

Spatial variability of soil and nutrient characteristics of semi-arid grasslands and shrublands, Jornada Basin, New Mexico

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ABSTRACT

Heterogeneity of vegetation and soil properties is characteristic of semi-arid and arid environments. The potential underlying causes of the dynamics that create this spatial variability, with consequent impacts on landscape connectivity and thus ecological and ecohydrological processes, are not clearly understood. An investigation was carried out into the spatial variability of ponded infiltration rate, soil moisture, soil-aggregate stability, vegetation cover, random roughness and nutrient content in the soil (ammonium, nitrate and phosphorus) at grassland and shrubland sites for two spatial scales in the Jornada Basin, in the northern part of the Chihuahuan desert. At the plant-interplant scale, statistically significant differences exist between vegetated and non-vegetated sites for soil moisture and infiltration rate within both shrublands and grasslands. The spatial distributions of all other parameters follow a more complex scheme at this scale. At the landscape scale, distinct differences exist for most parameters between the grasslands and the shrubland sites. Geostatistical analysis revealed that the autocorrelation lengths are not simply a function of average shrub sizes, but may be caused by a more complex pattern probably related to the spatial layout of rill and inter-rill areas and other localized transfers of soil resources through the redistribution of water and wind. These results demonstrate the importance of understanding spatial linkages of processes within the landscape in understanding dryland ecosystem dynamics. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS desertification; spatial variability; connectivity; landscape ecology; desert ecosystems; Jornada

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INTRODUCTION

Semi-arid and arid environments are often described as having very heterogeneous soil and vegetation characteristics (e.g. Whitford, 2002). This heterogeneity is manifest at a range of spatial scales. At a scale of a few metres (Figure 1(a), (i)), this heterogeneity is expressed as plant-interspace. Several studies have been carried out to investigate plant-interspace controls of this heterogeneity in the south-western part of the United States. Schlesinger *et al.* (1990), for example, argued that semi-arid and arid shrub communities form a self-sustaining system through plant–soil feedback mechanisms that lead to the formation of ‘islands of fertility’, a phrase first employed by Garcia-Moya and McKell (1970). Plant-interspace scale studies have allowed significant insights into the understanding of the ecohydrology of grassland and shrubland and stressed the importance of vegetation control on soil properties; however plant-interplant scale studies fail to explain fully the feedback mechanisms between the ecosystems and the hydrological cycle in the form of on-going land degradation processes that occur in the south-western part of the United States (Peters *et al.*, 2006).

Heterogeneity occurs at increasingly larger spatial scales, from individual plants to patches or patch mosaics to landscape units comprising bajadas, sandy basins and playas which are typically characterized by different vegetation associations of grass and shrub species. At these larger scales, heterogeneity occurs around rills forming so-called ‘bead’ areas (Wainwright *et al.*, 2002), and is due to patterns of both small rill networks and larger arroyos and channels that interconnect the landscape that is composed of different types of grassland and shrubland communities at a continuum of scales. The potential underlying causes of landscape-level patterns and the dynamics that create spatial variability at these spatial scales are often not clearly understood. According to, for example, Abrahams *et al.* (1995), Wainwright *et al.* (2000) and Peters *et al.* (2006), plant-level interactions cannot purely be related to landscape-level patterns through simple, linear extrapolation. Abrahams *et al.* (1995) carried out rainfall-simulation experiments in Arizona to investigate the influence of different vegetation communities (dominated either by grass or desert shrubs) and obtained different rates for infiltration, runoff and soil erosion as a function of plot size. Wainwright *et al.* (2000) concluded in their survey of plot-scale studies of vegetation and soil interactions in deserts of the south-western part of the United States that not only plant–soil feedback mechanisms but also interconnectivity

