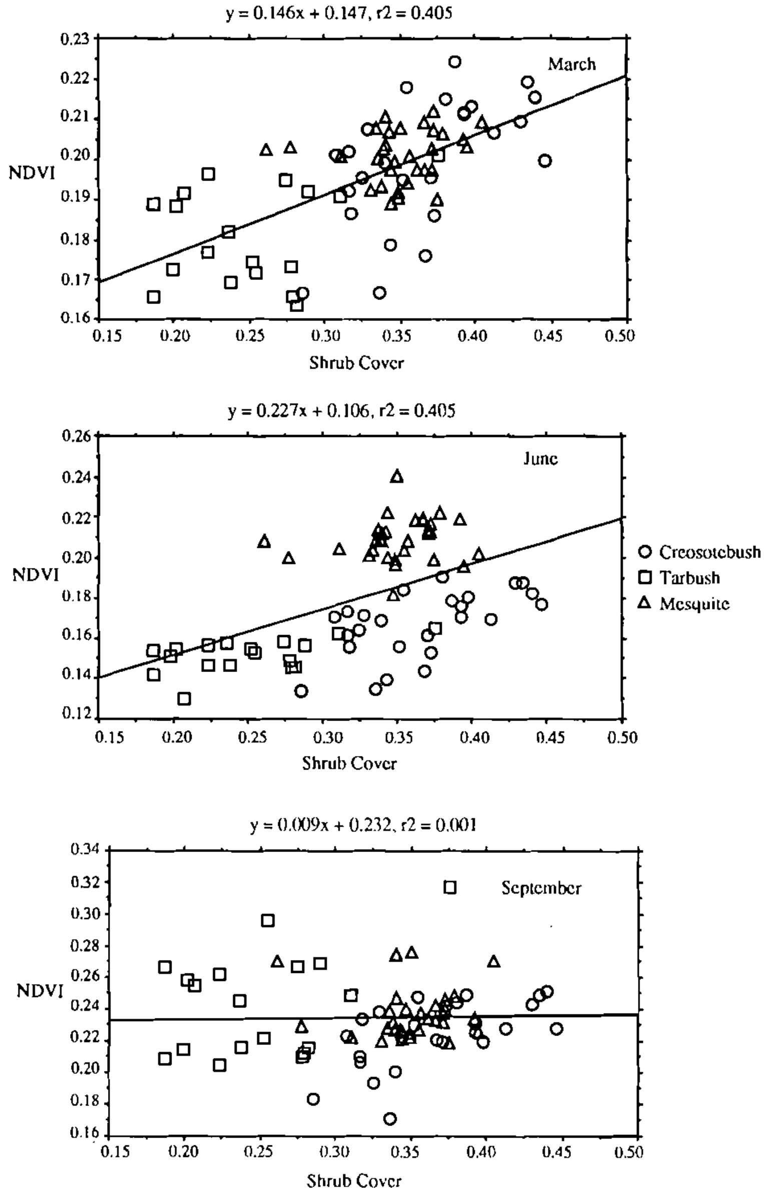

Figure 4. NDVI values regressed against pooled shrub cover (creosotebush, tarbush and mesquite area data combined); March, June and September images, 100 m by 100 m plot size (5 by 5 pixels). Shrub cover units are fractions of 1; $n=74$.

tarbush shrubs had reached maximum LAI resulting in an increase in tarbush plot NDVI values. In addition, the abundance of grass and forb green biomass was variable throughout the three shrub-dominant strata in September. The result was that none of the r^2 values were significant for greenness SVIs versus shrub cover based on September data.

Table 3. Results of regressing brightness SVIs (single band reflectances and the Jackson Brightness Index) against pooled data: three dates, two plot sizes. Pooled data are combined data from all three shrub-dominant areas. Data from four tarbush area plots were omitted due to the high grass and lichen cover ($n=70$).

