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Biomass Distribution Mapping Using Airborne Digital Video Imagery and Spatial Statistics in a Semi-Arid Environment

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High resolution airborne digital video image data, biomass measurements and spatial statistics were used to map above-ground biomass for the five major semi-arid plant communities in the Jornada Long Term Ecological Research (LTER) site (southern New Mexico). The two principal objectives were to determine: (1) spatial characteristics of arid shrub versus semi-arid grassland vegetation; and (2) a suitable image spatial resolution and ground sampling interval to map above-ground biomass spatial distribution for these vegetation types. The spatial characteristics of each plant community were established by analyzing digital images at varying pixel sizes using semi-variograms. As pixel size increased from 0·5 m to 16 m, little information on vegetation pattern and abundance was lost in grassland and playa grassland sites. In comparison, the pattern and abundance of vegetation became indistinct in shrubland sites once pixel size exceeded mean shrub diameter. This work illustrates the utility of variograms from remotely sensed data for two applications: (1) determining a suitable scale to examine an ecosystem's spatial structure; and (2) providing information on the spatial pattern of vegetation as an indicator of ecosystem condition in the context of a model for desertification.

Keywords: Jornada LTER, biomass, semi-variograms, sampling intervals, spatial statistics, semi-arid environment.

1. Introduction

In order to accurately map the spatial distribution of above-ground biomass using remotely sensed imagery and ground sampling techniques, vegetation structures and their scale of spatial variability should be taken into account (Woodcock and Strahler, 1987; Curran, 1988; Fortin *et al*., 1989). Vegetation structure is used here in reference to the horizontal and vertical arrangement of plant species and biomass into distinct patches. Incorporating information on vegetation structure into the design of a biomass mapping project ensures that: (1) an appropriate image spatial resolution (pixel size) is used to represent features of interest at a required scale; and (2) the number and

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spacing of ground sample points provides an accurate, unbiased measurement of the spatial distribution of biomass in the landscape that was sampled (Curran and Williamson, 1986; Atkinson, 1991).

Prior to mapping, a relationship must be established between remotely sensed data and the biophysical variable of interest at the appropriate scale, e.g. spectral reflectance and above ground biomass. Image data can then be converted to a measure of the biophysical variable calibrated from field data. In this paper, field biomass measurements have been made in conjunction with image acquisition overflights and we assume that a positive relationship exists between the Normalised Difference Vegetation Index (NDVI) and above-ground live biomass. This relationship is expected to be similar to one already established in this environment between NDVI and vegetation cover (Duncan *et al.*, 1993; Franklin *et al.*, 1993).

One of the principal remote sensing objectives in the Jornada Long Term Ecological Research (LTER) project has been to examine the effect different sensors with different spatial resolutions have on the ability to determine the type, patterns and abundance of vegetation in a disturbed semi-arid environment (Duncan *et al.*, 1993). This work focused on evaluating the utility of remotely sensed data to estimate the spatial distribution of above-ground biomass from the scale of individual plants (0·5 m pixels) to the previously used scales of satellite data (30 m pixels). The results obtained provide a link between the information on the spatial distribution of biomass determined from field based sampling and remotely sensed imagery from 0·5–30 m spatial resolution.

Information on vegetation pattern and abundance can be used to define ecosystem spatial structure. This definition would be particularly useful for models of desertification and shrubland invasion in the Jornada Basin that explain changes in ecosystem spatial structure (e.g. Grover and Musick, 1990; Schlesinger *et al.*, 1990). Each model incorporates mechanisms accounting for changes from previously uniform distribution of soil water and nutrients in grasslands to more heterogeneous clustered patches where shrubs develop. Similar types of ecosystem structural changes are expected in marginal semi-arid grassland areas as a result of global climate change. Techniques are required to monitor these changes at ecosystem scales, providing quantitative data down to the scale of individual vegetation and soil patches to parameterize ecosystem models (Roughgarden *et al.*, 1991; Ustin *et al.*, 1993). Both remotely sensed and field data can be used in combination to address this problem.

The principal objectives of this study were to utilize airborne digital video imagery, field based above-ground biomass measurements and spatial statistics to determine: (1) the spatial variability of vegetation and, hence, landscape structure within the five semi-arid plant communities of the Jornada LTER site; and (2) a suitable pixel size and ground sampling interval to map the spatial distribution of above-ground biomass within each plant community. We were also interested in evaluating the utility of low cost, high spatial resolution ($<1{\cdot}0\ m^2$) airborne video for applications that would link field measurements to studies of landscape scale biophysical patterns based on satellite imagery with spatial resolution $>400\ m^2$.

1.1. STUDY AREA

The Jornada LTER project site is located in the northern portion of the Chihuahuan desert and was established to investigate desertification of grasslands in south-western New Mexico (Schlesinger *et al.*, 1990). Anthropogenic and climatic changes influenced the replacement of native grassland plant communities with three dispersed shrub

TABLE 1. Jornada LTER ADAR imagery data set, October 1991

Plant community	Sample site images**	Size of ground resolution (pixel width)
Mesquite dunes	Mesquite Well,	0·5 m
	Mesquite Rabbit,	0·5 m
	Mesquite North	0·5 m
Tarbush flats	Tarbush Taylor,	0·5 m
	Tarbush East,	0·5 m
	Tarbush West	0·5 m
Creosote bajadas	Creosote Gravel,	1·16 m*
	Creosote Caliche,	1·16 m
	Creosote Sand	1·16 m
Playa grasslands	College Playa,	0·5 m
	Small Playa,	0·5 m
	Playa Tabosa	0·5 m
Black grama grasslands	Summerford Grassland*,	1·16 m
	Basin Grassland***,	0·5 m
	IBPE Grassland	0·5 m

*These sites were flown at a higher altitude (1·16 m pixels).
**Names correspond to Jornada LTER permanent sample site names.
***A remnant grassland but with different species composition.

communities (USDA, 1980; Gibbens and Beck, 1988). Remnant grassland species occur in black grama (*Bouteloua eriopoda*) grassland areas, while other grassland species occur in playas (low lying areas that are periodically flooded). Shrubland areas occur within specific geomorphic units: tarbush (*Florensia cernua*) shrubs in flat, clay sites; mesquite (*Prosopis glandulosa*) shrubs on dunes; and creosote (*Larrea tridentata*) shrubs on bajadas (alluvial fans). To monitor primary productivity and other ecosystem characteristics of vegetation in each of these plant communities, three 70 m × 70 m sites were identified in each plant community for detailed studies by LTER scientists. In total, there were 15 sample sites in the Jornada LTER site (Table 1), i.e. three in each of the five plant communities.

1.2. BACKGROUND

Above-ground plant biomass characteristics are often estimated from remotely sensed imagery by combining pixel brightness values from two or more image bands to produce spectral vegetation indices (SVIs). Preferably, pixel brightness values used to compute SVIs have been calibrated and adjusted for illumination conditions to represent spectral reflectance. Spectral vegetation indices are more highly correlated with biomass than individual band reflectance (Jensen, 1983; Asrar *et al.*, 1989). The most commonly used index, the NDVI, was developed because of the positive correlation of near infrared (NIR) reflectance and negative correlation of red reflectance with the amount of green vegetation matter (Rouse *et al.*, 1974). The NDVI is calculated from:

$$\text{NDVI} = \frac{\text{NIR} - \text{red}}{\text{NIR} + \text{red}} \tag{1}$$

where: NIR = near infrared pixel brightness value
Red = red pixel brightness value

The relationship between NDVI and above ground biomass was established mainly in rangeland and cultivated areas (Rouse *et al.*, 1974; Asrar *et al.*, 1989). NDVI image applications for biomass mapping and temporal change assessment are reviewed by Tucker (1979), Jensen (1983, 1986), Asrar *et al.* (1989) and Duncan *et al.* (1993). The application of NDVI in semi-arid areas has been scrutinized more closely due to the differences in plant structures and physiology of these areas relative to those where the index was originally developed. Due to the discontinuous nature of green vegetation in semi-arid areas, NDVI has been found to represent cover and canopy area more directly, which in turn may be related to biomass (Graetz *et al.*, 1986; Satterwhite and Henley, 1987; Franklin and Hiernaux, 1991; Duncan *et al.*, 1993).

Previous research investigating vegetation characteristics within the Jornada LTER has been based on satellite imagery with spatial resolution elements ranging from 20 m to 80 m (e.g. Warren and Hutchinson, 1983; Musick, 1984; Duncan *et al.*, 1993; Franklin *et al.*, 1993). These authors identified soil background along with vegetation physiognomy and phenology as major controls on the spectral reflectance properties of Jornada vegetation. Duncan *et al.* (1993) found a significant correlation between spectral vegetation indices and projected crown-cover (%) in shrub-dominated areas of the Jornada LTER.

In a preliminary study, NDVI images obtained from the Airborne Data Acquisition and Registration (ADAR) system 5000 described below, were used to map spatial patterns in vegetation cover for a single sample site from each of the five major plant communities. These high resolution multi-spectral data have been used for vegetation monitoring and forestry applications (e.g. Benkelmann *et al.*, 1992a, 1992b; Van Mouwerik, 1993). Other airborne video image acquisition systems used in rangeland assessment are described in Everitt and Nixon (1985), Everitt *et al.* (1986) and Hutchinson *et al.* (1990). Due to the ADAR pixel and frame sizes used, continuous data were provided to examine spatial patterns of biomass within the field sites where field data only provided a discontinuous grid sample.

In comparison to biomass distribution maps produced from spatially interpolated field data in the 70 m × 70 m sites, the image-based maps were significantly different for most sample sites. This was especially evident in shrub dominated sites where a continuous distribution of biomass was evident in the interpolated field data maps, while NDVI images indicated a landscape with numerous discrete shrubs separated by bare ground. Hence, a more detailed assessment of each plant community's spatial characteristics was warranted to identify suitable image and ground sampling scales for mapping biomass distribution.

The semi-variogram, referred to herein as the variogram, is one of the more frequently used spatial statistical techniques now being applied in remote sensing and ecological research (Davis *et al.*, 1991; Rossi *et al.*, 1992; Simmons *et al.*, 1992). For a remotely sensed image, the variogram provides a graphical representation portraying the average variance between pixel values as a function of the distance between pixels (Curran, 1988). More detailed explanations of the assumptions and mathematics involved in calculating variograms are presented in Craig and Labovitz (1981), Cressie (1991), and in the context of remotely sensed imagery by Jupp *et al.* (1988).

Dominant scales of spatial variability in an image usually correspond to the size of scene elements (Woodcock *et al.*, 1988a, 1988b). Hence, one of the principal variogram applications in remote sensing research involves determining the size of dominant objects and patterns within the image such as plant canopies or vegetation stands (e.g. Woodcock and Strahler, 1987; Woodcock *et al.*, 1988a, 1988b; Cohen *et al.*, 1990;

Atkinson, 1993). In an ecological context, these dimensions may be linked to components of ecosystem spatial structure and their controlling processes at a specific scale (Yoder *et al.*, 1987; Cohen *et al.*, 1990; Simmons *et al.*, 1992). A second application involves defining appropriate ground sampling intervals based on the spatial variability of scene objects (e.g. Curran and Williamson, 1986; Curran, 1988; Atkinson, 1991; Simmons *et al.*, 1992).