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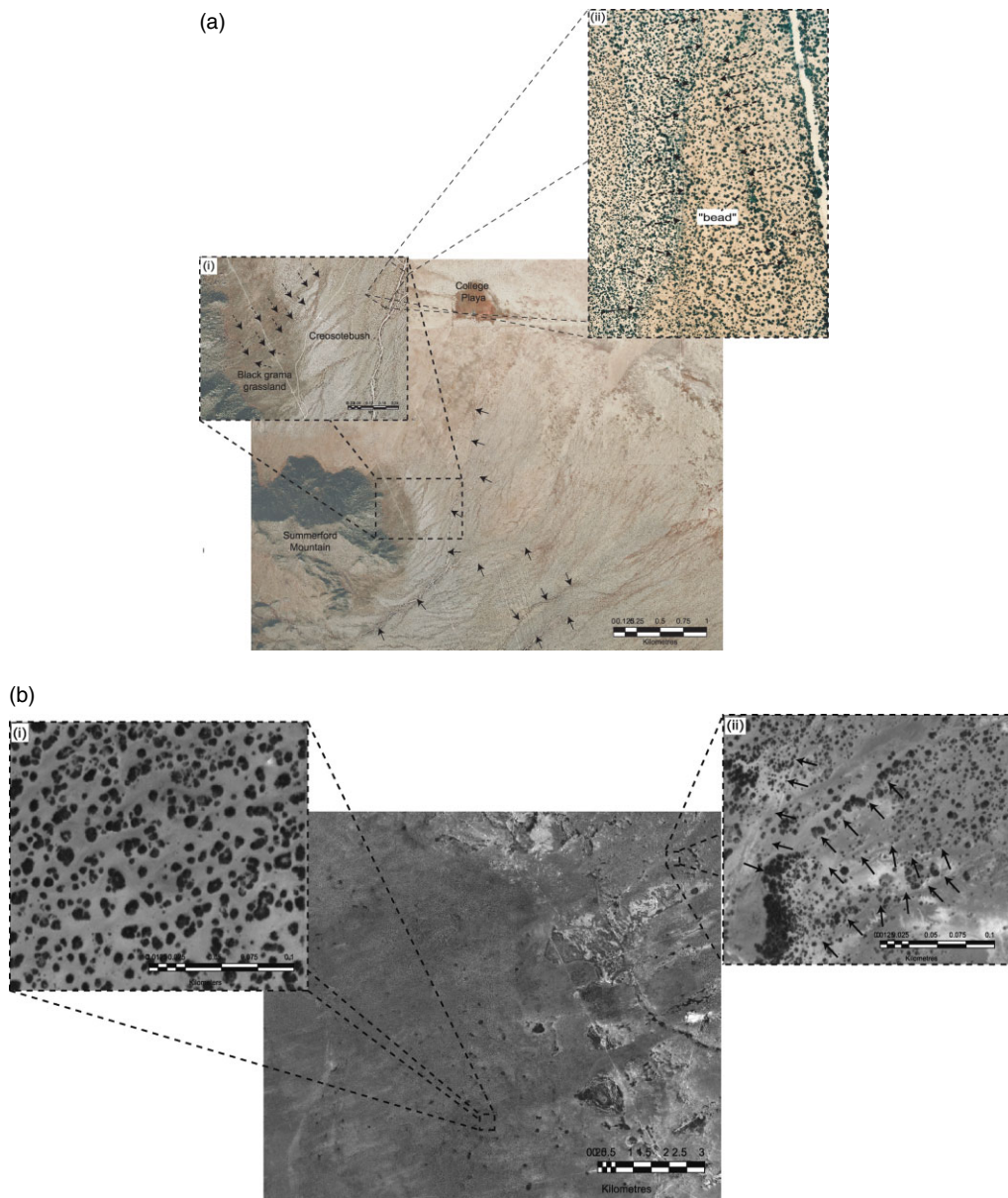


Figure 1. Example of landscape connectivity and patchiness at three successive spatial scales in an area of the Jornada Basin.

of landscape elements are important to explain and understand ecosystem functioning and landscape development, and thus also the dynamics that create spatial patterns. Finally, Peters *et al.* (2006) suggested a landscape linkages model that describes how complex soil and vegetation patterns in semi-arid environments are generated by the non-linear interactions of feedback mechanisms of vegetation, soil, water and animals not only at the plant-interplant scale but across multiple scales by the transport and redistribution mechanisms, for example water and wind and contagious processes that connect different plants, patches and landscape units. Ludwig *et al.* (1997) and Turner (2005) stressed the importance of connectivity on the landscape ecology through the transfer of materials between spatial units, as transport processes by water and wind affect landscape function and create distinct patterns and thereby spatial variability in vegetation and soils at multiple scales. This connectivity can

thus affect the ability of different species to colonize (e.g. Hastings *et al.*, 2005; Kauffman and Jules, 2006) with clear implications for the understanding of the conversion of grasslands to shrublands in the Chihuahuan Desert. Furthermore, understanding the spatial organization of ecosystem characteristics has a major effect on understanding the scale-dependency of both ecological and hydrological processes, with consequences for the extrapolation of ecosystem characteristics (e.g. Miller *et al.*, 2004) and the understanding of ecosystem dynamics (e.g. Perry, 2002). The crucial question is therefore how to capture and quantify the spatial variability at a range of scales and how to relate these heterogeneities to the potential underlying causes of landscape-level patterns. In this study, we employ an investigative, geostatistical analysis to examine the spatial patterns of soil and vegetation parameters at multiple scales to allow a more mechanistic view of spatial parameter distributions.

As the first objective, the study investigates quantitatively whether soil and vegetation parameters vary spatially as a function of vegetation patch sizes. On the basis of the autocorrelation lengths of the semivariogram analysis and the potential differences between samples from bare and vegetated sampling points, the article discusses why the spatial variability may not only be driven by the plant-interplant dimensions of a specific vegetation community, but proposes that spatial heterogeneity may as well be created by landscape dynamics and processes, for example related to the redistribution of soil resources by water and wind. It is anticipated that different shrub species exhibit different patch sizes, as for example reported by Peters *et al.* (2006) and thus requires a separate examination of all dominant shrubland types that occur in a landscape. The second objective of this study is therefore to carry out a statistical analysis to infer potential significant differences of soil and vegetation parameters of different vegetation associations in a typical grassland–shrubland environment of the southwestern part of the United States.

The parameters under investigation comprise key vegetation and soil parameters such as ponded infiltration rate, soil moisture, soil-aggregate stability, vegetation cover, random roughness and nutrient content in the soil (ammonium, nitrate and phosphorus). These specific parameters were chosen because they are all critical input parameters to study potential underlying causes of landscape-level patterns, for example, by using numerical modelling of redistribution transport processes of soil resources at the landscape scale and subsequently by quantifying the feedback effects of different vegetation patterns and progressions on hydrological processes.