	Plot size (pixels by pixels)					
	5 by 5	3 by 3	5 by 5	3 by 3	5 by 5	3 by 3
SVI	r^2 (se)		Slope		Intercept	
10 March						
Green	0·20 (0·01)***	0·17 (0·01)***	−0·09	−0·08	0·13	0·11
Red	0·30 (0·01)***	0·33 (0·03)***	−0·15	−0·15	0·19	0·20
NIR	0·16 (0·02)***	0·20 (0·02)***	−0·14	−0·15	0·26	0·26
Brightness	0·24 (0·02)***	0·27 (0·02)***	−0·22	−0·22	0·34	0·34
12 June						
Green	0·28 (0·02)***	0·12 (0·02)***	−0·13	−0·11	0·17	0·17
Red	0·46 (0·01)***	0·35 (0·01)***	−0·20	−0·16	0·26	0·25
NIR	0·24 (0·02)***	0·25 (0·02)***	−0·15	−0·15	0·33	0·33
Brightness	0·39 (0·02)***	0·36 (0·02)***	−0·26	−0·24	0·44	0·44
24 September						
Green	0·16 (0·01)***	0·15 (0·01)***	−0·09	−0·08	0·13	0·12
Red	0·27 (0·01)***	0·29 (0·01)***	−0·12	−0·13	0·19	0·19
NIR	0·20 (0·02)***	0·21 (0·02)***	−0·16	−0·14	0·29	0·30
Brightness	0·27 (0·02)***	0·29 (0·02)***	−0·21	−0·20	0·37	0·30

Significant at 0·001 level (***).

Table 4. Results of regressing greenness SVIs against shrub cover: pooled data, March and June images. Pooled data are combined data from all three shrub-dominant areas ($n=74$). None of the regressions utilizing September data were significant.

	Plot size (pixels by pixels)					
	5 by 5	3 by 3	5 by 5	3 by 3	5 by 5	3 by 3
SVI	r^2 (se)		Slope		Intercept	
10 March						
Ratio	0·41 (0·06)***	0·37 (0·07)***	0·45	0·43	1·30	1·30
NDVI	0·41 (0·02)***	0·37 (0·07)***	0·15	0·14	0·15	0·15
SAVI (0·25)	0·35 (0·02)***	0·26 (0·02)**	0·09	0·08	0·11	0·12
SAVI (0·50)	0·26 (0·02)***	0·17 (0·02)**	0·07	0·06	0·10	0·10
SAVI (1·0)	0·18 (0·01)**	0·11 (0·02)**	0·05	0·04	0·08	0·09
PVI	0·29 (0·01)***	0·33 (0·01)***	0·03	0·03	0·00	0·00
Greenness	0·18 (0·01)***	0·31 (0·01)***	0·04	0·07	0·00	−0·01
12 June						
Ratio	0·25 (0·14)***	0·10 (0·07)**	0·67	0·46	1·20	1·30
NDVI	0·26 (0·05)***	0·11 (0·05)**	0·23	0·16	0·11	0·13
SAVI (0·25)	0·21 (0·04)***	0·08 (0·04)*	0·17	0·11	0·09	0·11
SAVI (0·50)	0·19 (0·03)***	0·07 (0·04)*	0·14	0·09	0·09	0·10
SAVI (1·0)	0·17 (0·03)***	0·05 (0·04)*	0·11	0·07	0·08	0·09
PVI	0·23 (0·01)***	0·11 (0·02)**	0·07	0·05	−0·01	0·00
Greenness	0·18 (0·02)***	0·07 (0·02)*	0·08	0·06	−0·01	0·00

Significant at 0·05 level (*), 0·01 level (**), 0·001 level (***).

Table 5. Range of sampled shrub cover and coefficient of variation (CV) as a function of plot size.

	Minimum	Maximum	Range	CV (%)
Single pixels (20 m by 20 m)				
Creosote	0·14	0·69	0·55	19·9
Tarbush	0·00	0·63	0·63	32·3
Mesquite	0·10	0·59	0·49	18·7
Pooled data	0·00	0·69	0·69	22·4
3 by 3 pixels (60 m by 60 m)				
Creosote	0·29	0·45	0·16	12·3
Tarbush	0·18	0·39	0·21	20·5
Mesquite	0·26	0·43	0·17	10·9
Pooled data	0·18	0·49	0·31	19·5
5 by 5 pixels (100 m by 100 m)				
Creosote	0·29	0·45	0·16	12·3
Tarbush	0·19	0·38	0·17	19·7
Mesquite	0·26	0·41	0·15	8·6
Pooled data	0·19	0·45	0·27	18·7

Note: Proportional shrub cover was estimated from aerial photographs using the dot grid method. Shrub cover was estimated for each pixel (20 m by 20 m area) within each sample plot. Shrub cover minimums, maximums and ranges are listed as proportions. Pooled data refer to combined data from all three shrub-dominant areas.

