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Spatial patterns of ecohydrologic properties on a hillslope-alluvial fan transect, central New Mexico

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Abstract

Spatial patterns of soil properties are linked to patchy vegetation in arid and semi-arid landscapes. The patterns of soil properties are generally assumed to be linked to the ecohydrological functioning of patchy dryland vegetation ecosystems. We studied the effects of vegetation canopy, its spatial pattern, and landforms on soil properties affecting overland flow and infiltration in shrublands at the Sevilleta National Wildlife Refuge/LTER in central New Mexico, USA. We studied the patterns of microtopography and saturated conductivity (Ksat), and generally found it to be affected by vegetation canopy and pattern, as well as landform type. On gently sloping alluvial fans, both microtopography and Ksat are high under vegetation canopy and decay with distance from plant center. On steeper hillslope landforms, only microtopography was significantly higher under vegetation canopy, while there was no significant difference in Ksat between vegetation and interspaces. Using geostatistics, we found that the spatial pattern of soil properties was determined by the spatial pattern of vegetation. Most importantly, the effects of vegetation were present in the unvegetated interspaces 2–4 times the extent of vegetation canopy, on the order of 2–3 m. Our results have implications for the understanding the ecohydrologic function of semi-arid ecosystems as well as the parameterization of hydrologic models.

Keywords: Spatial patterns; Ecohydrology; Alluvial fans; Bajada; Hillslope; Vegetation; Soil properties

1. Introduction

The primary tenet of arid land ecology is that organisms must concentrate and conserve resources such as water, nutrients, and soil, typically in response to resource pulses (e.g. Ludwig and Tongway, 1995; Noy-Meir, 1973; Schwinning and Sala, 2004). One of the mechanisms attributed to resource concentration is the redistribution of resources linked to patchy vegetation and heterogeneous soil properties (Bergkamp et al., 1996; Breshears, 2006; Breshears et al., 1998; Ludwig et al., 2005; Sanchez and Puigdefabregas, 1994). Many studies have shown that the physical and chemical properties exhibiting heterogeneity are linked to maximizing water and nutrient availability (e.g. Schlesinger and Pilmanis, 1998). These heterogeneous properties are therefore ecohydrologic properties, in that they are a result of coupled hydrologic, vegetation, and climate systems (Rodriguez-Iturbe, 2000).

Arid and semi-arid ecosystems typically consist of vegetation patches and interpatch areas referred to here as a vegetation mosaic. The interpatch areas are typically bare ground, or can consist of other vegetation types such as in savannah ecosystems with shrub/tree patches and grassy interpatches. The unifying feature of vegetation mosaics is that the physical, chemical, and biologic properties between plant patches and interpatches are different (Bhark and Small, 2003; Burke et al., 1999; Dunkerley, 2000; Schlesinger and Pilmanis, 1998; Tongway and Ludwig, 1994). Commonly, local elevation (microtopography), infiltration rates, organic matter, limiting nutrients, and water holding capacity are higher in vegetation patches. The size of vegetation patches can depend on several factors, including vegetation functional type (e.g. grass tussocks, shrubs, tree groves), canopy

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structure, height differences between patch–interpatch soil surfaces, soil properties, and climate.