STUDY AREA

The study area is located within a semi-arid to arid dryland environment in the northern part of the Chihuahuan Desert, New Mexico in the Jornada del Muerto Basin. The field studies were undertaken at the Jornada Experimental Range, 40 km NNE of Las Cruces (32°31'N, 106°47'W), New Mexico, as part of the Jornada Basin Long-Term Ecological Research Program (LTER). The climate is typical of the northern Chihuahuan Desert with average annual precipitation and potential evaporation rates of *ca.* 245 mm and 2 204 mm, respectively (Wainwright, 2006). About 65% of rainfall occurs as summer precipitation primarily as short, high-intensive localized convective storms. Maximum summer temperatures reach 40 °C. Mean elevation is approximately 1250 m above sea level. There are four dominant plant communities in the Jornada Basin: black grama grassland (*Bouteloua eriopoda*), and three shrubland communities dominated by creosotebush (*Larrea tridentata*), honey mesquite (*Prosopis glandulosa*) and tarbush (*Flourensia cernua*). The soils in the Jornada Basin consist mostly of aridisols such as haplargids, and entisols such as torripsamments. Jornada soils are highly interactive with the

vegetation through plant–soil feedback processes (Buffington and Herbel, 1965; Bulloch and Neher, 1980). Grasslands are found on soils such as the Stellar series (great group: haplargids), which has a silty-clay texture, and consists of very deep, well-drained soil that formed in sediments on basin floors (Bulloch and Neher, 1980). Grasslands occur typically in the central plain of the basin in playas and other depressions; smaller grasslands can also be found on the alluvial piedmonts; at both locations the grass swards are degraded to various degrees. Creosotebush grows on soils such as the Nickel series (great group: calciorthids), which mostly has a gravely sandy loam texture and moderately coarse-textured subsoil. This series consists of deep, well-drained soils that are formed in alluvium from mixed sources. Creosotebush vegetation occurs within the lower and upper piedmont slopes of the basin. Tarbush is found on soils such as the Reagan series (great group: calciorthids). This soil series has a fine-silt texture, and consists of very deep, well-drained, moderately permeable calcareous soils that formed in calcareous loamy materials. Tarbush vegetation is found within the lower piedmont slope and the alluvial plain. Mesquite shrubs occur on soil such as the Pintura series (great group: torripsamments), which is characterized by nebkha dunes, with barren blown-out areas between the dunes (Gillette and Pitchford, 2004; Gillette *et al.*, 2006). This association exists predominantly in the eastern and central part of the Jornada Basin.

METHODS

Spatial sampling

One representative field plot was selected within each of the four vegetation associations: black grama grassland (at 32°30'32" N, 106°44'37" W) on silty-clay loam, honey mesquite (at 32°41'29"N, 106°44'19"W) on silty sand, creosotebush (at 32°38'53"N, 106°36'42"W) on gravely sand loam, and tarbush (at 32°32'49"N, 106°41'46"W) on sandy loam (Bulloch and Neher, 1980). Data collection was carried out during a 7-month period in the spring and summer of 2002 and 2003. A nested sampling strategy was developed, designed to capture the variations of the parameters at different spatial scales for the geostatistical analysis. The sampling design for each of the four field plots was based on a 60 m × 60 m field-plot area (3 600 m²). The field plot was subdivided into 30 m × 30 m, 10 m × 10 m and 3 m × 3 m rectangular cells; two sets of nine random locations have been chosen within the four 30 m cells, four sets of nine random locations in the 10 m cells, and six sets of random locations in the 3 m cells with nine sampling points lying on a 3 m × 3 m grid. This gave a total of 108 sampling points per sampling site (Figure 2). The sampling strategy enabled the quantification of the short-range (plant-interspace size <10 m) and the medium-range variations of several tens of metres (patch size >10 m including larger inter-rill spaces and a network of small rills and rill networks within each study plot).

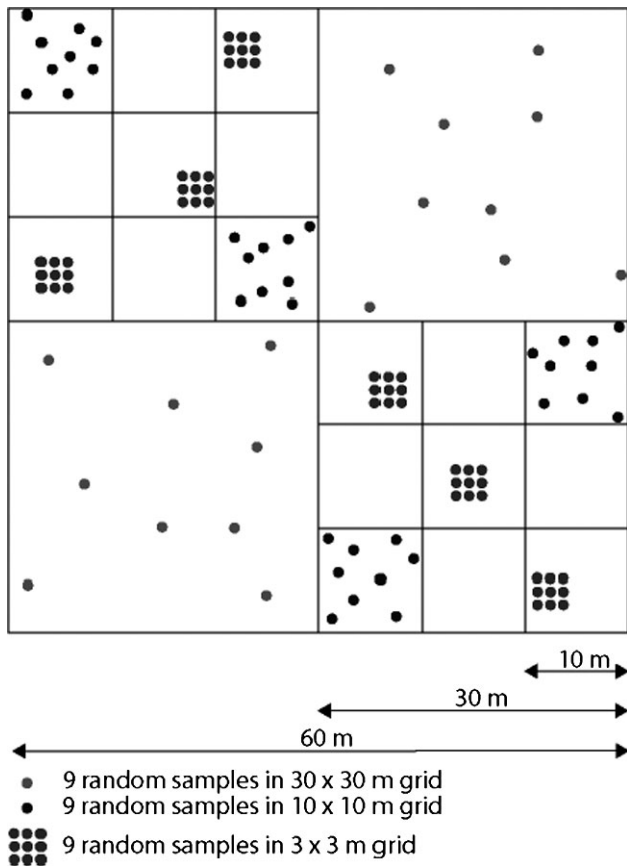


Figure 2. Nested sampling strategy used to define the spatial location of parameters sampled during the study.