While all the greenness SVIs varied with shrub phenology (timing of leaf-out, leaf age), the NDVI and the Ratio Index consistently yielded the highest r^2 values, particularly in March, when phenological variations were the greatest (table 4). In contrast, other studies have shown the PVI to correlate more strongly with semi-arid vegetation cover than the NDVI or Ratio Index (Richardson and Weigand 1977, Graetz *et al.* 1986).

Calculated r^2 values varied with plot size to some degree for all the tests; however, these differences were greatest for the greenness SVIs in June where the larger plot size r^2 values were consistently higher. The effect of plot size on the tested relationships will be discussed further in § 6.4.

6.3. *SVI/shrub cover relationships for data stratified by shrub type*

None of the brightness SVI/shrub cover regressions for mesquite and creosotebush data were significant. These two strata were represented by small ranges and low coefficients of variation of shrub cover in the sample, which hindered the analysis (table 5). Tarbush shrub cover, however, was strongly correlated with brightness SVIs when the four points previously described representing plots with high grass cover were excluded from the regressions (for example, $r^2 = 0{\cdot}77$, September red band, table 6, figure 5).

None of the regressions of greenness SVIs with mesquite shrub cover were significant. The mesquite strata had the lowest range and coefficient of variation of cover among the three shrub samples (table 5). However, the results involving creosotebush and tarbush data were more encouraging. As would be expected for an evergreen shrub, the relationships of creosotebush cover to greenness SVIs were relatively consistent over the three image dates with respect to r^2 value, particularly for a given index and plot size. For example, r^2 values varied from 0·32 to 0·35 for the NDVI at the 5 by 5 plot size (table 7 and see figure 6). Conversely, the greenness SVI/tarbush cover relationship varied over the three image dates. For the most part, the r^2 values increased over the three dates, coincident with tarbush leaf-out for all the tested greenness SVIs (for example, 0·29, 0·46, 0·55 for PVI in March, June and September, respectively, table 8). It is important to note that tarbush results are influenced by a single data point representing a tarbush plot with high shrub cover (figure 7).

As was the case with pooled data, the r^2 values for the NDVI and Ratio Index were generally equal to or higher than those of the PVI except for September tarbush data (tables 7 and 8). In almost all cases, the SAVI with the correction factor of 0·25 yielded the highest r^2 values among the three correction factors tested, but in only two cases was its r^2 value higher than the PVI and NDVI for a given date and shrub type. The SAVI has been found to be most effective under intermediate cover conditions (Huete 1988). The amount of shrub cover in these study plots may have been below the effective range of the SAVI.

In most cases slopes and intercepts differed between creosotebush and tarbush data for the same greenness SVI, date and plot size (tables 7 and 8). However, in only 6 of 84 cases were these differences significant (0·05 level or less). The six cases involved the PVI and Greenness indices in March, June and September, at plot sizes 5 by 5, 5 by 5, and 3 by 3, respectively. This result indicates that the relationship of greenness SVIs with shrub cover varied little with shrub type; however, there is some

Table 6. Results of regressing brightness SVIs (single band reflectances and Jackson Brightness) against shrub cover: tarbush area, three dates, two plot sizes. Data from four tarbush area plots were omitted due to high grass cover ($n=14$).