The spatial patterns of ecohydrologic properties in a mosaic arise from feedbacks between a variety of processes that link vegetation and soil properties. Some of these processes include bioturbation, differential rainsplash, root growth, accentuated nutrient cycling, and eolian and overland flow erosion/deposition (e.g. Bochet et al., 2000; Cross and Schlesinger, 1999; Sanchez and Puigdefabregas, 1994; Schlesinger et al., 1996; Wainwright et al., 1999). These processes are inherently difficult to study. Therefore, we study the patterns arising from processes in order to better understand the processes themselves. Because these processes may be driven by multiple gradients and at different temporal and spatial scales, they need to be studied in that context. We expect that patterns created by multiple processes, each with different relative affects will change as the gradients driving differing processes change. These gradients are chiefly attributed to three interrelated features of a landscape. Some of these features are vegetation types and morphology, landforms that describe steepness and aspect, and soil characteristics such as texture. An example of the dynamic interactions between vegetation and landforms comes from SE Spain, where the pattern of grass tussocks and associated microtopography vary as a function of position along a hillslope. The pattern arises from linked runoff and erosion/deposition from upslope interspaces that are dependant on slope, and plant growth and mortality (Sanchez and Puigdefabregas, 1994). This shows that processes affecting ecohydrologic properties are a function of the physical setting such as soils and landforms, as well as biotic enhancement or reduction of process efficiency. We therefore expect that the patterns or extents of vegetation influence of soil properties will vary with landscape position and form.

Vegetation cover is often used as an indicator of soil patterns, in which it is viewed as a binary system of under-vegetation soil and between-vegetation (interspace) soil. However, because the processes creating heterogeneity associated with vegetation are dependant on variable gradients (e.g. slope), it is likely that vegetation mosaics may not be simple binary systems. For example, Dunkerley (2000) showed that infiltration rates decayed as a function of distance from shrubs and that "shrub-like" infiltration rates extended $\sim$3 times the extent of shrub canopy. This brings into question the common practice of assigning net areal soil properties based on the amount of cover. At best, the areal extent of soil properties associated with vegetation may only be proportional to vegetation characteristics such as cover. However, it is likely that the proportions (i.e. coefficient given to shrub-like properties) will change as the vegetation, soils and geomorphic contexts change.

Given the hypothesis that landform and vegetation pattern are the dominant factors affecting soil characteristics, a natural test is possible by investigating changes in soil pattern with landscape type and position. In this paper, we analyze the spatial patterns of ecohydrologic properties on two landforms: a hillslope and an alluvial fan. The following sections provide a brief introduction to these landforms, previous research on them, and methods used to evaluate spatial patterns.

1.1. Common arid and semi-arid landforms

Hillslope landforms are typically bedrock-controlled with a thin mantle of soil. They commonly exhibit a "catena" effect where soil texture tends to fine, and soil depth tends to increase, down the landform from the crest to the base of the hillslope (e.g. Moore et al., 1993). Hillslopes are erosional, and their morphology results from slope-driven diffusive surface processes such as soil creep and erosion by overland flow. Hillslopes in arid lands commonly exhibit coupled variation in soil properties, soil moisture, vegetation, and are common sources of runoff and sediment (Brown and Dunkerley, 1996; Canfield et al., 2001; Cerda, 1998; Florinsky and Kuryakova, 1996; Puigdefabregas et al., 1999; Western et al., 1999; Wilcox et al., 2003). Dunne et al. (1991; Dunne, 1991) have showed on hillslopes in Kenya, that the interrelationships between rainfall, hillslope form, runoff depths, and vegetation-influenced infiltration rates and microtopography can strongly affect runoff amounts and landform characteristics.

Alluvial fans are commonly found at the base of large hillslopes and mountain fronts. They are depositional in nature and exhibit soil textural fining away from the hillslope/mountain front (Bull, 1977; Lustig, 1965). They also commonly have soils of different ages. These soils exhibit differing physical and chemical properties due to the effects of pedogenesis, and differing types and amounts of vegetation (McAuliffe, 1994; McAuliffe and McDonald, 1995). Many authors have also noted that total vegetation cover, and often species diversity, tends to decrease with distance from hillslope/mountain front (Bowers and Lowe, 1986; Key et al., 1984; McAuliffe, 1994; Parker, 1995; Phillips and MacMahon, 1978; Shreve, 1964; Solbrig et al., 1977). These trends in alluvial fan vegetation have been attributed to hydraulic property gradients associated with textural fining affecting infiltration and evapotranspiration rates (Alizai and Hulbert, 1970; Clothier et al., 1977; Fernandez-Illescas et al., 2001; Halvorson and Patten, 1974; Klikoff, 1967).