2. Methods

To achieve the research objectives, the following four problems were assessed. First, the vegetation structural characteristics (individual plant horizontal extent, spacing and pattern) in each of the five Jornada plant communities were determined, based on analysis of their appearance in airborne scanner images and corresponding variogram form. Next, variograms from each plant community's images at increasing pixel sizes were examined to establish the image resolutions at which vegetation structures remained undistorted. Third, biomass distribution maps produced by kriging (interpolating) field-based biomass samples were compared to images of different pixel sizes. Finally, variograms were interpreted for images representing each plant community type, providing a quantitative measure of landscape structure. This information was used to determine appropriate pixel size and ground sampling intervals for mapping above-ground biomass spatial distribution.

2.1. Biomass data and processing

For each of the 15 sample sites, a non-destructive sampling scheme was used to record vegetation species and dimensions in a grid with 1 m^2 quadrats at 10 m intervals along seven adjacent, 70 m long, north–south transects (49 samples per site). These data were regressed with biomass measurements made from destructively sampled plots of the same species outside each sample site to provide species specific estimates of standing biomass in g/m^2. Each sample site's biomass and distribution of ground cover was represented by 49 samples in a 7×7 grid over a $70\ m \times 70\ m$ square.

The ground-based biomass estimates were made in September 1991 for each of the 15 sample sites approximately 1 month before the ADAR 5000 image data acquisition. The ground based and image samples were considered to represent the same vegetation conditions. Both sampling periods are from the same season and, because much of the vegetation is perennial between September and October, image changes were not expected.

Interpolation of the field sampled biomass data to produce a continuous surface was performed using the kriging option in the SURFER and GEO-EAS software packages (Englund and Sparks, 1991; Golden Software, 1992). Model variogram parameters of range and form, provided from the ADAR images for each sample site, were used in the kriging. Assumptions concerning the distributional properties of data to be interpolated and the use of variograms are explained in the analytic procedures section. Variograms were also computed from field-based biomass data using GEO-EAS software. Differences between the rasterized, field-based biomass maps and the pattern on corresponding NDVI images are identified and explained in relation to the sampling strategies used.

2.2. Image data acquisition and processing

ADAR 5000 multi-spectral digital image data were obtained for each of the three sample sites in each of the five Jornada plant communities during October 1991 at a pixel resolution of 0·5 m or 1·16 m (Table 1). All three Creosote sites and the Summerford Grassland sites were flown at a higher altitude, yielding a minimum pixel size of 1·16 m. Each ADAR image frame contained 760 × 435 pixel brightness values for blue (426–494 nm), green (521–599 nm), red (620–694 nm) and near-infrared (813–1001 nm) spectral bandwidths.

ADAR system 5000 data were collected using four charge-coupled device (CCD) cameras whose video signal was digitally captured onboard a light aircraft (Benkelmann *et al.*, 1990). The corner points of each site were marked on the ground when the images were taken, allowing their location to be identified and corresponding pixel data to be extracted. Because this was one of the first acquisitions of ADAR data the processed data was not spatially registered between image bands. Manual band-to-band registration was required for each image frame once downloaded. In most cases, the mis-registration was minimal. However, some frames were unable to be accurately registered (e.g. Figure 1(b), IBPE grassland and basin grassland, Figure 2, mesquite well and mesquite rabbit).

Each sample site's original 0·5 m (1·16 m for Creosote sites and Summerford Grassland) resolution image was regridded by bilinear interpolated averaging to pixel sizes of 1·0 m, 2·0 m, 4·0 m, 8·0 m and 16·0 m (2·32 m, 4·64 m, 9·28 m, 18·56 m and 37·12 m for Creosote and Summerford Grassland sites). This was done to examine the effect that different image spatial resolutions have on the spatial pattern of above ground biomass as indicated by NDVI variations. NDVI images for each site were then calculated at each different pixel resolution using digital numbers in Equation (1).

2.3. Analytic procedures

We utilized the following vegetation spatial characteristics to describe landscape structure in each plant community from NDVI imagery and their variograms: surface cover (continuous or discontinuous) patterns and horizontal plant structure dimensions. Surface cover referred to the presence of live and dead biomass in the sample site and its spatial form or connectedness. Pattern was the arrangement of patches or individual plants. Horizontal plant structural (arrangements of plant species and biomass) dimensions for individual plants were estimated from variogram range values for each site.

Variograms were calculated for images at each pixel size and sample site using an Image Processing Workbench (IPW) program (Frew, 1990; R. Dubayah, pers. comm.). A random sample of points at each lag distance was first generated by this program, then the pixel pairs at each lag were used to calculate semi-variance. The variogram was the appropriate measure to use as the data were assumed to meet the intrinsic hypothesis for a regionalized variable. This hypothesis requires weak second order stationarity in the data, that is, variance in the image data should only be a function of the distance between pixels. Conditions of weak stationarity, along with variogram and also kriging applications are invalidated when the local mean or variance changes over an image or sample site (Jupp *et al.*, 1988; Atkinson *et al.*, 1992). Several authors consider variograms to only provide a partial indication of dominant spatial patterns and structure (Turner *et al.*, 1991; Rossi *et al.*, 1992).

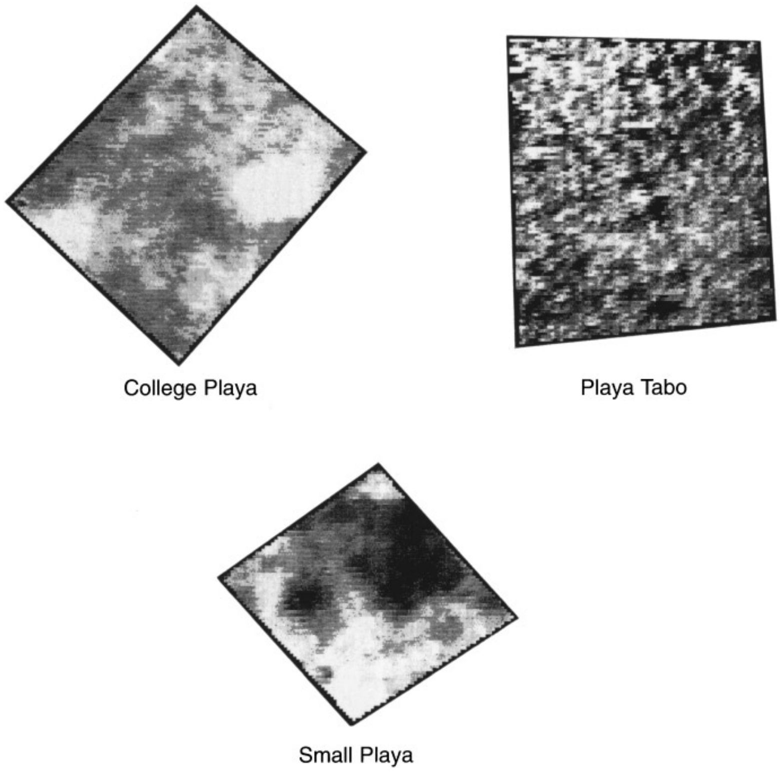


Figure 1a. Jornada LTER: Playa study sites. Pixel size = 0·5 m. Bright areas = high NDVI, dark area = low NDVI.

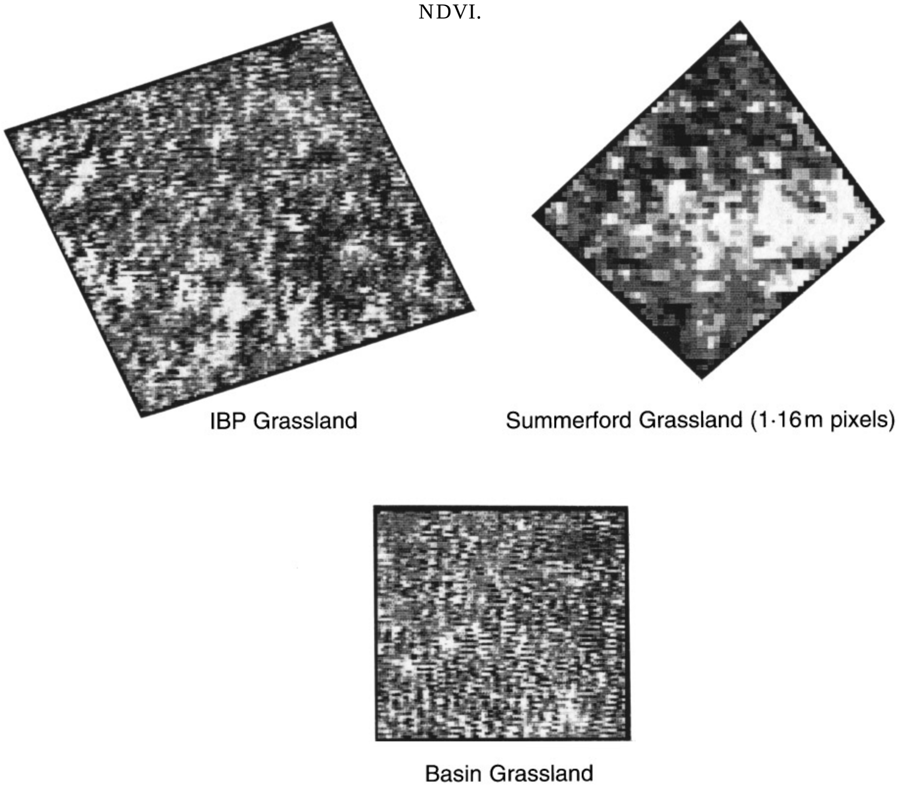


Figure 1b. Jornada LTER: Grassland study sites. Pixel size = 0·5 m.