	Plot size (pixels by pixels)					
	5 by 5	3 by 3	5 by 5	3 by 3	5 by 5	3 by 3
SVI	r^2 (se)		Slope		Intercept	
10 March						
Green band	0·35 (0·05)*	0·49 (0·05)**	−0·14	−0·17	0·13	0·14
Red band	0·38 (0·08)*	0·61 (0·07)**	−0·24	−0·32	0·22	0·24
NIR band	0·36 (0·10)*	0·57 (0·09)**	−0·28	−0·36	0·30	0·32
Brightness	0·37 (0·15)*	0·58 (0·13)**	−0·39	−0·51	0·39	0·42
12 June						
Green band	0·36 (0·04)*	0·42 (0·04)**	−0·09	−0·12	0·17	0·17
Red band	0·46 (0·06)**	0·65 (0·05)***	−0·19	−0·24	0·26	0·27
NIR band	0·41 (0·07)*	0·59 (0·06)***	−0·20	−0·25	0·34	0·35
Brightness	0·43 (0·10)	0·62 (0·08)***	−0·29	−0·36	0·46	0·48
24 September						
Green band	0·45 (0·06)**	0·59 (0·04)***	−0·13	−0·18	0·14	0·15
Red band	0·50 (0·06)**	0·77 (0·05)***	−0·23	−0·33	0·22	0·25
NIR band	0·25 (0·06)	0·45 (0·05)**	−0·12	−0·15	0·38	0·30
Brightness	0·45 (0·08)**	0·72 (0·07)***	−0·27	−0·36	0·38	0·41

Significant at 0·05 level (*), 0·01 level (**), 0·001 level (***).

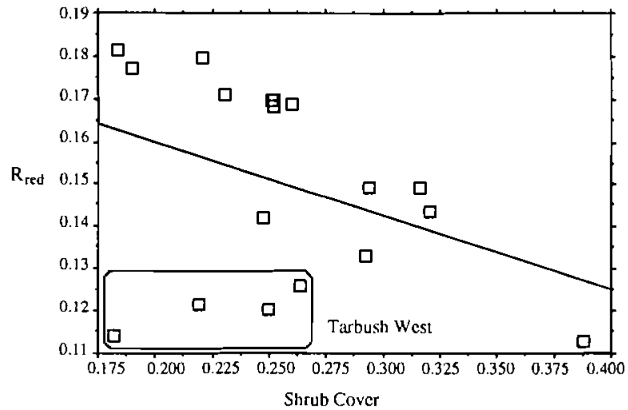

Figure 5. Red band reflectance (Rred) regressed against shrub cover: tarbush area, September image, 60 m by 60 m plot size (3 by 3 pixels). Tarbush plots with high grass cover are outlined. Reflectance and proportional shrub cover units are fractions of 1; $n=18$.

indication of a greater sensitivity among the orthogonal-type indices (PVI, Greenness) to variations in canopy architecture, leaf colour, type and condition.

6.4. *Effect of plot size*

As was the case of pooled shrub cover and greenness SVIs in June, r^2 values varied substantially with plot size for data stratified by shrub type (tables 7 and 8). For creosotebush data, the r^2 values for the 60 m by 60 m plot size data were more variable and always lower than the 100 m by 100 m values. In the case of tarbush data r^2 were higher for the smaller 60 m by 60 m data over all dates. This was also true for the tarbush results involving brightness SVIs (table 6). The major cause of the variations due to plot size in both strata was probably related to misregistration between sample plot location on the aerial photographs and the SPOT image data, and to local heterogeneity in shrub cover and background composition.

As noted earlier, many studies have incorporated the technique of averaging over large sample plots as a means of overcoming the effects of spatial misregistration between ground-based measurements and satellite measurements (Musick 1984, Foran 1987, Graetz *et al.* 1988). This technique is effective when the chosen plot size is significantly greater than the size of the spatially varying landscape features that have a significant impact on composite surface reflectance. Such was the case in the relatively homogeneous creosotebush area. However, the tarbush study area was comprised of areas of moderate to low shrub cover, areas of high grass cover and eroded, barren patches varying from 1 to 10 ha in extent. Many of the study plots were located next to, or contained portions of, barren patches and patches of high grass cover. Therefore, averaging the larger 5 by 5 plot size in the tarbush samples resulted in the inclusion of spectral noise, which did not occur for the more homogeneous creosote region.

In the case of the pooled datasets, the background differences between the creosotebush and tarbush strata effectively cancelled each other in March and September resulting in no statistical effect on the regressions. In June, mesquite area

SVI values were of a higher magnitude than that of creosotebush and tarbush data (figure 4). Possible misregistration of mesquite area data may therefore have had a greater effect on the pooled data relationships at this time resulting in the observed differences in r^2 values related to plot size (table 4). This analysis is somewhat problematic given the lack of statistically significant relationships involving the mesquite area data alone.