1.2. Geostatistics

Geostatistics have been used to quantify the spatial pattern of soil properties (e.g. Bhark and Small, 2003; Halvorson et al., 1995; Jackson and Caldwell, 1993; Schlesinger et al., 1996), plant ecological parameters (Rossi et al., 1992; Wagner, 2003), and have been one of the methods used in describing plant-associated spatial variability in arid land ecosystems (Halvorson et al., 1994; Schlesinger and Pilmanis, 1998). Multivariate geostatistics have also been used to document the covariance between ecosystem properties (e.g. Goovaerts, 1994; Rossi et al., 1992). Many authors have specifically analyzed the multivariate geostatistical relationships between vegetation and soil properties or other vegetation patterns (e.g. Halvorson et al., 1995; Maestre and Cortina, 2002; Maestre et al., 2005; Wagner, 2003).

In order to quantify spatial structure, continuous models are developed from experimental (i.e. sampled) data. These models are variograms which are described by three common parameters: 1) the nugget which represents the variability at smaller scales than sampled and/or measurement variability, 2) the sill which is the variance that is spatially structured and is generally close to the entire sample variance, and 3) the range which is the distance at which the sill is met (Isaaks and Srivastava, 1989). The range is considered to be the limit of spatial dependence (Webster and Oliver, 2001). We use it to quantitatively compare length scales of variability.

In this paper, we analyze the spatial patterns of soil properties and vegetation in the context of varying landform and position within landform. We address three primary questions: 1) are soil properties different below shrub canopy and in bare interspaces, 2) do ecohydrologic properties change with respect to type and position within a landform, and 3) do spatial patterns of ecohydrologic properties and correlation to vegetation patterns change with respect to landform type and/or landform position? We characterize the spatial structure of ecohydrologic properties with geostatistics. We then describe differences in length scales of spatial structure and describe the dependence of ecohydrologic soil properties on vegetation pattern. From this data we can then infer how our results may inform on ecohydrologic processes in these environments.

2. Methods

2.1. Site description

The study site is located in the Valle de la Joya area of the Sevilleta National Wildlife Refuge and Long Term Ecological Research site in central New Mexico (Fig. 1). Six 10 by 10 m plots were established on hillslope and contiguous alluvial fan landforms at approximately 1600 m elevation. The climate is semi-arid with approximately 240 mm mean annual rainfall of which more than half occurs between July and September associated with the North American Monsoon System (Sheppard et al., 2002). At the Sevilleta, most of the rainfall only wets the upper ~5 cm of soil, and soil moisture pulses due to rain events return to background (i.e. relatively dry) values via evapotranspiration within days (Kurc and Small, 2004). This emphasizes that vegetation in the region is reliant on pulsed water inputs that require concentration and conservation for persistent vegetation. The dominant vegetation at our site is the evergreen shrub creosote bush (*Larrea tridentata*). Other shrubs and sub shrubs include Honey mesquite (*Prosopis glandulosa*),