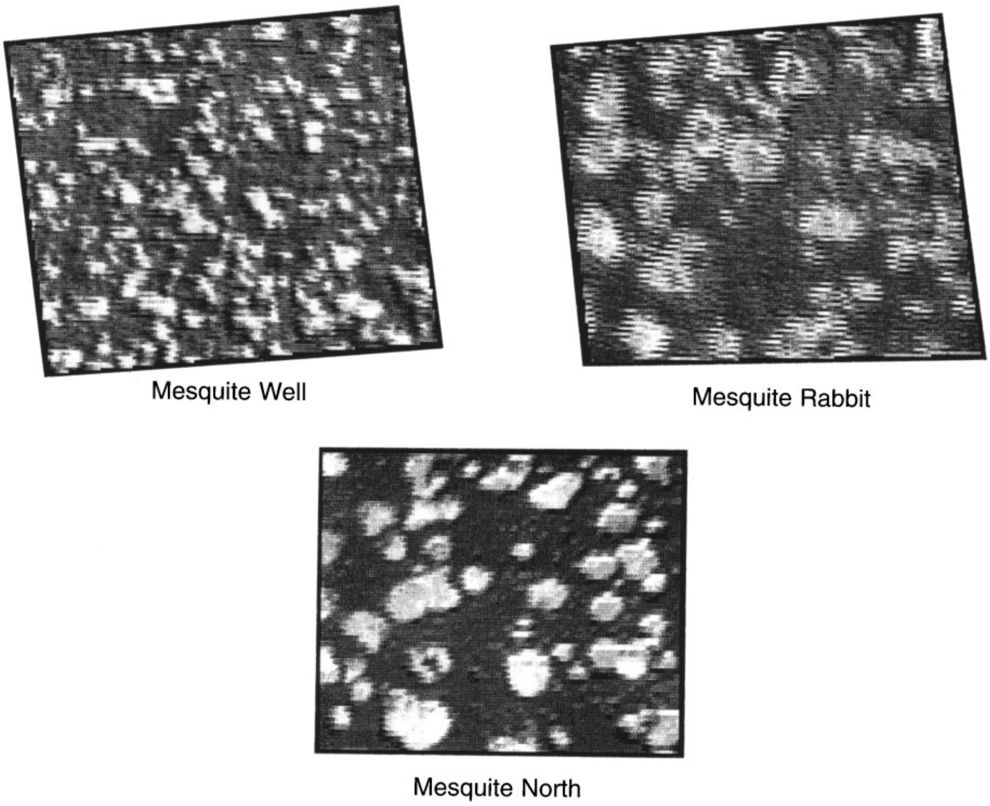


Figure 2. Jornada LTER: Mesquite dune study sites. Pixel size = 0·5 m.

Imagery and variograms for each sample site were interpreted over the range of different pixel sizes. Quantitative verification of observed changes in images was provided by interpreting the changes in corresponding variogram form. The simple scene structure in the Jornada plant communities, with either shrubs or grass on a bare soil background, enabled significant features and patterns at each pixel resolution to be identified. In addition, the resolution at which ground features were no longer spatially and spectrally discrete in the image was able to be defined from changes in variogram form. Several components of the variogram were used to quantify object dimensions and patterns, assuming a simple scene with one object and one background type:

(1) Range is related to the size of dominant objects in the scene;
(2) Height of the variogram sill is proportional to the density of objects or covered background; and
(3) Shape or form of a variogram is a function of the pattern of objects in a scene and variance distribution of scene objects.

We found the "range" of an image's variogram to be particularly diagnostic, as it represents the distance of pixel separation beyond which image features are dissimilar and below which they are similar. For example, in an image with pixels less than 2·5 m, composed of shrubs approximately 5·0 m in diameter, spaced 5·0 m apart on bare soil, variogram ranges would also be approximately 5·0 m.

Table 2. NDVI image (0·5 m pixels) spatial characteristics interpretation from all site's images and variograms

Plant community	Resolution (pixel size)	Image patterns	Plant spacing dimensions (all sites)	Variogram form			Range (m)		
				1	2	3*	1	2	3*
Black grama	0·5	Speckled (high	High NDVI pixels appear	trans	trans	—	8	15	—
grassland	1·0 (1·16)	frequency variation)	1–3 m apart	+ve	trans	+ve	—	20	—
1. Basin	2·0 (2·32)			+ve	trans	+ve	—	18	—
2. IBPE	4·0 (4·64)			+ve	trans	+ve	—	20	—
3. Summerford	8·0 (9·28)			flat	—	+ve	—	—	—
	16·0 (18·56)			+ve	—	—	—	—	—
	biomass			+ve	—	—	20	—	—
Playa grasslands	0·5	Limited variation in	Playa form evident as large,	+ve	+ve	trans	—	20	4
1. Small	1·0	playas	30–40 m wide patches of	trans	+ve	trans	15	23	5
2. College	2·0		high NDVI	trans	+ve	trans	16	28	8
3. Tabosa	4·0			+ve	+ve	+ve	—	24	—
	8·0			+ve	—	—	—	—	—
	16·0			+ve	—	—	—	—	—
	biomass			+ve	—	—	—	—	—
Tarbush flats	0·5	Linear strips of high	Shrubs are 1–3 m wide, spacing	trans	+ve	trans	5	—	13
1. East	1·0	NDVI	of 15–20 m between shrub rows	trans	trans	trans	5	20	16
2. West	2·0			trans	+ve	trans	2	20	16
3. Taylor	4·0			trans	+ve	+ve	4	—	—
	8·0			+ve	—	—	32	—	—
	16·0			flat	—	—	—	—	—
	biomass			flat	—	—	—	—	—
Mesquite dunes	0·5	Checker board	Mesquite North and Rabbit	trans	trans	trans	7	7·5	7·5
1. North	1·0	appearance	sites had 2·5–10 m shrubs,	trans	trans	trans	10	5	7·5
2. Well	2·0		Mesquite Well had 1–5 m	trans	flat	trans	10	—	8
3. Rabbit	4·0		shrubs	trans	+ve	trans	10	8	16
	8·0			trans	—	—	10	—	—
	16·0			trans	—	—	10	—	—
	biomass			flat	—	—	—	—	—
Creosote bajadas	1·16	Irregular clumps of	Linear clumps of shrubs	+ve	trans	trans	—	6·6	11
1. Sand	2·32	high NDVI	and spacing, 2–10 m wide	+ve	trans	trans	—	4·6	12
2. Gravel	4·64			trans	trans	trans	23	—	9+28
3. Caliche	9·28			trans	+ve	trans	—	—	9+28
	18·56			trans	—	—	18	—	—
	biomass			flat	—	—	—	—	—

Variogram form abbreviations: trans = transitional form with flat sill and definite range (exponential, spherical or power models may fit); +ve = linear, unbounded variogram with a positive slope, no sill or range; flat = pure nugget effect with no spatial autocorrelation.

* = numbers correspond to plant community types in the first column.

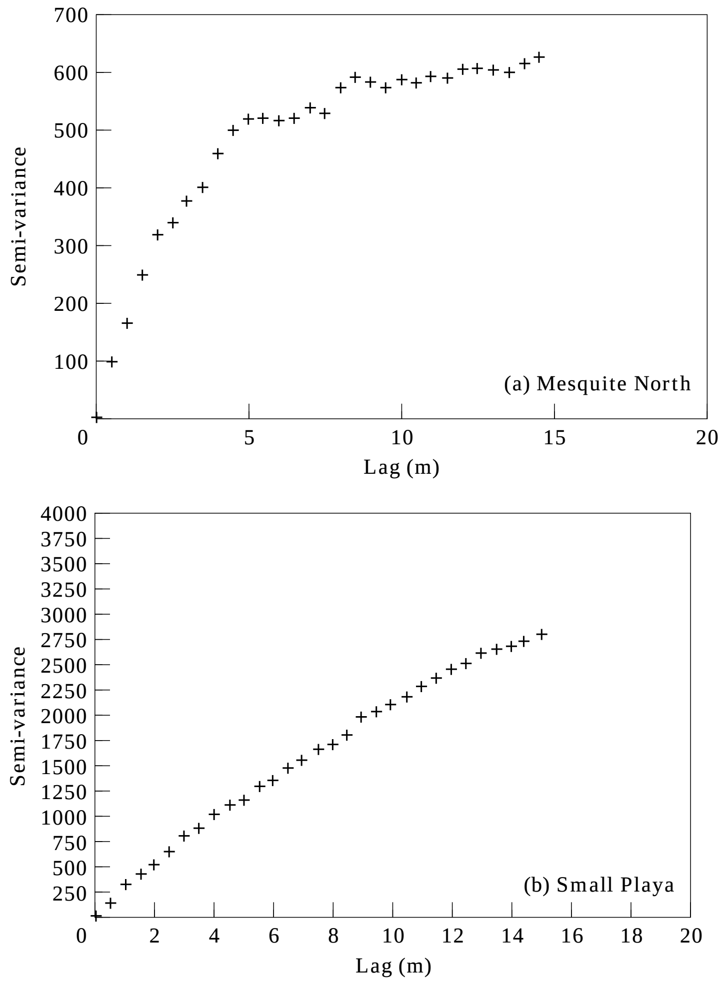


Figure 3. NDVI image variograms.

3. Results and discussion

3.1. PLANT COMMUNITY SPATIAL CHARACTERISTICS

Differences in the spatial scales and patterns of vegetation structures between the grassland, playa grassland and shrubland sites (described in Table 2) were evident in the ADAR imagery (Figures 1 and 2). Quantitative definitions of structure were provided by the form of their variograms.

According to the Jornada ecosystem desertification model (Schlesinger *et al.*, 1990) and shrubland invasion model (Grover and Musick, 1990), remnant grasslands are characterized by a uniform distribution of soil resources and therefore the spatial distribution of biomass should be uniform. This was observed in the apparent landscape structure exhibited by NDVI images for the Summerford and Basin grassland sites as well as the College and Small playa sites. Within these sites a uniform distribution of soil resources (water and nutrients) may be hypothesized to be supporting a continuous

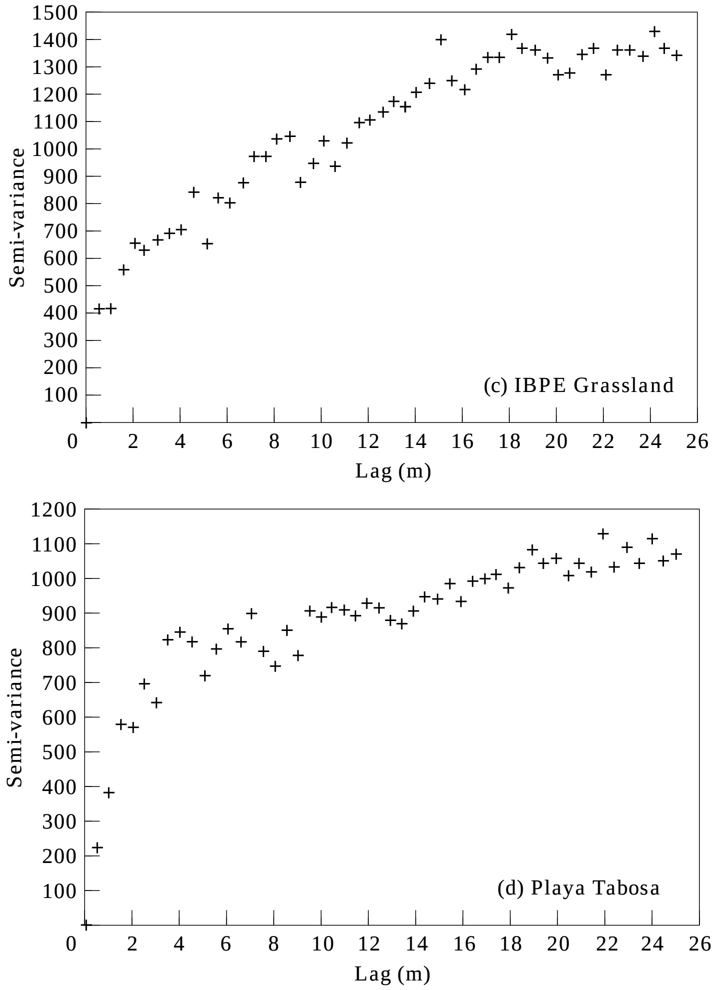


Figure 3.—*continued*

surface cover. In the playa sites the extent of grass cover may also be a function of geomorphic controls on soil characteristics and nutrients. This may occur possibly at the scale indicated by variogram ranges for these sites, 15–25 m in Table 2. The playa grasslands with different grass species exhibited a more continuous cover of high NDVI values within playa boundaries. In contrast, grassland sites exhibited high frequency variation in NDVI values, producing a speckled, highly variable image. This may indicate varying proportions of cover produced by live and dead biomass.