At each plot, measurements of vegetation cover, ponded infiltration rate, soil moisture, random roughness, soil-aggregate stability, and nutrient (ammonium, nitrate and phosphorus) content in soil were made. The surface cover was recorded for each sampling point and data points were classified according to whether they fell under a vegetated or bare (interspace) position so that details of the plant-interspace characteristics could be evaluated. This classification was not available for the random roughness data.

Field and laboratory techniques

Vegetation cover [%] was estimated for 1-m² plots using a 35-mm SLR camera with a 35-mm lens mounted on a 2-metre-high tripod and used to take transparencies which were then scanned at a resolution of 1250 × 1900 pixels.

Ponded infiltration rate [mm/h] was measured using a single-ring infiltrometer with a diameter of 12.5 cm (equivalent to a support of ca. 0.012 m²) following the guidelines of Herrick *et al.* (2005). Before the measurement, aboveground vegetative parts were removed and the soil pre-wetted. A Mariotte siphon was placed inside the ring and height measurements of water level in the siphon were taken every one to 15 min depending on the current infiltration rate. Final ponded infiltration rate was determined when height measurements remained constant for several consecutive readings. It should be noted that problems arose with the measurements at the Mesquite

site. Even though the sampling points were properly pre-wetted, the sandy surface crust broke when the ring was pressed into the ground resulting in the formation of fissures, which potentially has led to an over-prediction of the actual ponded infiltration rate. Although cylinder infiltrometers tend to overestimate infiltration when compared to other techniques such as rainfall simulations, there is no reason to assume that this specific problem affects the *relative* patterns of measured infiltration rates on bare and vegetated points. However, the quantitative comparison of mean ponded infiltration values for different sampling sites should be considered with care, as the method does not reproduce the actual infiltration rate as well as rainfall-simulation experiments.

Volumetric soil moisture content [%] was measured for the upper soil layer of 6 cm using an HH2 hand-held reader with a theta probe sensor supplied by Delta-T Devices Ltd. Cambridge with a support of 0.001 m².

Random roughness [mm] was estimated using a standard microtopography meter constructed by the USDA-ARS Jornada Experimental Range. The meter covered a length (equivalent to the support) of ca. 0.5 m with 24 pins, each 0.02 m apart, which followed the contour of the soil. Cross-slope microtopography was measured from transects taken across the slope along generalized contour directions at each sampling point. The standard deviation of pin heights is used as an index of random surface roughness (Kincaid and Williams, 1966).

Soil-aggregate stability [dimensionless] was estimated using the soil-aggregate stability kit developed by Herrick *et al.* (2001) with an approximate support of 0.0005 m². The kit is a combination of a slake test (classes 0 to 3) and a stability test (classes 3 to 6) with overlap at class 3. At each sampling point, a surface sample and a sub-surface sample at a depth of 2–3 cm below the surface were collected.

Nutrient content in soil [µg/g] was estimated from air-dried soil samples with a support of ca. 0.01 m², which were sieved (<2 mm) and analysed for ammonium (NH₄⁺) and nitrate (NO₃⁻) using the potassium chloride extraction (KCl) method; and phosphorus (PO₄⁻) using Olsen's sodium bicarbonate extraction method as described in the standard soil analysis handbook of reference methods (Soil and Plant Analysis Council, 2000). The elements were extracted by shaking a 6-g sub-sample of soil for 30 min with 30 ml of 2 mol/l KCl for the nitrate and ammonium analysis and 30 ml of 0.5 mol/l sodium bicarbonate (at a pH of 8.5) for the phosphorus analysis. All extracts were centrifuged for 10 min. The extracts for phosphorus analysis were mixed with 0.9N HCl and left to degas for 48 h. All extracts were filtered with Seraclear filters and the supernatant was analysed for nutrient content using Traacs 800 autoanalyser methods.

Statistical and geostatistical methods

An investigative, geostatistical analysis was employed to evaluate the spatial patterns of soil and vegetation parameters at multiple scales by calculating the experimental,

omnidirectional semivariograms from the spatial data set derived with the nested sampling strategy (Figure 2). The experimental semivariogram is derived by calculating one-half of the average squared difference in data values for every pair of data locations and plotting these values against the distances between the data pairs. The semivariogram contains information on the autocorrelation commonly observed in spatial data, where data values from neighbouring locations are more similar than data values from locations far apart. For patterned data, the semivariogram first rises from comparisons of neighbouring samples that are similar and autocorrelated and then levels off at the *sill*, indicating the distance beyond which samples are independent. This distance is commonly termed the *range* value. In other words, the *range* of the semivariogram describes the extent of spatial dependence, i.e. the *autocorrelation length*: samples separated by distances closer than the actual range are related spatially, whereas those separated by distances greater than the actual range are said to be not spatially related. In contrast, for randomly distributed data, little change in the semi-variance is encountered with increasing distance and the semivariogram is essentially flat (Rossi *et al.*, 1992). Variance that exists at a spatial scale finer than the sampling is found at zero lag distance and is termed *nugget variance*: a high nugget value indicates that most variance occurs over very short distances. Normal score transformations were used to transform the estimated distribution functions of the field data to a standardized normal distribution, as it makes the calculation more robust against the influence of extreme outliers (Deutsch and Journel, 1998; Olea, 1999). The Gaussian and the exponential models, which are commonly used to fit semivariogram models, were employed to model the experimental semivariograms and are given by:

$$\text{Gaussian model: } \gamma(h) = C \cdot \left[1 - \exp\left(-\frac{(3h)^2}{a^2}\right) \right],$$

$$\text{Exponential model: } \gamma(h) = C \cdot \left[1 - \exp\left(-\frac{3h}{a}\right) \right],$$

where γ is the semi-variance, C is the sill value, h is the lag distance, and a is the range (Olea, 1999). As the field data were transformed with the normal score transformation, the sill value C equals 1 (Deutsch and Journel, 1998). The derived autocorrelation lengths and the nugget values thus enabled quantification of the spatial variability of the field data and an evaluation to which extent the data vary spatially as a function of vegetation patch sizes. To support the findings of the semivariogram analysis, a t -test analysis was employed to infer statistically significant differences between parameters collected from bare and grass-cover surfaces at the grassland site, and bare and shrub-cover surfaces at the three shrubland sites ($p = 0.05$). ANOVA analysis and a multiple comparison procedure (Tamhane's T2 test using the SPSS built-in function) were used to determine if the average values of the field parameters differ significantly among the four

vegetation associations (black grama, tarbush, mesquite and creosotebush) to tackle the second objective of this study.

RESULTS AND DISCUSSION

Plant-interplant variability of the soil and nutrient parameters

The descriptive statistics of the field data, including the overall mean values and the mean values related to vegetated and bare surface covers as a function of vegetation association are summarized in Table I. For all parameters and all vegetation associations, the coefficient of variation (given as $\text{CoV} = \text{standard deviation}/\text{mean}$) value is generally high, in particular for vegetation cover, ponded infiltration rates and nitrate content in soil (Table I). Here, the CoV can be interpreted as a quantitative evidence for the high spatial variability of samples taken from a relatively small area of 3 600 m² compared to the landscape or basin scale with an areal extent of *ca.* 1 000 km². Plant-interplant variability is considerable for all studied vegetation types. Statistically significant differences between vegetated and bare surface covers for all four vegetation types exist only for the average ponded infiltration rate, the soil-moisture content and the ammonium content (except for the creosotebush site). However, the nitrate and phosphorus content is not significantly different between vegetated and bare surface covers in most cases for the shrubland sites. Thus, the heterogeneity of the field data set that is apparent through the high coefficient of variation is not solely explained by the existence of plant-interplant related processes, but is potentially related to processes that occur at larger scales, as discussed below.

Vegetation association variability of the soil and nutrient parameters

The ANOVA multiple comparison procedure revealed that the average values for vegetation cover, ponded infiltration rate, soil-aggregate stability, nitrate and phosphorus content are significantly different among all four sites (Table I). Several other field studies have reported on the differences of grassland and shrubland characteristics (e.g. Schlesinger *et al.*, 1996; Wainwright *et al.*, 2000; Bhark and Small, 2003). This quantitative evidence of statistically significant differences of soil- and vegetation-related parameters for different vegetation associations signifies the heterogeneity of parameters even within different shrubland communities at the landscape scale. That implies that environments like the Jornada Basin cannot simply be divided and categorized into landscape units according to grass or shrub vegetation, but that to understand the ecological landscape dynamics and processes, it must be recognized that different shrubland communities behave differently and therefore should be examined individually. The differences in soil types associated with the four vegetation types ranging from silty-clay loam at the grassland site to silty sand at the creosotebush site

Table I. Descriptive statistics of field parameters: ANOVA results for differences between vegetation association (no. of samples: 540, $p < 0.001$) and t -test results to examine the influence of vegetated versus bare surface cover.