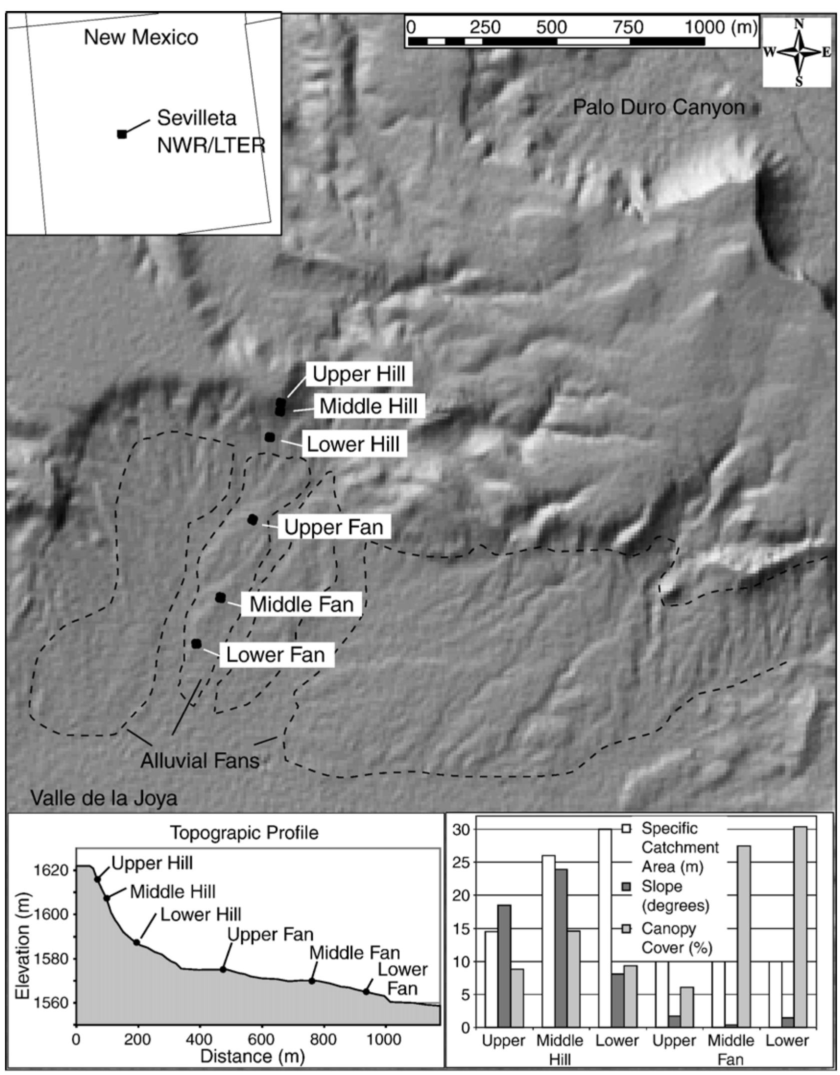

Fig. 1. Study area showing location of study plots and their topographic and vegetation characteristics.

Mormon tea (*Ephedra torreyana*), and snakeweed (*Gutierrezia sarothrae*). Very minor bunches of perennial black grama (*Bouteloua eriopoda*) grass were also noted. No soil lichens or other soil crust organisms were observed.

Topographic characteristics of the plot transect are presented in Fig. 1. The primary topographic differences between hillslope and alluvial fan plots are slope and drainage area relationships. The hillslope plots have steep slopes, and the soils are relatively thin (<1 m) and generated by local weathering. The hillslope shows characteristic trends in topographic characteristics such as increasing specific catchment area (drainage area per unit contour), and slight concave-up to planar cross-section profile. The alluvial fan is contiguous with the base of the hillslope, and likely was derived through hillslope erosion. Some sediment was likely from the catchment to the east of the hillslope. The alluvial fan sits 1–2 m above recently active stream channels. Only one soil-geomorphic surface is present on the fan, excluding incised channels. Topographic characteristics of the alluvial fan are typical of divergent landforms: little to no changes in specific catchment area, and little to no changes in slope with landform position, and concave-down in cross-section profile.

2.2. Data collection

Measurements of microtopography, infiltration, and soil texture were made at each 10 by 10 m plot according to the sampling scheme in Fig. 2. All infiltration and soil texture measurements were co-located with microtopography measurements. Perennial vegetation was measured as it occurs within or overhanging the plots.

We define microtopography, Zm, as the deviation of the ground surface from a plane parallel to the overall slope of the surface, over the extent of each plot. Zm is a portion of overall topography, which can be defined as:

$$Z = \mathrm{Zl} + \mathrm{Zm} + \mathrm{error} \quad (1)$$

where Z is the ground surface elevation, Zl is the portion of Z defined by landform topography (curvature), Zm is microtopography generally in the mm-decimeter scale, and error is a measurement error term. At finer scales (e.g.<1 cm), differences between soil particle sizes and other perturbations are sources of elevation differences and are not addressed here. Fig. 3 illustrates these components and the measurement of Zm in one-dimension.