The Playa Tabosa and IBPE grassland sites exhibited more of a transitional variogram form, compared to the linear, unbounded forms of those described above (Figure 3). Variogram range values indicated clustering of NDVI values at different scales in each site, 4–8 m in Playa Tabosa and 15–20 m in IBPE grassland. In the case of Playa Tabosa this may represent a transition to more high frequency spatial variation in landscape structure as in the other grasslands. For the IBPE site, the clumping evident in the imagery and variogram may be due to geomorphic and edaphic controls

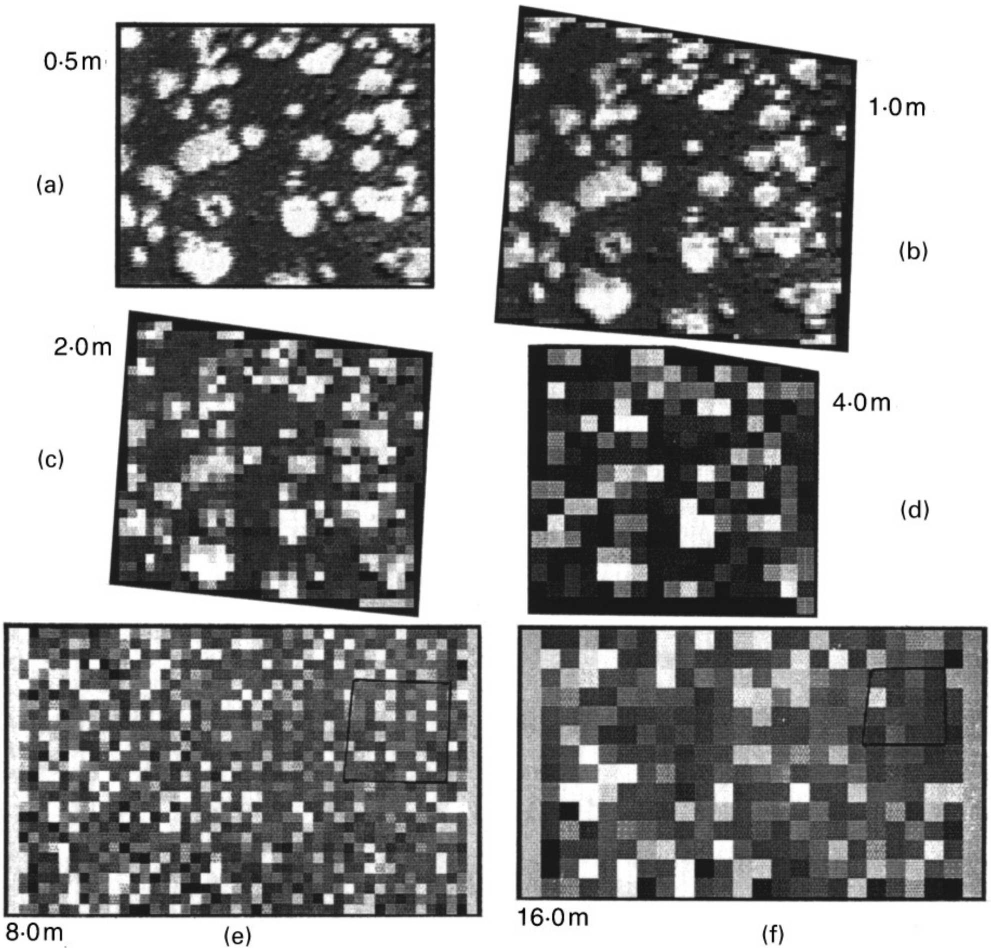


Figure 4. Mesquite North ADAR NDVI images. Bright areas = high NDVI, dark areas = low NDVI.

on soil resource distribution affecting plant distribution and growth. These effects were not present at other grassland sites.

Shrubland sites (tarbush flats, mesquite dunes, creosote bajadas) exhibited a discontinuous surface coverage with a repetitive pattern of shrubs at constant spacings (Figure 2) and show the classic "transitional" variogram form [Figure 3(a)]. Well defined shrubs of similar size, such as mesquite, produce a transitional variogram with distinct range and sill. The distinctive range and sill indicate the distance within which NDVI values are highly correlated, approximating average shrub dimensions, shrub spacing intervals and coppice dunes formed around shrubs (Table 2). For example, mesquite shrubs [Figure 2 and Figure 3(a)] have a typical diameter of 2·5–10 m, with similar spacing. Creosote shrubs in the Caliche site are small (1·0 m in diameter) with 1·0–2·0 m spacing.

Within shrubland sites, observed differences in variogram form are due to the variability in shrub size and spacing. As the variability of shrub shape and inter-shrub spacing increases, the transitional variogram becomes more rounded, e.g. Tarbush east

TABLE 3. Pixel sizes for realistic interpretation of the spatial pattern of biomass from NDVI images

Sample site image	Pixel size for accurate discrimination of NDVI patterns (m)	Pixel size beyond which NDVI patterns are undistinguishable (m)
College Playa	0·5	2·0
Small Playa	0·5	1·0
Playa Tabo	1·0	2·0
IBPE Grassland	1·0	2·0
Summerford Grassland	1·2	4·6
Basin Grassland	1·0	2·0
Mesquite Well	0·5	1·0
Mesquite Rabbit	1·0	2·0
Mesquite North	0·5	8·0
Tarbush Taylor	1·0	2·0
Tarbush East	0·5	2·0
Tarbush West	0·5	2·0
Creosote Gravel	1·2	2·3
Creosote Sand	1·2	4·6
Creosote Caliche	1·2	2·3

and taylor, Creosote gravel and caliche (Woodcock *et al.*, 1988b). Extreme variability and mixture of shrub types in a scene may explain their almost linear variograms (e.g. Creosote sand and Tarbush west). This may suggest the presence of a more even distribution of soil nutrients in some areas.

Vegetation spatial characteristics in each plant community were clearly represented in high resolution ADAR NDVI images: (1) grassland plant communities (black grama grasslands and others) exhibiting a continuous surface cover and high frequency internal variations; (2) playa grassland communities with low frequency spatial variation in a continuous NDVI cover within playa extents; and (3) shrubland plant communities exhibiting a discontinuous shrub cover with regular dimensions and spacing. These observations support the earlier hypothesis included in the Jornada desertification model of Schlesinger *et al*. (1990) that Jornada grasslands exhibit a more homogeneous spatial distribution of biomass than disturbed shrub areas.

The effects of apparent desertification on a local scale landscape structure are evident from comparisons of the shrubland sites' (Mesquite, Tarbush, Creosote) imagery and variograms to those of the playas and grasslands. Grassland and playa grasslands with uniform soil resources and continuous patterns of NDVI were typified by linear, unbounded variograms. The more arid shrublands were characterized by discontinuous, clumped NDVI patterns with transitional variogram form. Presumably, variogram range values less than 10 m are indicative of shrub diameter and inter-shrub spacing. Further field checking to measure the spatial scales of biomass distribution is required to validate these assertions and to determine the associated scales of variability of soil nutrients in the grassland and shrubland environments.

These findings indicate the utility of variograms from high resolution imagery as an indicator of changes in landscape structure. Information from the variogram may be used to define the transitional stage of a landscape in the context of the Jornada desertification model (Schlesinger *et al.*, 1990), or the shrub invasion model (Grover and Musick, 1990).

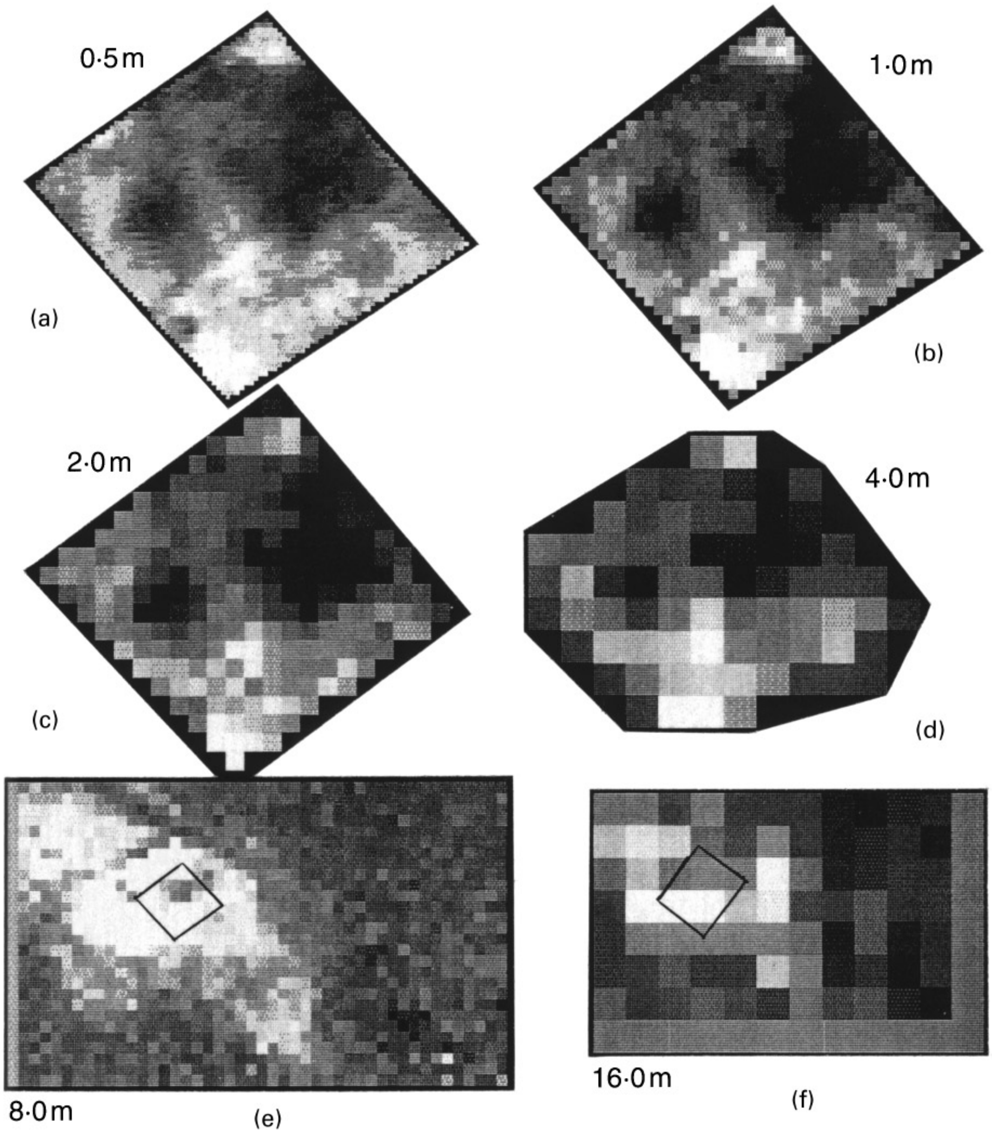


Figure 5. Small playa ADAR NDVI images. Bright areas = high NDVI, dark areas = low NDVI.