Parameter	Vegetation	Mean \pm Std. Err. ^a	CoV [%]	F statistics ^a	Vegetated mean	Bare mean	t statistics ^b	Level of sign. ^b
Vegetation cover [%]	Grass	41 \pm 2 a	59	14.4				
	Mesquite	21 \pm 3 b	155					—
	Tarbush	20 \pm 2 b	102					
	Creosote	23 \pm 3 b	119					
Ponded infiltration [mm/h]	Grass	30.7 \pm 4.5 a	147	78.0	60.6	16.5	3.142	0.006
	Mesquite	229.5 \pm 10.3 b	46		226.4	231.0	0.191	0.849
	Tarbush	160.6 \pm 11.9 c	77		285.6	133.6	-4.649	<0.001
	Creosote	80.6 \pm 7.6 d	88		149.4	59.8	-5.086	<0.001
Soil-aggregate stability (surface) [-]	Grass	3.4 \pm 0.1 a	44	32.7	25.3	22.4	-2.814	0.006
	Mesquite	1.4 \pm 0.1 b	66		9.1	11.6	4.031	0.001
	Tarbush	2.5 \pm 0.2 c	67		12.0	11.6	-0.341	0.734
	Creosote	2.6 \pm 0.1 c	47		4.1	6.3	2.661	0.009
Soil-aggregate stability (sub-surface) [-]	Grass	3.2 \pm 0.1 a	38	46.9	3.8	3.2	815	0.022
	Mesquite	1.5 \pm 0.1 b	68		1.7	1.4	910	0.822
	Tarbush	1.5 \pm 0.1 b	59		2.3	2.6	366	0.482
	Creosote	2.2 \pm 0.1 c	60		3.2	2.3	288	0.134
Ammonium [μ g/g soil]	Grass	11.0 \pm 0.7 a	67	52.0	3.7	2.7	569	<0.001
	Mesquite	3.7 \pm 0.3 b	90		2.3	1.3	483	<0.001
	Tarbush	6.2 \pm 0.2 c	34		2.1	1.4	249	0.011
	Creosote	7.3 \pm 0.4 c	59		2.9	1.9	327	0.380
Nitrate [μ g/g soil]	Grass	5.3 \pm 0.4 a	84	53.0	11.6	10.0	-1.175	0.243
	Mesquite	1.2 \pm 0.1 b	120		4.1	3.6	-0.584	0.560
	Tarbush	1.2 \pm 0.1 b	85		5.5	6.4	1.000	0.320
	Creosote	1.4 \pm 0.1 b	105		6.8	7.2	0.246	0.806
Phosphorus [μ g/g soil]	Grass	18.0 \pm 0.7 a	39	331.0	6.5	3.8	-4.102	<0.001
	Mesquite	4.3 \pm 0.1 b	36		2.9	0.7	-4.781	<0.001
	Tarbush	1.8 \pm 0.1 c	37		1.0	1.2	0.338	0.736
	Creosote	14.6 \pm 0.3 d	24		1.9	1.3	-1.089	0.279
Random roughness [mm]	Grass	6.3 \pm 0.3 a	55	2.9				
	Mesquite	6.4 \pm 0.3 a	50					
	Tarbush	5.8 \pm 0.3 a	57					
	Creosote	6.2 \pm 0.3 a	45					no data available

CoV: Coefficient of Variation.

^a ANOVA analysis: mean values followed by the same letter within one block are not significantly different ($p < 0.001$).

^b t -test analysis between vegetated and bare mean: t statistics and corresponding level of significance, significant differences marked with boldface type.

play a fundamental role in explaining the statistically significant differences of the various soil and vegetation parameters. However, these differences in soil types were created through soil and vegetation interactions over the past century. About 100 to 150 years ago, most parts of the Jornada Basin were covered with grasslands, whereas now due to degradation processes and invasion of shrubs into former grassland, the Jornada Basin is mainly dominated by shrublands (Buffington and Herbel, 1965). The differences of soil and vegetation parameters for the four vegetation associations are therefore explained by the fact that different vegetation prefers different soil types. More importantly, through degradation processes and plant-soil feedback mechanisms that, for example, lead to the formation of the 'islands of fertility', the entire ecosystem has changed.

Spatial continuity of the soil and nutrient parameters

The geostatistical parameters, range and nugget of the fitted models to the experimental semivariograms of the field data are summarized in Table II. As an example,

Figure 3 displays the experimental semivariograms and the corresponding fitted models for all parameters of the creosotebush site. The data on soil-aggregate stability were excluded from the geostatistical analysis due to their ordinal character.

The range values show considerable variability among the different parameter sets and vegetation types ranging from 0 m (pure nugget) to 24 m. The grassland site shows overall the largest range values and consequently the largest extent of spatial dependency for all parameters, except soil moisture, followed by the tarbush and mesquite sites. The creosotebush site has the lowest range values. There are three strong similarities in range values for individual parameters as a function of vegetation type. They are discussed in the following text.

Nutrient content data. The vegetation cover show similar range values as the three nutrients (ammonium, nitrate and phosphorus) for the grass, the mesquite and the creosotebush sites, but not for the tarbush site. Schlesinger *et al.* (1996) and Cross and Schlesinger (1999) investigated the spatial distribution of nutrient parameters on

Table II. Range and nugget parameters for the fitted Gaussian models of the experimental semivariograms for all field data.

Vegetation	Parameter	Nugget	Range [m]
Grass	Vegetation cover ^a	0.2	20.0
	Ponded infiltration rate	0.7	9.0
	Soil moisture	1.0	—
	Ammonium	0.64	15.0
	Nitrate	0.56	24.0
	Phosphorus	0.27	16.0
	Random roughness	0.55	22.0
Mesquite	Vegetation cover	0.3	5.5
	Ponded infiltration rate	0.48	18.0
	Soil moisture	0.73	17.0
	Ammonium	0.72	4.0
	Nitrate	0.5	6.0
	Phosphorus	0.49	6.0
	Random roughness	0.8	7.0
Tarbush	Vegetation cover ^a	0.15	6.0
	Ponded infiltration rate	0.22	8.0
	Soil moisture	0.62	11.0
	Ammonium	0.7	15.0
	Nitrate	0.45	20.0
	Phosphorus	0.52	17.0
	Random roughness	0.42	9.0
Creosote	Vegetation cover	0.3	3.0
	Ponded infiltration rate	0.57	3.0
	Soil moisture	1.0	—
	Ammonium	0.5	5.0
	Nitrate	0.7	2.0
	Phosphorus	0.52	24.0
	Random roughness	0.85	3.0

^a Exponential model instead of Gaussian model was used.