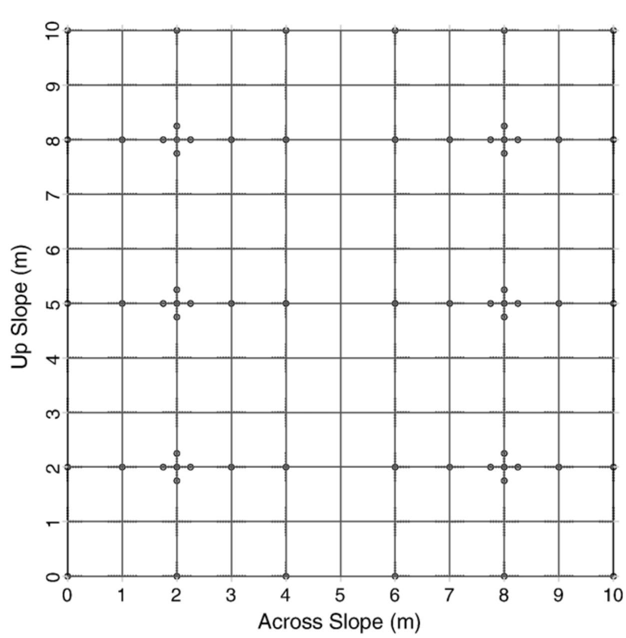

Fig. 2. Sampling scheme for Zm (black dots, $n\sim1500$) and Ksat (circles, $n=66$).

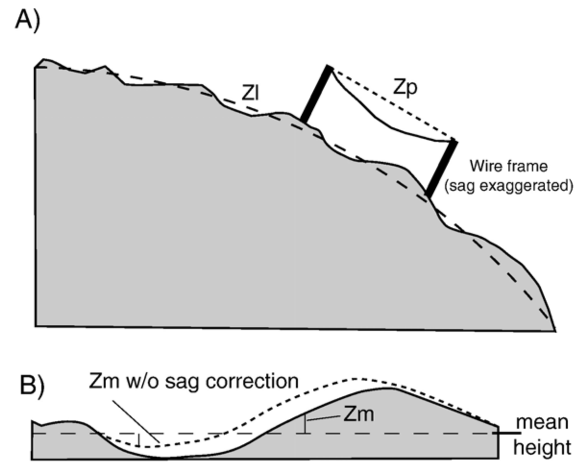

Fig. 3. A) Diagram of one-dimensional measurement and components of topography (gray). Zp represents the plane parallel to the ground surface (line in one-dimension). The distance from Zp (the wire frame) to the ground surface is measured, including an error from sagging of the wire. Adjustment for wire sag may include some curvature from the landform (Zl) but Zl is not explicitly accounted for. B) Microtopography (Zm) is defined as the perpendicular distance of the ground surface from Zp such that the mean microZ value is 0. Shown is the profile below the wire frame in A.

Zm was measured using a wire frame installed parallel to the ground surface as determined by eye. We determine the elevation of the frame, Zp, to be the slope of a plane over the surface (Fig. 3). We assume that the wire frame represents Zl, and that the deviation of Zp from Zl is not a significant component of topography at our plot size and locations (i.e. Zp~Zl). The distance from the wire frame to the ground was measured to the nearest millimeter and the ground condition noted. Common ground conditions noted were bare ground, plant canopy and type, and large rocks.