3.2. IMAGE RESAMPLING AND FEATURE DISCRIMINATION

Increasing pixel size by image resampling caused small scale features and detail (e.g. small shrubs, internal NDVI variation in shrubs) to be progressively lost. In contrast, larger, less frequently occurring features (e.g. large shrubs, geomorphological units) were retained. For images of shrubland sites (e.g. Figure 4), shrub forms and NDVI variation within a shrub were enhanced at the highest pixel resolutions. Beyond 1·0 m pixel sizes, variations within the crown became less evident. Continuing beyond the 2·0–4·0 m pixel size, shrub forms became unrecognizable. Variations in NDVI values due to spatial differences in vegetation cover, biomass and/or vigor conditions were

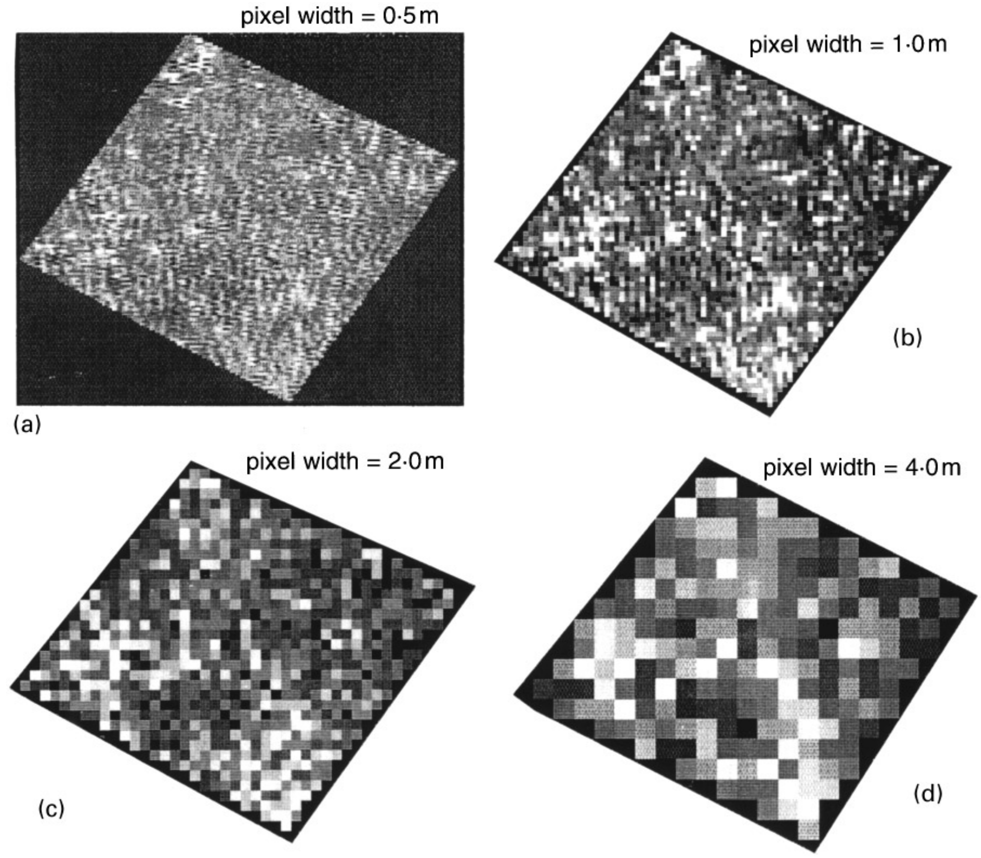


Figure 6. Basin Grassland ADAR NDVI images. Bright areas = high NDVI, dark areas = low NDVI.

evident at larger pixel sizes in the more continuously covered grassland and playa sites (Table 3). Features larger than individual shrubs in the shrubland sites were evident in these images representing bare and vegetated areas, and soil or geomorphological units were evident in the ADAR NDVI imagery up to 8 m pixel sizes (e.g. Figure 5).

Observed changes in each site's variogram characteristics at increasing pixel sizes indicated a decrease in NDVI variability. The variograms most representative of changes observed are shown in Figure 7. For sites containing shrubs, the form of the variogram was preserved at each pixel size until a rapid change occurred beyond the scale where features became uninterpretable (e.g. 4·0 m pixels in Figure 7). Smoothing or loss of detailedfeatures, reducing the range of NDVI detail in the image was indicated by the lowering of the sill (maximum variance) as regional variance decreased. In contrast, the variogram form for most grassland and playa grassland sites remained linear [e.g. Figure 3(b)] at all pixel sizes as overall landscape structure was retained (Figure 6). These results indicate that in grassland and playa grassland plant communities, information on the larger scale spatial distribution of vegetation (e.g. patches) was preserved as image resolution was increased. In shrublands, information was lost once the pixel size exceeded the average size of the shrubs. These results are consistent with principles established by Woodcock and Strahler (1987) and Woodcock *et al*. (1988a,

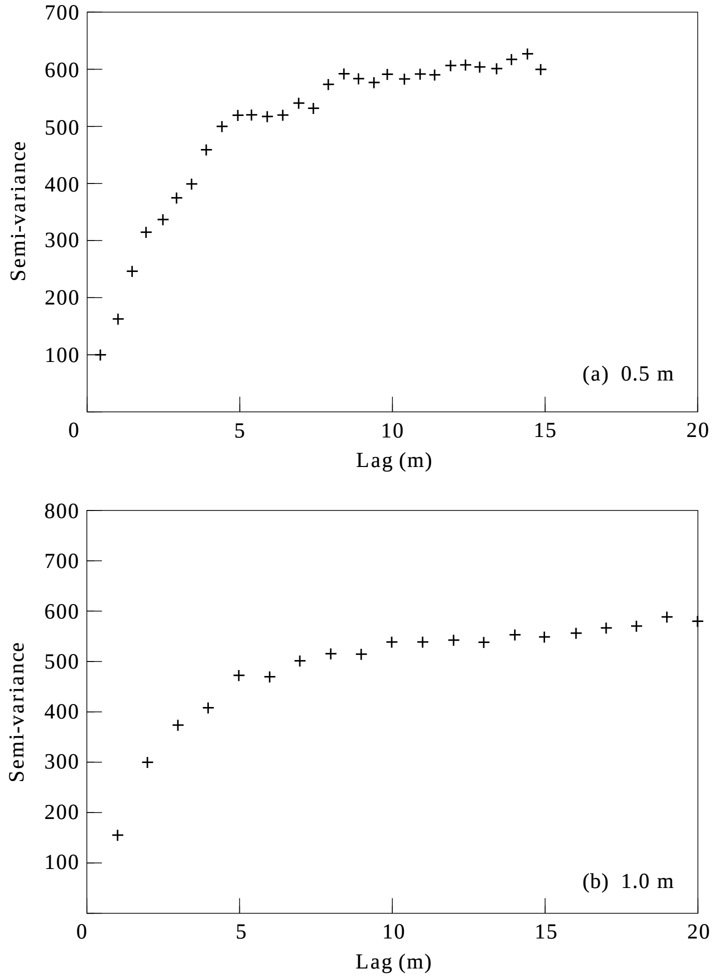


Figure 7. Mesquite North NDVI variograms.

1988b), who examined the effect of increasing pixel size on the spatial structure of simulated and real images and the form of variograms.

3.3. COMPARISON OF NDVI IMAGES VERSUS RASTERIZED BIOMASS MAPS

Maps of the spatial distribution of biomass produced by a kriging interpolation of the field sampled measurements could not be accurately registered with the corresponding NDVI imagery for each site. Therefore, comparing variogram form and parameters for the kriged above-ground biomass data and NDVI imagery provided an alternative, quantitative means to assess suitability of the sampling design used. Details on the variograms calculated for one site of each vegetation community type are listed in Table 2.

For the shrubland sites (Mesquite, Creosote, Tarbush), all variograms from biomass field samples exhibited a pure “nugget” effect [Figure 8(b)]. A flat variogram with very

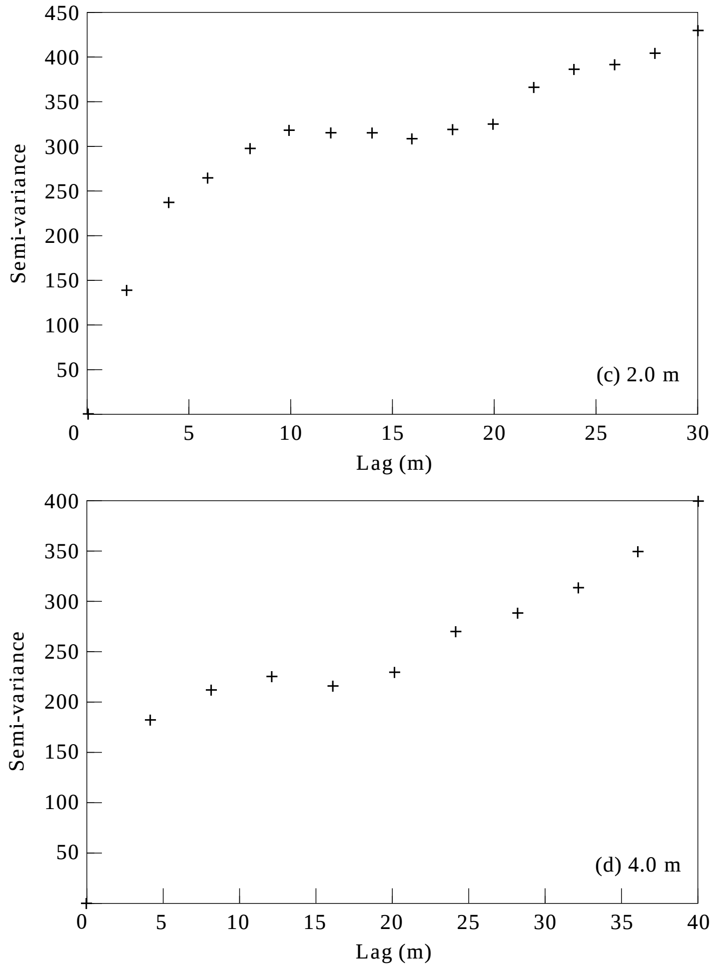


Figure 7.—*continued*.

limited slope indicated that the majority of the spatial autocorrelation (e.g. in biomass) occurred at a spatial scale less than that of the 10 m interval used. The variograms for the NDVI imagery at 0·5 m pixel resolution for shrubland sites suggested that NDVI values were highly autocorrelated within distances of 5·0–16·0 m, indicative of either shrub or inter-shrub dimensions. In comparison, the variograms for the playa grasslands and grassland biomass samples [Figures 8(d), 8(e)] both exhibited positive linear forms. Similar variograms were produced for those site's NDVI imagery at 0·5 m pixel resolution. This coincidence of form suggests that the 10 m field sampling interval was capturing the same landscape structure as that detected using a 0·5 m sampling interval.