black grama grassland and creosotebush shrubland in the Chihuahuan Desert. Cross and Schlesinger (1999) showed that nutrient distribution followed a uniform pattern in grassland, and a patchy distribution in creosotebush shrubland with significantly higher concentration of nitrogen in samples taken under shrubs than from the bare interspaces. They related these findings to the spatial homogeneity of the grass sward versus the spatial heterogeneity of individual shrubs in the shrubland. Schlesinger *et al.* (1996) used geostatistics to show that available nitrogen (in their study the sum of ammonium and nitrate content) in grassland is autocorrelated over distances extending to 7 m, whereas for shrubland the distances are only over 1–3 m. They suggested that the shorter autocorrelation length for creosotebush shrubland is due to biogeochemical cycling, acting at the scale of individual shrubs. This study confirms their finding by showing similar range values for vegetation cover and the ammonium and nitrate content at the creosotebush site and all three nutrients at the mesquite shrub site. In contrast to their results are the comparatively large range values for ammonium and nitrate content for the grassland and tarbush sites in the present study. The range values of 15 to 20 m for the three nutrients at the tarbush site are considerably larger than the range value of 6 m for the vegetation cover.

Furthermore, the autocorrelation lengths for phosphorus content are notably larger than the ones for vegetation cover for the tarbush and creosotebush sites. Previous field studies suggested that phosphorus, in contrast to the

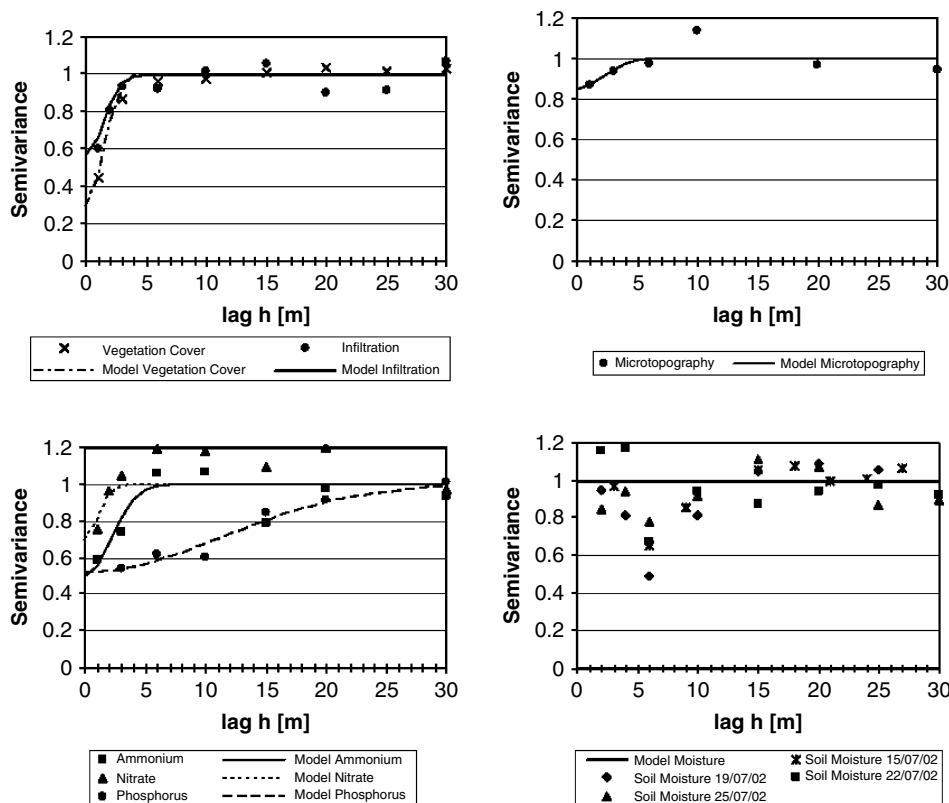


Figure 3. Experimental semivariograms and fitted models—examples for the creosotebush site (fitted semivariogram model parameters as given in Table II).

nitrogen content, is not a limiting element in primary production within the Chihuahuan Desert (Whitford, 2002). This fact might explain why the spatial distribution of phosphorus content does not follow rigorously the plant-interplant or patch pattern of the two shrub types and why it is therefore not solely accumulated around and close to individual shrub mounds. This finding is also supported by the lack of significant differences between bare and vegetated mean values (Table I). In contrast, the mesquite shrubland site shows both a statistically significant difference of phosphorus content between interspace and vegetated surface cover and very similar range values for phosphorus and vegetation cover.

Random roughness data. The range values of the random roughness data of all four vegetation associations show similar values as the ones for the corresponding vegetation cover for each vegetation association. This result can be related to the formation of rather smooth surfaces in the form of desert pavement in the intershrub areas and the development of a rather bumpy surface due to the root network and the formation of individual shrub mounds in the vegetated areas. This finding is supported by the extensive field data sets by Kincaid and Williams (1966) who found that the random roughness is smaller on bare interplant spaces than it is on vegetated areas on creosotebush shrubland at the Walnut Gulch Experimental Watershed in Arizona.