The wire frame consisted of cables stretched across the plot in the upslope direction. Although the wire appeared visually straight, the wire had ~5 cm sag at the center. To account for sagging of the wire, which introduces the deviation from Zp and affects Zm (Fig. 3B we solve for a parabolic error term. We fit a 2nd order polynomial in the upslope direction of our measurements. We then adjusted the measured wire heights by the deviation of the parabolic fit from a datum parallel to the end-points of the wire frame (Zp). The adjusted distances from the wire frame to the ground are then converted to Zm by subtracting all measured distances from the mean value of all measured distances for each plot. This correction also removes some secondary trend in the data due to down-slope landform curvature, which cannot be separated from the wire sag, and are assumed to be negligible. In short, Zm values are all relative to a datum, the mean plane 'fitted' to the area of the plot: negative Zm values are below the plane, and positive are above.

Infiltration rate is a complex function of soil water contents and potentials through time, thus we simplify using a single value to describe infiltration. We use saturated conductivity (Ksat), which is the minimum infiltration rate that would be observed under unlimited water application conditions. We determined Ksat with single-ring constant head infiltrometers. The infiltrometer rings are 5 cm in diameter, and were inserted to a depth of 5 cm. A 5 cm head (ponding depth) was maintained in the rings with the use of Marriotte tubes. A data logger and pressure transducer measured pressure in the Marriotte tubes every 5 s. Pressure in the Marriotte tube changes as a calibrated linear function of the rate of water drop in the tubes, which is the rate of "field" infiltration. Infiltration was allowed to progress for 35–45 min to allow the infiltration to approximate steady state. Our "field" infiltration rates actually represent 3-d flow in the soil, the characteristics of which are predominantly affected by ring geometry, ponding depth, and soil properties (Reynolds and Elrick, 1990). We approximate true, 1-dimensional, Ksat rate by using the method of Wu et al. (1999) which states that field determined infiltration is ~f-times larger than true 1-dimensional infiltration rate. The method of Wu et al. (1999) accounts for the ring and soil properties, as well as the time-series of each individual infiltration measurement. For our data, f is approximately 2.3, but varies with soil texture. We determined soil texture at the location of each Ksat measurement with the methods of Kettler et al. (2001). We then quantified the necessary values for calculating the f parameter with the Rosetta software program (Schaap et al., 2001).

Perennial vegetation was measured manually and surveyed with a Total Station. The maximum height, maximum canopy width, canopy width perpendicular to the maximum width, and two basal widths were measured with a meter stick, to the nearest centimeter. We also surveyed the locations of the basal center, and the maximum and perpendicular to maximum canopy widths using a Total Station. The Total Station survey of the basal center and maximum widths (as above) is used to calculate cover because it accounts for plant canopies that overlap. Basal width refers to the width of all shrub stems or grass clump entering the ground surface, the center of which is estimated by eye. We then calculated per-plant average width and basal width, as well as canopy area and volume. We calculated canopy area assuming a circular area rather than an elliptical area using the average of our width measurements. Our volume calculations for all plant species follow Hamerlynck et al. (2002), assuming a truncated, inverted cone shape with:

$$\text{Volume} = [1/3]\pi H\left[(W/4)^2+(B/4)^2+(W/4+B/4)\right] \qquad (2)$$

where H is the maximum height, W is the average width, and B is the average basal width.

We determined the spatial pattern of vegetation by quantifying Plant Distance (PD), which is the distance to the nearest shrub base for every location in the plot. We calculated PD because we wish to determine how ecohydrologic properties vary as a function of distance from plants, as well as how plant patterns may change across landforms. PD values therefore enable characterization of vegetation pattern via univariate statistics and geostatistics. Significant relationships to other properties such as Zm and Ksat can then be used in extrapolation such as cokriging. This method is an inversion of traditional point pattern analysis where distances from isolated points, such as plant centers to their nearest neighbor(s), are calculated (e.g. Dale, 1999). We discretized each plot area into 5 by 5 cm grids, and for every grid location we calculated the Euclidean distance to the nearest shrub base as determined by the Total Station survey. We did not differentiate plant species or functional types in this analysis. We used the base of the shrub as the datum for PD as opposed to canopy edge because initial data explorations showed that the data were more strongly related to PD calculated from the shrub base.