6.5. *Grass cover effects on the shrub cover–spectral index relationship*

The regression of dark background estimates from aerial photographs against field-estimated grass cover for six tarbush plots yielded a good linear fit ($r^2=0.95$, figure 8). The slope of 2·211 indicated a systematic overestimation of grass cover by air photo interpretation, probably due to the difficulty in distinguishing shadow and lichen from grass cover due to the scale of the aerial photographs. The regression equation was used to predict the proportional grass cover of all 18 tarbush plots. Grass cover was predicted only for the 5 by 5 plot size because the field estimates of grass cover were performed for this plot size. Grass cover predicted by the regression

Table 7. Results of regressing greenness SVIs against shrub cover: creosotebush area, three dates, two plot sizes ($n=25$).

	Plot size (pixels by pixels)					
	5 by 5	3 by 3	5 by 5	3 by 3	5 by 5	3 by 3
SVI	r^2 (se)		Slope		Intercept	
10 March						
Ratio	0·32 (0·19)**	0·18 (0·13)	0·67	0·27	1·30	1·40
NDVI	0·32 (0·06)**	0·18 (0·04)	0·20	0·09	0·13	0·17
SAVI (0·25)	0·35 (0·04)**	0·17 (0·03)	0·12	0·07	−0·10	0·12
SAVI (0·50)	0·32 (0·03)**	0·16 (0·03)	0·10	0·06	0·08	0·10
SAVI (1·0)	0·28 (0·03)**	0·14 (0·03)	0·08	0·05	0·07	0·08
PVI	0·35 (0·01)**	0·18 (0·01)	0·04	0·02	0·00	0·01
Greenness	0·23 (0·02)**	0·16 (0·01)	0·06	0·03	−0·01	0·00
12 June						
Ratio	0·35 (0·18)**	0·25 (0·16)*	0·62	0·45	1·20	1·20
NDVI	0·35 (0·06)**	0·25 (0·06)*	0·21	0·16	0·09	0·11
SAVI (0·25)	0·38 (0·04)**	0·26 (0·04)**	0·16	0·11	0·08	0·09
SAVI (0·50)	0·38 (0·04)**	0·26 (0·03)**	0·16	0·11	0·07	0·08
SAVI (1·0)	0·35 (0·03)**	0·26 (0·03)**	0·11	0·08	0·06	0·07
PVI	0·33 (0·02)**	0·23 (0·01)**	0·05	0·04	−0·01	−0·01
Greenness	0·32 (0·03)**	0·23 (0·02)*	0·08	0·06	−0·22	−0·02
24 September						
Ratio	0·36 (0·05)**	0·30 (0·24)**	0·90	0·75	1·30	1·30
NDVI	0·35 (0·08)**	0·30 (0·07)**	0·27	0·23	0·12	0·14
SAVI (0·25)	0·31 (0·06)**	0·28 (0·05)**	0·18	0·16	0·09	0·10
SAVI (0·50)	0·27 (0·05)**	0·26 (0·04)*	0·15	0·13	0·09	0·10
SAVI (1·0)	0·24 (0·05)**	0·23 (0·04)*	0·12	0·10	0·08	0·08
PVI	0·31 (0·02)**	0·28 (0·02)**	0·07	0·06	0·00	0·00
Greenness	0·31 (0·02)**	0·28 (0·02)**	0·08	0·07	−0·01	0·00

Significant at 0·05 level (*), 0·01 level (**), 0·001 level (***).