Infiltration and soil-moisture data. The range values for infiltration rate and soil-moisture content show similar values for each of the three shrub sites. The statistical analysis showed that for grasslands, infiltration rate and soil moisture are significantly higher under grass cover than on a bare surface (Table I). For the shrublands on the other hand (except mesquite shrub), infiltration rates are significantly higher, whereas soil moisture is significantly lower for vegetated surface covers than for bare surface covers. On the basis of these purely statistical results it would appear plausible that these two parameters would follow a spatial dependency based on shrub or shrub-patch size. However, for the creosotebush site and to a lesser content for the tarbush site, but not for the mesquite and the grassland sites, the range values for vegetation cover show considerable similarity to the ones of the infiltration rate and the soil moisture. The field study by Bhark and Small (2003) arrived at similar results for creosotebush shrublands of the Chihuahuan Desert, where they estimated range values of ca. 0.5 m suggesting that the autocorrelation length for shrubland is controlled by the size of the shrub canopies. Nonetheless, the geostatistical analysis implies that this pattern does not hold true for the mesquite shrubland and to a lesser extent for the tarbush site.

In summary, the spatial analysis of the field data shows that certain continuity patterns of the fitted semivariogram models are conspicuous and suggest an intrinsic behaviour both as a function of parameter type and vegetation association. The soil and vegetation parameters

vary to a certain extent spatially as a function of vegetation patch size. However, taking into consideration all parameters, it is unlikely that the autocorrelation lengths are purely related to average grass- or shrub-patch sizes. Thus, the field data give quantitative evidence that the spatial variability at the grassland and shrubland sites may not only be driven by the plant-interplant dimensions of a specific vegetation community but that spatial heterogeneity may also be created by hydrological and geomorphological landscape dynamics and processes, as was hypothesized in the introduction.

The field plots used in this study had an extent of 3 600 m² containing small rills and rill networks that were created by overland-flow processes. Hence, the areal extent employed here is considerably larger than the field plots, for example Schlesinger *et al.* (1996) used field data from plots with a size of 96 m² for their geostatistical analysis on spatial nutrient distributions. Whereas their data sets exhibit mainly the influence of plant-interplant processes, the data of this study were potentially influenced by processes that occur at larger spatial scale. One process that can be related to the creation of spatial variability of soil and nutrient parameters and thus of landscape-level patterns is the action of overland-flow generation. Wainwright *et al.* (2002) for example stated that through resource redistribution of overland-flow, spatial heterogeneity is created at large scales where rills and washes are present to provide longer distance transport of water and nutrient resources. Overland-flow also plays an important role in the redistribution of nutrient resources as was recently reported by Parsons *et al.* (2003), who determined the nitrogen loss of vegetated and interplant areas within mesquite shrublands using rainfall simulations in the field. Hence, at this point and on the basis of the quantitative evidence collected in this field study, it could be hypothesized that the spatial patterns of the field parameters may—to a greater or lesser extent—be influenced not only by plant–interplant interactions but also by the spatial layout of rills and rill networks as the major pathways of overland-flow, as was suggested in Figure 1. Other landscape-level processes may be equally important in creating spatial variability such as aeolian processes as suggested by Gillette and Pitchford (2004), see annotation in Figure 1 or the actions by small mammals as stated by Peters *et al.* (2006). To test this hypothesis, further field studies are necessary to estimate parameter values in relation to larger hydrological or ecological units, such as sampling locations within coherent inter-rill areas, stratified sampling within minor and major rill networks and larger channels and arroyos or sampling at the mosaic-patch scale containing several patches of vegetation associations.

SUMMARY AND CONCLUSION

This study provided quantitative data on the spatial variability of soil and vegetation parameters at several scales. In regard to the first objective, an investigative,

geostatistical analysis that allowed the scale of spatial dependence of the field parameters to be determined revealed that the autocorrelation lengths of the field data are not simply a function of average shrub sizes, as previously suggested for soil-nutrient content by Schlesinger *et al.* (1996), but that the parameters under investigation exhibit a more complex pattern. In regard to the second objective, the statistical analysis has shown that strong spatial heterogeneity exists at both the plant-interplant scale and the landscape scale for most of the parameters investigated as a function of both surface cover and vegetation type.

On the basis of this result, it can now be hypothesized that spatial heterogeneity may be created not only by vegetation–soil interactions but also by landscape–linkage processes such as the redistribution processes of soil resources through the action of water and wind at the landscape scale, as previously suggested by Peters *et al.* (2006). The investigation of landscape linkages is thus important to fully comprehend the intrinsic heterogeneity that characterizes semi-arid grassland and shrubland environments. A possible future way to study the landscape-level patterns of soil and vegetation parameters of this type of semi-arid shrubland environment, for example in regard to connectivity patterns or in regard to ecohydrological feedback mechanisms, is to set up a new line of field studies to estimate parameter values in relation to larger ecological and hydrological units, e.g. along the spatial layout of rills and channel networks or at the next larger scale, the mosaic-patch scale. Furthermore, it is now possible to use the information on the spatial distribution of the soil and nutrient parameters to study potential underlying causes of landscape-level patterns, for example, through the usage of numerical modelling of redistribution processes of soil resources at the landscape scale, especially as these processes are often difficult to measure directly in the field. An important area of application in this context includes the parameterization of spatially distributed, transport models that implicitly incorporate this heterogeneity and investigates the importance of landscape linkages and resultant resources fluxes as well as feedback mechanisms of hydrological and ecological processes in the form of on-going land degradation and propagation of shrubs into grasslands.

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The spatial data sets of this study will be made available to the research community through the Jornada

Basin Long-Term Ecological Research (LTER) Information Management System, which can be assessed via the internet on www.lternet.edu. We would like to thank the anonymous reviewers whose comments have led to the generation of a greatly improved version of this article.

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