2.3. Statistics

Most of our statistical techniques assume normally distributed populations. We used probability (Q–Q) plots to qualitatively check for normality, and we test for normality with the Shapiro–Wilk's W-statistic (Insightful Corporation, 2001). The W-statistic is limited to populations of less than 5,000 ata points and cannot be computed for PD (>40,000 samples per plot). For PD, we use Q–Q normal probability plots to qualitatively determine normality. Probability plots suggested that Zm is relatively normally distributed, the exception being at the far end of both tails of the distributions. W-statistics for Zm are high, but p-values were not sufficient to definitively describe the data as normal. Because the data diverge from normal only at the extreme tails, have low skewness, and do not approximate other distributions with reliable back-transforms, we determine that Zm roughly approximates a normal distribution. Probability plots and W-statistics for Ksat show that the data are normally distributed following a log-10 transform. Probability plots and summary statistics suggest that PD approximates a normal distribution when the data is square root transformed.

We use paired F-tests and Anova methods to test for differences between population variances and means, respectively. We test for differences between landforms, plots (i.e. testing for the effect of landscape position), and between canopy and interspace within plots. Because Zm at each plot has a mean of zero, we cannot use the Anova methods to test for differences in sample means, thus we use F-tests with permutations of plot combinations to test for different Zm variances between plots. All other data, including Zm between canopy and interspace, are tested with Anova and Tukey's multiple comparison methods. In all cases, we perform a two-tailed test at 95% confidence with the null hypothesis being that the population means (or variances for Zm across plots) are equal.

2.4. Geostatistics

We use geostatistics to quantify spatial patterns. Omnidirectional experimental variograms and cross-variograms are calculated, and

Table 1
Summary statistics and statistical differences for vegetation measurements

Comparison	Height (cm)	Anova[1]	Average width (cm)	Anova[1]	Average base (cm)	Anova[1]	Canopy area (m^2)	Anova[1]	Volume (m^3)	Anova[1]	Cover (%)
Hillslope	71±26	A	96±38	A	13±6	A	0.8±0.5	A	0.23±0.19	A	11
Alluvial Fan	102±28	B	133±45	B	21±7	B	1.5±1.1	B	0.62±0.57	B	22
Upper Hill	59±29	A	83±39	A	11±5	A	0.7±0.5	A	0.17±0.15	A	9
Middle Hill	80±26	A	104±30	A	14±6	A	0.9±0.5	AC	0.28±0.20	B	15
Lower Hill	67±16	A	97±36	A	15±6	AC	0.8±0.6	AC	0.21±0.19	AB	9
Upper Fan	76±18	A	104±25	A	22±5	B	0.9±0.4	AD	0.26±0.14	ABC	6
Middle Fan	107±21	B	149±49	B	23±8	B	1.9±1.3	BD	0.79±0.66	C	28
Lower Fan	112±29	B	134±43	B	18±7	BC	1.6±1.0	BCD	0.67±0.56	C	30

[1] Different letters denote different means at 95% confidence level.

we fit theoretical variograms numerically. We then use (cross-) variogram parameters, specifically the range, to quantify the extent of spatial variability. We use transformed values that approximate a normal distribution for all calculations.

We calculate the univariate semivariogram with:

$$\gamma(h) = \left(\frac{1}{2N(h)}\right)\sum_{i=1}^{N(h)}(x_{i+h} - x_i)^2 \quad (3)$$

where h is a separation vector between measurements, $N(h)$ is the number of measurement pairs, x is the data values at locations x_i and x_{i+h} (Deutsch and Journel, 1998).