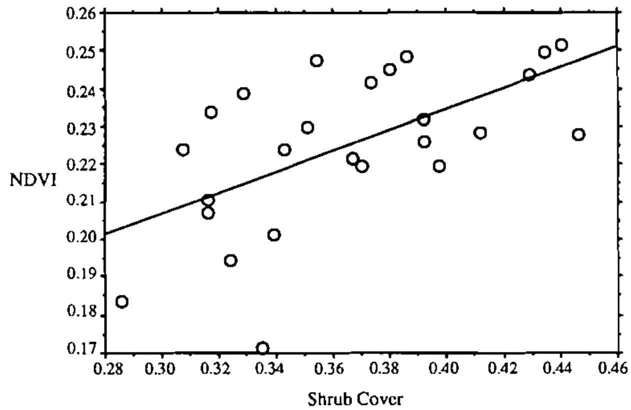

Figure 6. NDVI values regressed against shrub cover: creosotebush area, September image, 100 m by 100 m plot size (5 by 5 pixels). Proportional shrub cover units are fractions of 1; $n=25$.

Table 8. Results of regressing greenness SVIs against shrub cover: tarbush area, three dates, two plot sizes ($n=18$).

	Plot size (pixels by pixels)					
	5 by 5	3 by 3	5 by 5	3 by 3	5 by 5	3 by 3
SVI	r^2 (se)		Slope		Intercept	
10 March						
Ratio	0·06 (0·18)	0·30 (0·20)*	0·18	0·52	1·40	1·30
NDVI	0·06 (0·06)	0·29 (0·07)*	0·06	0·17	0·17	0·14
SAVI (0·25)	0·22 (0·02)	0·25 (0·03)*	0·05	0·06	0·12	0·12
SAVI (0·50)	0·13 (0·02)	0·08 (0·03)	0·04	0·03	0·10	0·10
SAVI (1·0)	0·07 (0·03)	0·01 (0·03)	0·03	0·01	0·09	0·09
PVI	0·01 (0·03)	0·29 (0·01)*	0·01	0·03	0·06	0·00
J. Greenness	0·24 (0·01)*	0·29 (0·03)*	0·02	0·04	0·01	−0·01
12 June						
Ratio	0·26 (0·10)*	0·48 (0·09)**	0·23	0·33	1·30	1·30
NDVI	0·26 (0·04)*	0·48 (0·03)**	0·08	0·12	0·13	0·12
SAVI (0·25)	0·34 (0·02)*	0·49 (0·02)**	0·07	0·07	0·11	0·11
SAVI (0·50)	0·31 (0·02)*	0·36 (0·02)**	0·06	0·06	0·10	0·10
SAVI (1·0)	0·24 (0·02)*	0·20 (0·02)	0·05	0·04	0·09	0·09
PVI	0·23 (0·01)*	0·46 (0·01)**	0·02	0·03	0·00	−0·01
J. Greenness	0·30 (0·01)*	0·40 (0·01)**	0·03	0·04	−0·01	−0·01
24 September						
Ratio	0·16 (0·55)	0·48 (0·58)**	0·97	2·21	1·40	1·10
NDVI	0·15 (0·15)	0·47 (0·15)**	0·25	0·57	0·18	0·10
SAVI (0·25)	0·28 (0·09)*	0·55 (0·09)**	0·23	0·41	0·13	0·08
SAVI (0·50)	0·33 (0·08)*	0·57 (0·07)**	0·22	0·34	0·11	0·07
SAVI (1·0)	0·36 (0·06)*	0·56 (0·06)**	0·19	0·28	0·09	0·07
PAVI	0·28 (0·03)	0·55 (0·03)**	0·09	0·14	0·01	−0·01
J. Greenness	0·30 (0·04)*	0·55 (0·04)**	0·10	0·15	0·01	−0·01

Significant at 0·05 level (*), 0·01 level (**), 0·001 level (***).

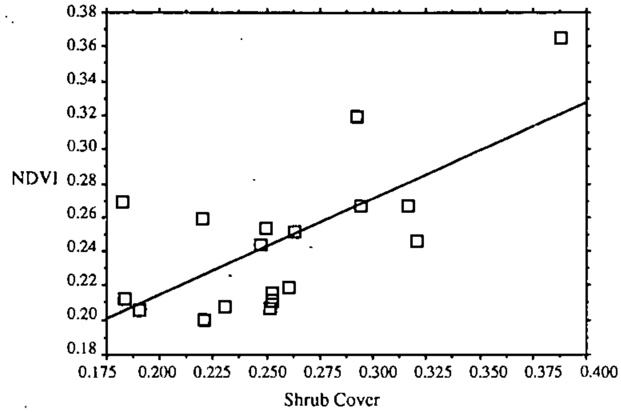

Figure 7. NDVI values regressed against shrub cover: tarbush area, September image, 60 m by 60 m plot size (3 by 3 pixels). Proportional shrub cover units are fractions of 1; $n=18$.

model was uncorrelated with shrub cover ($r=-0{\cdot}186$), and the two cover variables were used in a multiple regression against the SVIs.