The Mesquite North shrubland environment has a distinctive spatial structure, characterized by shrubs 5–7·5 m in diameter, with 5–10 m spaces of bare soil between them. As portrayed on the interpolated data, the majority of field sample points for biomass appeared to coincide with spacing between the shrubs. The SURFER program assumes a linear variogram with a positive slope for its kriging interpolation. As a result the typical extent of autocorrelation for features with high NDVI values (e.g.

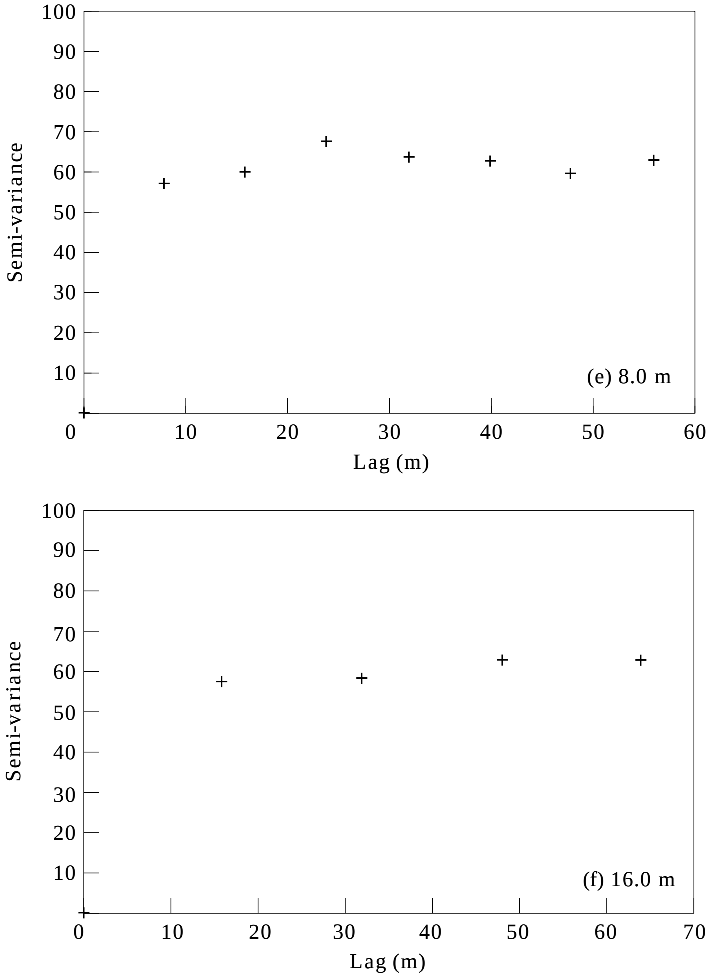
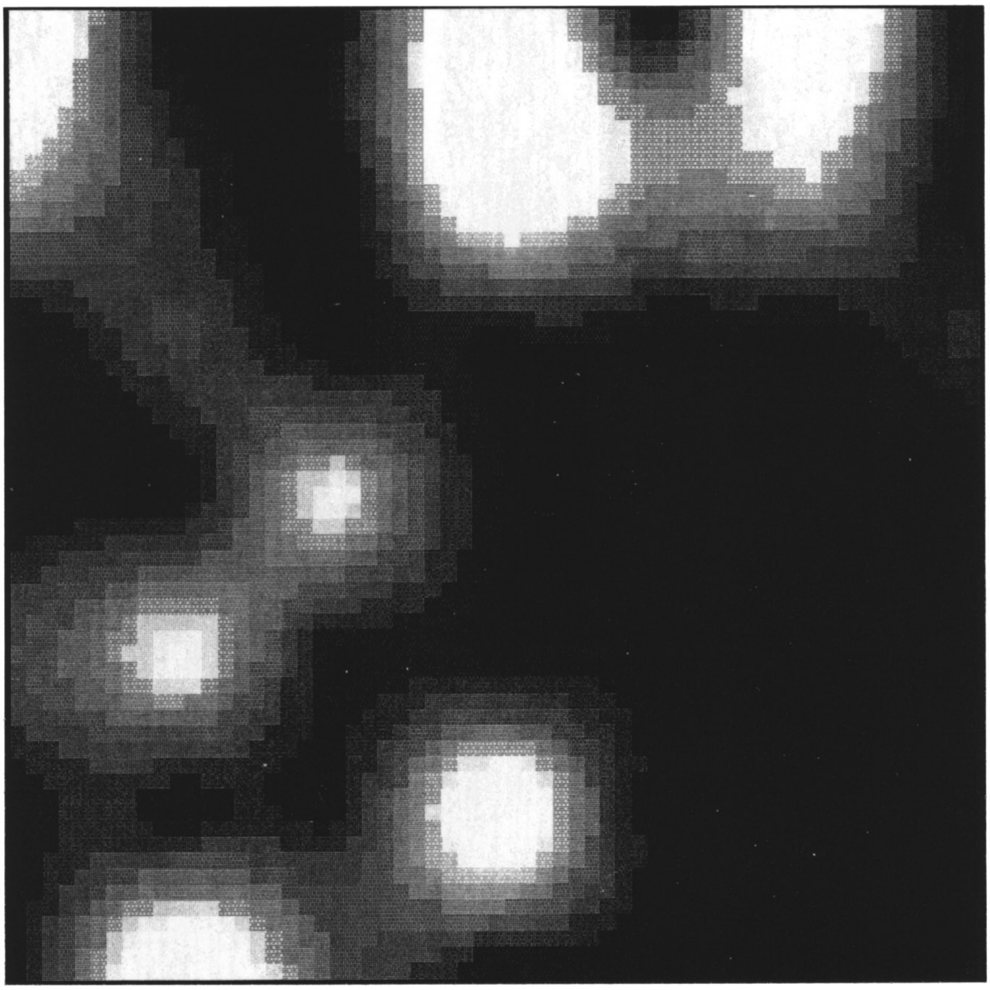


Figure 7.—*continued*.

shrubs) is not taken into account and a linear decrease in NDVI is assumed. This produces an image without small-scale features at the characteristic autocorrelation length corresponding to shrubs.

To apply the appropriate variogram model for kriging the biomass data, the range and form of the NDVI image variogram for the Mesquite North sample site [Figure 3(a)] were used to specify input parameters. The resulting interpolation of biomass spatial distribution still did not produce a pattern similar to the site's NDVI image (Figure 2). No discrete shrub-like patches of high NDVI were evident, nor did the general distribution of high NDVI values coincide with the actual shrub distribution. Even though the model variogram for kriging had been adjusted to the spatial structures evident in the 0·5 m pixel NDVI image, a lack of sample points coinciding with shrubs biased the interpolation.

A similar procedure, using NDVI image variogram parameters for kriging, was applied to biomass data from each of the other plant community types, Small playa



(a) Mesquite North map.

Figure 8. Rasterized biomass maps and variograms, September 1991 data. Bright areas = high biomass. Dark areas = low biomass.

and Basin grassland. Kriged maps of biomass spatial distribution were produced for each site. The output maps appeared identical to those in Figures 8(c) and 8(e). This similarity results from each of these site's NDVI image characteristic linear variogram form. This type of variogram model was used in the kriging routine by the SURFER program to produce Figures 8(c) and 8(e).

3.4. Appropriate image resolution and ground sampling interval

Although the 10 m ground sampling interval adequately represented the biomass distribution in the grassland, playa grasslands and more continuously covered shrubland sites, it did not realistically represent the spatial pattern of plant abundance in the Mesquite North site. An optimum sampling interval should provide non-biased data to serve the sampling purpose, taking into account the spatial structure of the population

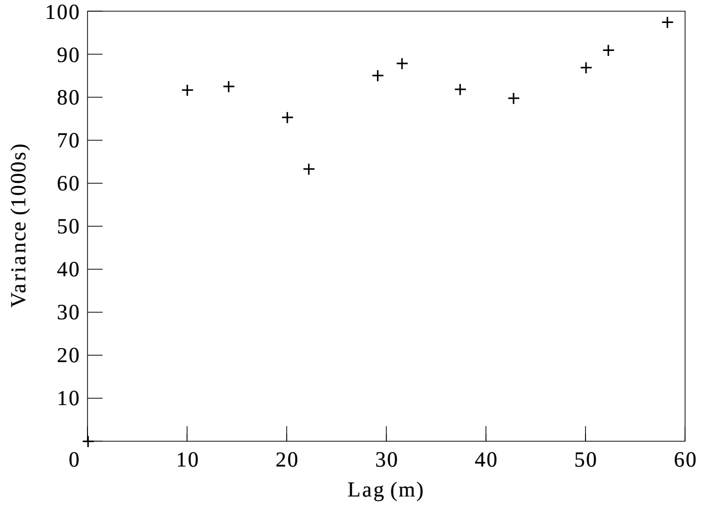


Figure 8(b) Mesquite North variogram.

being sampled and the type of application to which it will be applied. The pixel size beyond which vegetative features required for estimating biomass distribution, such as individual shrubs and grassland patches, became unresolvable, was used as the primary criterion. In the case of Jornada shrub communities, the pixel resolution should be smaller than the average diameter of the smallest shrubs.

Based on the summary of observed pixel size and image feature interactions in Table 3, the most realistic representation of biomass distribution at the scale of field sites in the Jornada LTER would be achieved using a 1·0 m pixel size. At this resolution individual shrub forms and high frequency, small-scale NDVI patterns are still clearly discernible for all sites.

The aim of a ground sampling strategy is to obtain an accurate representation of biomass distribution in a given plant community. Specific considerations in grassland and playa grassland sites were continuous surface coverage in 15–20 m patches, no discrete shrubs and high frequency NDVI variation. In shrubland sites, shrub dimensions and spacing were the main considerations and these varied between each plant community (Table 2). The strategy that we selected utilized the regular, systematic sampling approach used in the biomass sampling (by L. Huenneke), except that a 5·0 m interval between sample measurements was chosen. The 5·0 m interval should be small enough to ensure that sample points do not coincide with shrub or inter-shrub patterns in the shrubland sites and to identify feature boundaries in grassland areas.

The systematic sampling strategy with the 5·0 m interval was applied to NDVI images of grassland sites (Basin Grassland), playa grassland sites (Small Playa) and shrubland sites (Mesquite North, Tarbush East, Creosote Sand). Sample sets of NDVI values were then interpolated in GEO-EAS and SURFER using the same parameters used to krige the 1991 biomass data with parameters from NDVI images for these sites.