The adjusted r^2 values resulting from the multiple regression were high for both index types but less so in June (table 9). For example, the red band r^2 values for March, June and September, were 0·68, 0·40 and 0·69, respectively, while the corresponding NDVI values were 0·61, 0·20 and 0·72. An examination of the coefficients for shrub and grass cover for greenness SVI data indicated that these results may be related to the variable green-up of tarbush shrubs and grass.

Correlations between greenness SVIs and vegetation cover would be expected to increase as the ratio of green biomass to woody or senescent material increases. The shrub cover standardized coefficients from the greenness SVI multiple regressions all increased in significance and magnitude over the three dates, indicating the effect of

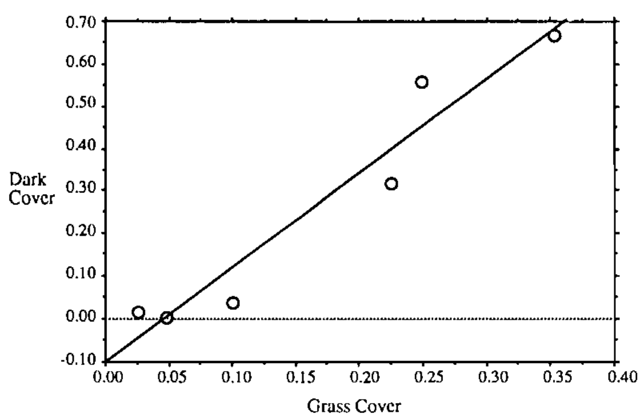

Figure 8. Field estimates of proportional grass cover regressed against proportional dark background estimates for six tarbush plots (100 m by 100 m plot size). Grass cover (x axis) was estimated in the field using cover transects. Dark background cover (y axis) was estimated from aerial photographs using the dot grid method.

Table 9. Results of a multiple regression of SVIs against shrub cover and predicted grass cover: tarbush area, three dates ($n = 18$).

			Shrub	Pred. grass
SVIs	r^2	Adj. r^2	Std. Coef. (se)	Std. Coef. (se)
10 March				
Green	0·61	0·56	−0·25 (0·04)	−0·79 (0·01)***
Red	0·72	0·68	−0·19 (0·06)	−0·87 (0·02)***
NIR	0·70	0·66	−0·15 (0·08)	−0·85 (0·03)***
Brightness	0·70	0·66	−0·17 (0·11)	−0·85 (0·04)***
Ratio	0·66	0·62	0·40 (0·11)*	0·79 (0·04)***
NDVI	0·66	0·61	0·39 (0·03)**	0·78 (0·01)***
SAVI (0·25)	0·46	0·21	0·47 (0·02)	0·02 (0·01)
SAVI (0·50)	0·31	0·22	0·27 (0·02)	−0·44 (0·01)
SAVI (1·0)	0·45	0·37	0·14 (0·02)	−0·63 (0·01)**
PVI	0·65	0·61	−0·08 (0·02)	−0·82 (0·01)***
Greenness	0·52	0·27	0·52 (0·01)*	0·19 (0·00)
12 June				
Green	0·33	0·25	−0·26 (0·04)	−0·57 (0·01)*
Red	0·47	0·40	−0·22 (0·06)	−0·69 (0·02)**
NIR	0·51	0·44	−0·13 (0·07)	−0·72 (0·03)**
Brightness	0·48	0·41	−0·17 (0·10)	−0·70 (0·04)**
Radio	0·31	0·21	0·55 (0·10)*	0·22 (0·04)
NDVI	0·30	0·20	0·54 (0·02)*	0·21 (0·01)
SAVI (0·25)	0·36	0·27	0·55 (0·02)*	−0·15 (0·01)
SAVI (0·50)	0·42	0·34	0·48 (0·02)*	−0·34 (0·01)
SAVI (1·0)	0·47	0·40	0·40 (0·02)	−0·49 (0·01)*
PVI	0·50	0·44	0·57 (0·01)**	0·54 (0·00)*
Greenness	0·30	0·21	0·53 (0·01)*	−0·08 (0·01)
24 September				
Green	0·64	0·59	−0·17 (0·04)	−0·81 (0·02)***
Red	0·72	0·69	−0·16 (0·06)	−0·87 (0·02)***
NIR	0·52	0·45	0·16 (0·09)	−0·67 (0·04)**
Brightness	0·52	0·57	0·01 (0·11)	−0·78 (0·04)**
Ratio	0·74	0·71	0·55 (0·32)***	0·78 (0·12)***
NDVI	0·76	0·72	0·53 (0·08)**	0·80 (0·03)***
SAVI (0·25)	0·64	0·59	0·64 (0·07)**	0·61 (0·02)***
SAVI (0·50)	0·57	0·51	0·67 (0·06)**	0·50 (0·02)*
SAVI (1·0)	0·50	0·44	0·67 (0·06)**	0·38 (0·02)
PVI	0·64	0·59	0·64 (0·03)**	0·61 (0·01)**
Greenness	0·59	0·54	0·65 (0·03)**	0·55 (0·01)**

Significant at 0·05 level (*), 0·01 level (**), 0·001 level (***).

shrub leaf-out. The corresponding grass coefficients were lower in magnitude and/or significance in June than in either March or September. This may have been the result of greater variance in the ratio of green to senescent grass in June. In September, grass cover coefficients were high which is consistent with greater grass cover and overall greenness.

The correlations between the PVI and shrub and grass cover were not significantly greater than were those involving the NDVI or Ratio. In fact, the empirical relationship between shrub and grass cover and the NDVI or Ratio Index was strong even in March, when the shrubs were without leaves and the grass was senescent. However, only the PVI standardized coefficients exhibited a change in sign and an increase in magnitude over the growing season for both shrub and grass cover. Therefore, the PVI may have been a better indicator of the presence of green biomass in the tarbush area than the NDVI or Ratio.

7. Conclusions

The results of our study indicated a high degree of correlation between SVIs derived from SPOT multi-spectral data and shrub cover in the Jornada study area for a number of cases, with r^2 values as high as 0·77. However, many of the correlations were not significant or resulted in low r^2 values, particularly those involving data stratified by shrub type where samples had low shrub cover variance. A limited cover range has been shown to negatively affect correlations between satellite data and vegetation cover (for example, Girard *et al.* 1990). Clearly, regression models capable of predicting shrub cover in the Jornada with acceptable levels of accuracy need to be parameterized and validated over a full range of shrub cover amounts.

In an effort to use a plot size commersurate with field-based ecological process studies, a new source of variance was introduced, i.e., plots were small enough that the spatial pattern of the vegetation affected the results. Many previous researchers avoided this problem through large-area averaging. These results indicate that the choice of plot size (and satellite spatial resolution) should be made explicitly in conjunction with information about surface heterogeneity. This could be facilitated through the increased use of geostatistics, e.g., the semivariance, in determining experimental design (Woodcock *et al.* 1988 a,b). Further, the georegistration of satellite data could be improved through the use of global positioning systems (GPS) increasing the utility of fine-scale satellite data.

Our results indicate that stratification by shrub type may not be a necessary or advisable step in the development of spectral models of shrub cover involving greenness or brightness-type SVIs in the Jornada. However, the results involving June data and greenness SVIs indicated a clear spectral difference between mesquite and creosotebush shrubs possibly caused by the colour of new mesquite leaves. Shrub cover may be spectrally separable from grass cover at certain times through a growing season due to phenological differences. Therefore, a promising avenue of further research would be to explore the application of mixture models with multi-temporal satellite data to resolve the spectrally significant components of mixed pixels, i.e., soil, grass and different shrub types (Huete 1986, Smith *et al.* 1990). However, the use of multi-temporal data requires careful implementation of spatial registration and radiometric normalization techniques.

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