For the grassland and playa grassland sites, the rasterized NDVI maps from the 5·0 m sampling interval represented the main variations in vegetation distribution indicated on the 0·5 m NDVI image. However, very high frequency, small-scale NDVI variations in the grassland and playa sites (e.g. Summerford and Basin grassland, Playa

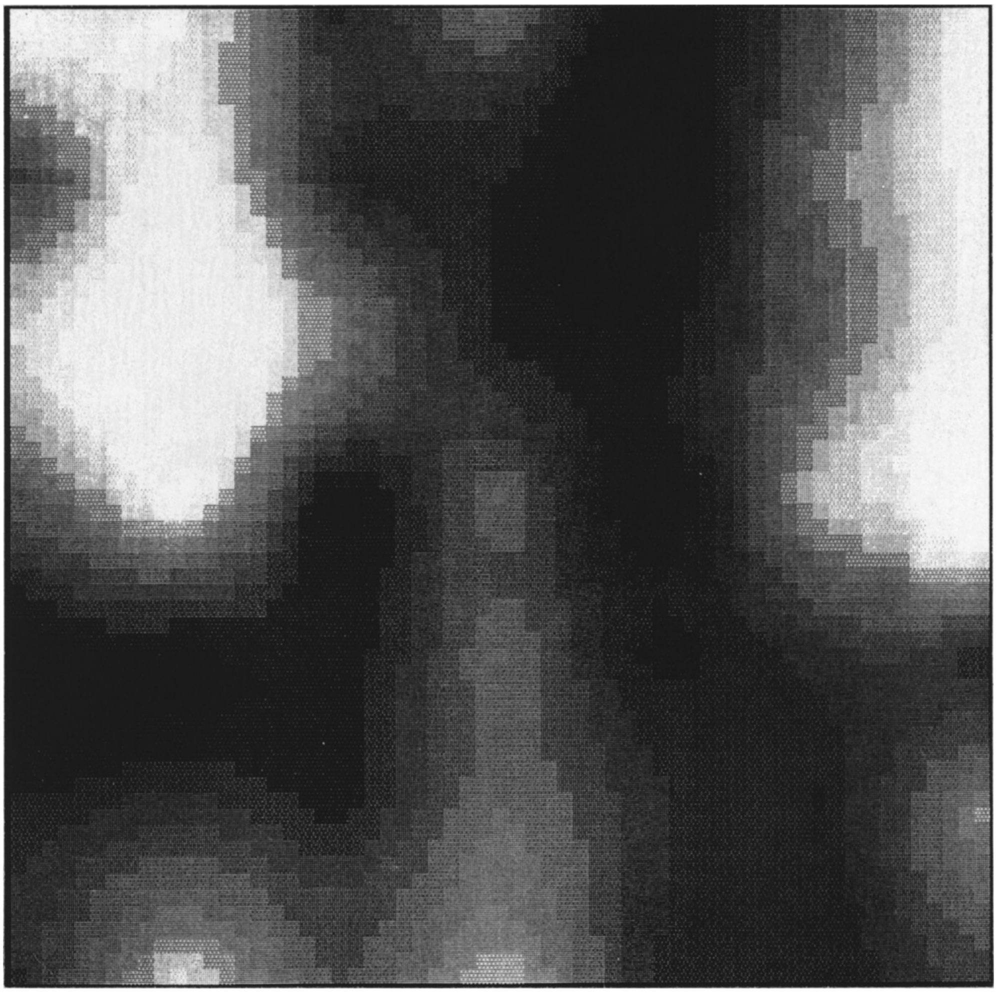


Figure 8(c) Small Playa map.

Tabosa) were not represented due to the size of the sampling interval and the interpolation process. Comparison of the rasterized NDVI maps produced from the 5·0 m sampling interval with the rasterized field-based biomass samples, based on 10 m intervals, indicated a correspondence of large-scale features between maps in both grasslands and playas.

Similar effects were observed in the shrubland sites, especially Mesquite North. The 5·0 m sampling interval identified the outline of individual shrubs and their internal variability. The use of a 5·0 m sampling interval in shrubland sites appears to represent a significant improvement on the previous results obtained from using a 10 m sampling interval. The extent of the difference between the actual biomass distribution [e.g. Figure 4(a)] and 10 m sampled biomass distribution [e.g. Figure 8(a)] indicates the necessity for a more intensive sampling scheme.

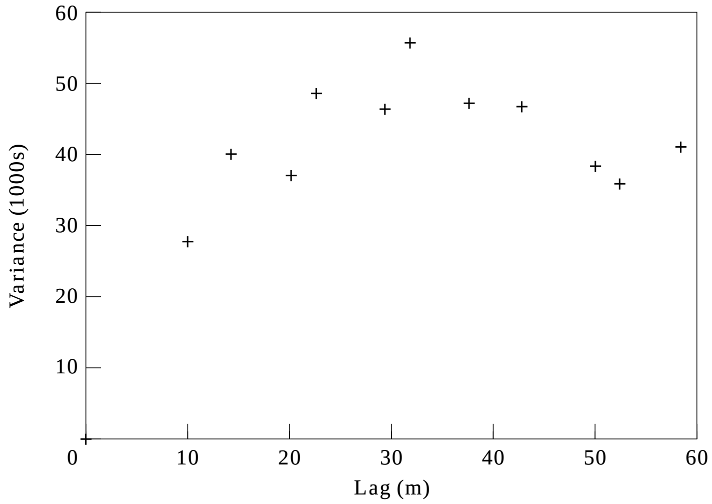


Figure 8(d) Small Playa variogram.

4. Conclusion

This research highlights the need to understand the spatial characteristics (size, patterning and scale of variability) of the environment being investigated prior to acquiring and processing data for mapping. More specifically, the spatial characteristics of any environment should be considered where remotely sensed data or field-based techniques will be used to map the spatial distribution of above-ground biomass. Applying exploratory spatial statistical techniques, such as the variogram, to remotely sensed imagery enables the presence and scale of the relevant spatial characteristics to be identified and analyzed (Simmons *et al.*, 1992; Dutilleul, 1993). Our results illustrate the utility of high spatial resolution imagery for providing a means to determine the effect that the spatial scale of sampling from pixel and field sampling intervals has on the measurement of the spatial distribution of above-ground biomass. An assessment may also be made using this approach of the difference in information content between field-sampling scale measurements and lower resolution satellite data.

In this sense, the variogram has been used as an exploratory tool for structural analysis of landscape or ecosystem structure. Similar variogram forms may be produced from images of landscapes with different spatial structures, hence, additional spatial statistics should be used to provide information on landscape spatial structure (Rossi *et al.*, 1992). In the case of the simple scene model applicable to the shrub and grass communities in the Jornada basin, the variogram appears sufficient. For the Jornada model of desertification (Schlesinger *et al.*, 1990), the variogram serves as a potential ecological indicator for changes in landscape structure from the semi-arid grasslands with uniform ground cover to the more arid and spatially heterogeneous shrublands. The combined application of high-resolution remotely sensed data and the variogram may also be applicable in ecosystem and regional scale models outside semi-arid areas, where landscape structure is linked to biogeochemical cycles and their spatial variation. Extension of remotely sensed data in this direction using variograms furthers initial works of Curran (1988), Atkinson (1991) and Simmons *et al.* (1992), by using the variogram as a tool to link remotely sensed data to the spatial dimensions of ecosystem structures and processes.

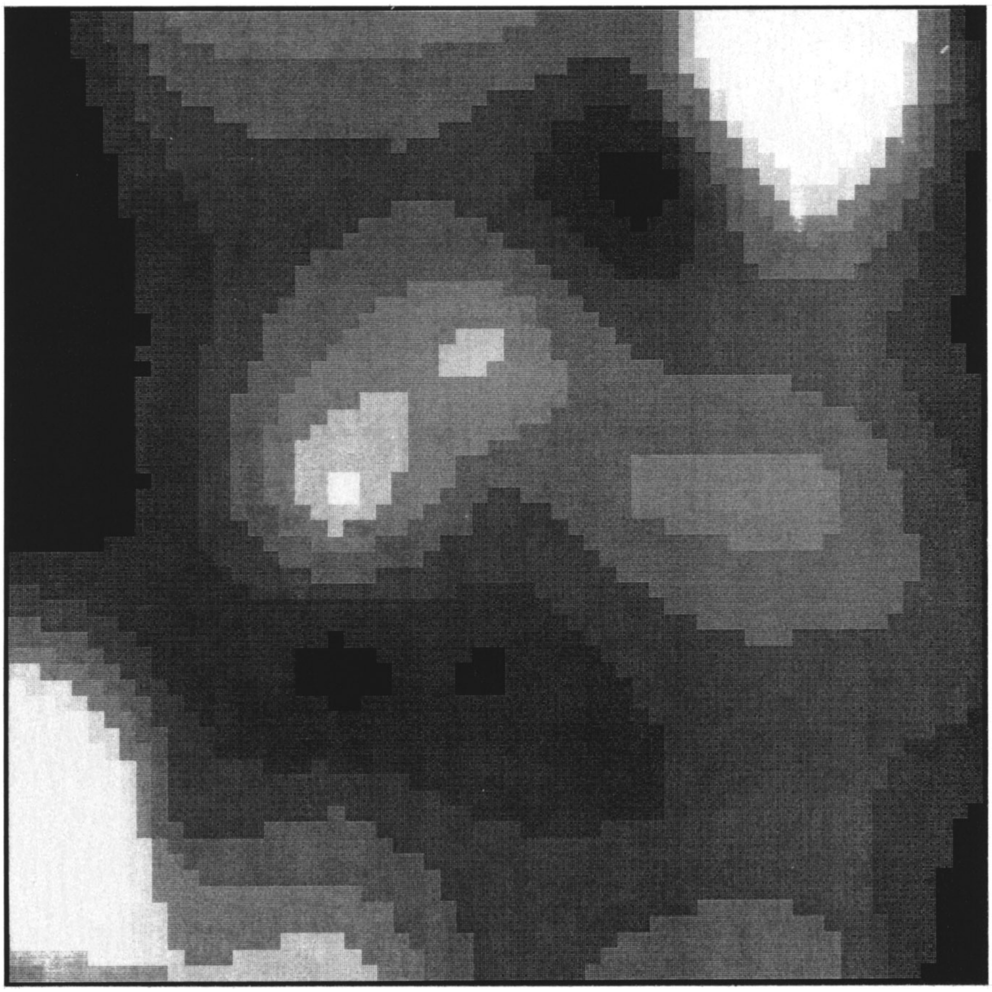


Figure 8(e) Basin Grassland map.

Assessing the spatial characteristics of ADAR images acquired for portions of the Jornada LTER site using variograms and visual analysis indicated three characteristic patterns of spatial variability: (1) grassland plant communities (black grama grasslands) exhibiting a continuous surface cover and high frequency internal variations; (2) playa grassland communities exhibiting a continuous surface cover with low frequency internal variations; and (3) shrubland plant communities (mesquite dunes, tarbush flats, creosote bajadas) exhibiting a discontinuous shrub cover with regular dimensions and spacing. The optimal pixel resolution (1·0 m) and ground sampling interval (5·0 m) for representing spatial distribution of above ground biomass were specified to account for the spatial structure of vegetation in each plant community.

Continued research is necessary in this area to better utilize remotely sensed data and spatial statistics other than variograms for addressing specific questions on ecosystem spatial structure and dynamics. Further interpretative assessment and field validation of variogram parameters in relation to vegetation and soil patch structure is essential.

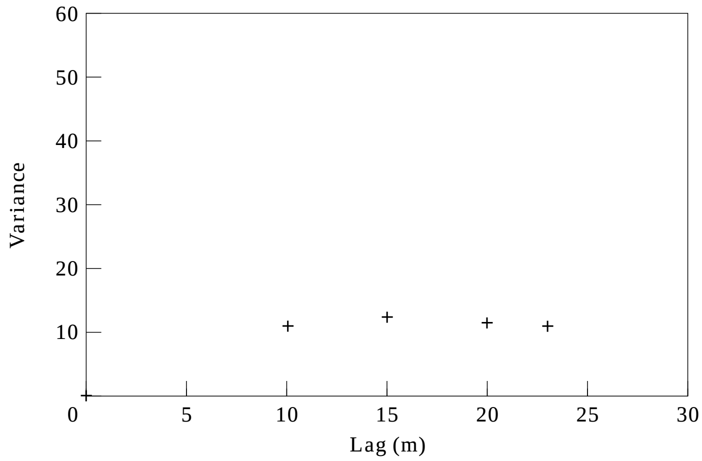


Figure 8(f) Basin Grassland variogram.

Such work will enable more functional links to be established between the spatial and spectral-radiometric characteristics of imagery and ecological characteristics of the environment being investigated.

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References

Asrar, G., Myneni, R. B. and Kanemasu, E. T. (1989). Estimation of plant-canopy attributes from spectral reflectance measurements. In *Theory and Applications of Optical Remote Sensing* (G. Asrar, ed.), pp. 252–296. New York: John Wiley & Sons.

Atkinson, P. M. (1991). Optimal ground-based sampling for remote sensing investigations: estimating the regional mean. *International Journal of Remote Sensing* **12**, 559–567.

Atkinson, P. M. (1993). The effect of spatial resolution on the experimental variogram of airborne MSS imagery. *International Journal of Remote Sensing* **14**, 1005–1011.

Atkinson, P. M., Webster, R. and Curran, P. J. (1992). Co-Kriging with ground based radiometry. *Remote Sensing of the Environment* **41**, 45–60.

Benkelmann, C. A., Behrendt, R. H. and Johnston, D. R. (1990). The high resolution Airborne Data Acquisition and Registration (ADAR) system. *GIS/LIS '90 Conference Proceedings*, Anaheim, California.

Benkelmann, C. A., Cohen, W., Stow, D. and Hope, A. (1992a). High resolution digital imagery applied to vegetation studies. *AASPRS '92 Conference Proceedings*, Washington, D.C.

Benkelmann, C. A., Verbyla, D. and Cohen, W. (1992b). Application of high resolution digital imagery to forestry studies. *ASPRS/ACSM '92 Conference Proceedings*, Albuquerque, New Mexico.

Cohen, W. B., Spies, T. A. and Bradshaw, G. A. (1990). Semi-variograms of digital imagery for analysis of conifer canopy structure. *Remote Sensing of the Environment* **34**, 167–178.

Craig, R. G. and Labovitz, M. L. (eds) (1981). *Future Trends in Geomathematics*. Norwich: Page Brothers.

Cressie, N. (1991). *Statistics for Spatial Data*. New York: Wiley & Sons.

Curran, P. (1988). The semi-variogram in remote sensing: an introduction. *Remote Sensing of the Environment* **24**, 493–507.

Curran, P. and Williamson, H. D. (1986). Sample size for ground and remotely sensed data. *Remote Sensing of Environment* **20**, 31–41.

Davis, F. W., Quattrochi, D. A., Ridd, M. K., S.-N. Lam, N., Walsh, S. J., Michaelsen, J. C., Franklin, J., Stow, D. A., Johannsen, C. J. and Johnston, C. A. (1991). Environmental analysis using integrated GIS and remotely sensed data: some research needs and priorities. *Photogrammetric Engineering and Remote Sensing* **57(6)**, 689–697.

Duncan, J. A., Stow, D., Franklin, J. and Hope, A. (1993). Assessing the relationship between spectral vegetation indices and shrub cover in the Jornada Basin, New Mexico. *International Journal of Remote Sensing* **14**, 3395–3416.

Dutilleul, P. (1993). Spatial heterogeneity and the design of ecological field experiments. *Ecology* **74**, 1646–1658.

Englund, E. and Sparks, A. (1991). *GEO-EAS User's Guide*. Las Vegas: Environmental Monitoring Systems Laboratory, Office of Research and Development, Environmental Protection Agency.

Everitt, J. H. and Nixon, P. R. (1985). False colour video imagery: a potential remote sensing tool for range management. *Photogrammetric Engineering and Remote Sensing* **51**, 675–689.

Everitt, J. H., Hussey, M. A., Escobar, D. E., Nixon, P. R. and Pinkerton, B. (1986). Assessment of grassland phytomass with airborne video imagery. *Remote Sensing of Environment* **20**, 299–306.

Fortin, M.-J., Drapeau, P. and Legendre, P. (1989). Spatial auto-correlation and sampling design in plant ecology. *Vegetation* **83**, 209–222.

Franklin, J. and Hiernaux, P. H. Y. (1991). Estimating foliage and woody biomass in Sahelian and Sudanian woodlands using remote sensing model. *International Journal of Remote Sensing* **12**, 1387–1404.

Franklin, J., Duncan, J. and Turner, D. L. (1993). Reflectance of vegetation and soil in Chihuahuan desert plant communities from ground radiometry using SPOT wavebands. *Remote Sensing of Environment* **46**, 1–25.

Frew, J. (1990). The image processing workbench. PhD. Dissertation, Department of Geography, University of California at Santa Barbara, California, U.S.A.

Gibbens, R. P. and Beck, R. F. (1988). Changes in grass basal areas and forb densities over a 64 year period on grassland types of the Jornada experimental range. *Journal of Rangelands Management* **41**, 186–192.

Golden Software (1992). *SURFER* Version 3.0, Reference Manual. Golden, Colorado.

Graetz, R. D., Pech, R. P., Gentel, M. R. and O'Callaghan, J. F. (1986). The application of Landsat image data to rangeland assessment and monitoring: the development and demonstration of a land image based resource information system (LIBRIS). *Journal of Arid Environments* **10**, 58–80.

Grover, H. D. and Musick, H. B. (1990). Shrubland encroachment in southern New Mexico, U.S.A.: An analysis of desertification processes in the American southwest. *Climatic Change* **17**, 305–330.

Hutchinson, C. F., Schowengerdt, R. A. and Ralph Baker, L. (1990). A two-channel multiplex video remote sensing system. *Photogrammetric Engineering and Remote Sensing* **56**, 1125–1128.

Jensen, J. R. (1983). Biophysical remote sensing. *Annals of the Association of American Geographers* **73**, 111–132.

Jensen, J. R. (1986). *Introductory Digital Image Processing. A Remote Sensing Perspective*. New Jersey: Prentice Hall.

Jupp, D. L. B., Strahler, A. H. and Woodcock, C. E. (1988). Auto-correlation and regularisation in digital images: I. Basic theory. *IEEE Transactions on Geoscience and Remote Sensing* **26**, 463–473.

Musick, H. B. (1984). Assessment of Landsat MSS indexes for monitoring arid rangeland. *IEEE Transactions on Geoscience and Remote Sensing* **GE-22**, 512–519.

Rossi, R. E., Mulla, D. J., Journel, A. G. and Franz, E. H. (1992). Geo-statistical tools for modelling and interpreting ecological spatial dependence. *Ecological Monographs* **62**, 277–314.

Roughgarden, J., Running, S. W. and Matson, P. A. (1991). What does remote sensing do for ecology? *Ecology* **72**, 1918–1922.

Rouse, J. W., Haas, R. H., Deering, D. W. and Schell, J. A. (1974). *Monitoring the Vernel Advancement and Retrogradation (Green Wave Effect) of Natural Vegetation*. Final report 1974–8. Texas: Remote Sensing Centre, Texas A&M University, College Station, 348pp.

Satterwhite, M. B. and Ponder-Henley, J. (1987). Spectral characteristics of selected soils and vegetation in northern Nevada and their discrimination using band ratio techniques. *Remote Sensing of the Environment* **23**, 155–175.

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A. and Whitford, W. G. (1990). Biological feedbacks in global desertification. *Science* **247**, 1043–1048.

Simmons, M. A., Cullinan, V. I. and Thomas, J. M. (1992). Satellite imagery as a tool to evaluate ecological scale. *Landscape Ecology* **7**, 77–85.

Tucker, C. J. (1979). Red and photographic linear infrared combinations for monitoring vegetation. *Remote Sensing of the Environment* **8**, 127–150.

Turner, S. J., O'Neill, R. V., Conley, W. and Conley, M. R. (1991). Pattern and scale: Statistics for landscape ecology. In *Quantitative Methods in Landscape Ecology* (M. G. Turner and R. H. Gardner, eds), Vol. 82, pp. 17–50. New York: Springer Verlag.

USDA (1980). *Soil Survey of the Dona Ana County Area, New Mexico*. U.S. Department of Agriculture, Soil Conservation Service, Bureau of Land Management, New Mexico Agricultural Experimental Station.

Ustin, S. L., Smith, M. O. and Adams, J. B. (1993). Remote sensing of ecological processes: a strategy for developing and testing mixture models using spectral mixture analyses. In *Scaling Physiological Processes. Leaf to Globe* (J. R. Ehleringer and C. B. Field, eds), pp. 339–357. New York: Academic Press.

Van Mouwerik, D. (1993). Assessing vegetation abundance of *Spartina foliosa* in a southern California salt marsh using remote sensing. M.A. Thesis, Department of Geography, San Diego State University, California, U.S.A.

Warren, P. L. and Hutchinson, C. F. (1983). Indicators of rangeland change and their potential for remote sensing. *Journal of Arid Environments* **7**, 107–126.

Woodcock, C. E. and Strahler, A. H. (1987). The factor of scale in remote sensing. *Remote Sensing of the Environment* **21**, 311–332.

Woodcock, C. E., Strahler, A. H. and Jupp, D. L. B. (1988a). The use of variograms in remote sensing: I. Scene models and simulated images. *Remote Sensing of the Environment* **25**, 323–348.

Woodcock, C. E., Strahler, A. H. and Jupp, D. L. B. (1988b). The use of variograms in remote sensing: II. Real digital images. *Remote Sensing of the Environment* **25**, 349–379.

Yoder, J. A., McClain, C. R., Blanton, J. O. and Oey, L. Y. (1987). Spatial scales in CZCS-chlorophyll imagery of the southeastern U.S. continental shelf. *Limnology and Oceanography* **32**, 929–941.