We calculate the bivariate cross-semivariogram with:

$$\gamma_{ZY}(h) = \left(\frac{1}{2N(h)}\right)\sum_{i=1}^{N(h)}(z_i - z_{i+h})(y_i - y_{i+h}) \quad (4)$$

where z_i is the value of attribute z, z_{i+h} is the value at the location separated by vector h, and y_i is as z except for the other attribute (Deutsch and Journel, 1998). We rescale data values to range from 0 to 1 in order to equally compare values with different units (Deutsch and Journel, 1998) with:

$$x' = \frac{(x - x_{\min})}{(x_{\max} - x_{\min})} \quad (5)$$

where x' is the rescaled value, x is the original value and $x_{\min}$ and $x_{\max}$ are the minimum and maximum values of x, respectively. We limit variograms to a maximum separation of 7 m, which is one-half the maximum distance between measured points, and is considered the largest reliable sampling domain (Deutsch and Journel, 1998). In some cases, we limit the maximum distance to less than 7 m in order to achieve closure on fitting routines.

We fit variogram models mathematically as opposed to fitting by eye. In order to place confidence intervals on variogram model parameters with which to compare parameters, we adopted a rigorous statistical method for assessing the variogram and its parameters. There are three levels of statistical rigor for mathematically fitting variograms: ordinary least squares fits, weighted least squares (WLS), and generalized least squares (GLS). WLS is the most commonly used variogram fitting method where lag variogram values are given weights according to the number of sample pairs, or the variance associated with the variogram lag (e.g. Cressie, 1985; Jian et al., 1996). GLS incorporates both the sampling variance and/or the correlation of lag variogram values that arises from samples being used in multiple lag

Table 2
Summary statistics and statistical differences for Zm and PD between landforms, plots and mosaic components

	n	Mean	Upper Quartile (mound height)	Different variance (*F*-test)1	Different mean (Anova)[1,2]	Percent difference (interspace vs canopy)
Zm (cm)						
Interspace	6964	−0.3±3.1	–	A	A	
Canopy	2068	0.9±4.0	3.3	B	B	133
Hillslope	4553	0±4.1		A	–	–
Interspace	3502	−0.2±3.9	–	a[2]	a[2]	
Canopy	1051	0.7±4.8	3.9	b[2]	b[2]	129
Alluvial Fan	4479	0±2.4		B	–	–
Interspace	3462	−0.3±2.1	–	a[2]	a[2]	
Canopy	1017	1.0±2.9	2.9	b[2]	b[2]	130
Upper Hill	1538	0±5.0		A	–	–
Interspace	1266	−0.2±4.9	–	a[2]	a[2]	
Canopy	272	0.8±5.6	5.6	b[2]	b[2]	125
Middle Hill	1477	0±4.8		B	–	–
Interspace	1002	−0.2±4.4	–	a[2]	a[2]	
Canopy	475	0.5±5.4	4.2	b[2]	b[2]	140
Lower Hill	1538	0±1.8		C	–	–
Interspace	1234	−0.2±1.5	–	a[2]	a[2]	
Canopy	304	0.9±2.3	2.5	b[2]	b[2]	122
Upper Fan	1538	0±1.9		D	–	–
Interspace	1353	−0.2±1.7	–	a[2]	a[2]	
Canopy	185	1.5±2.1	2.9	b[2]	b[2]	113
Middle Fan	1453	0±2.8		E	–	–
Interspace	1090	−0.4±2.6	–	a[2]	a[2]	
Canopy	363	1.1±3.1	3.2	b[2]	b[2]	136
Lower Fan	1488	0±2.5		F	–	–
Interspace	1019	−0.4±1.9	–		a[2]	
Canopy	469	0.8±3.2	2.5		b[2]	150
PD (cm)						
Upper Hill	40,401	92±50	–	–	A	–
Middle Hill	40,401	96±51	–	–	B	
Lower Hill	40,401	127±76	–	–	C	
Upper Fan	40,401	138±72	–	–	D	
Middle Fan	40,401	113±57	–	–	E	
Lower Fan	40,401	106±60	–	–	F	

Comparisons with different letters are significantly different: Large letters denote differences between plots, and small letters denote differences between mosaic components.
[1] Different letters denote differences at 95% confidence level.
[2] Within-plot differences.

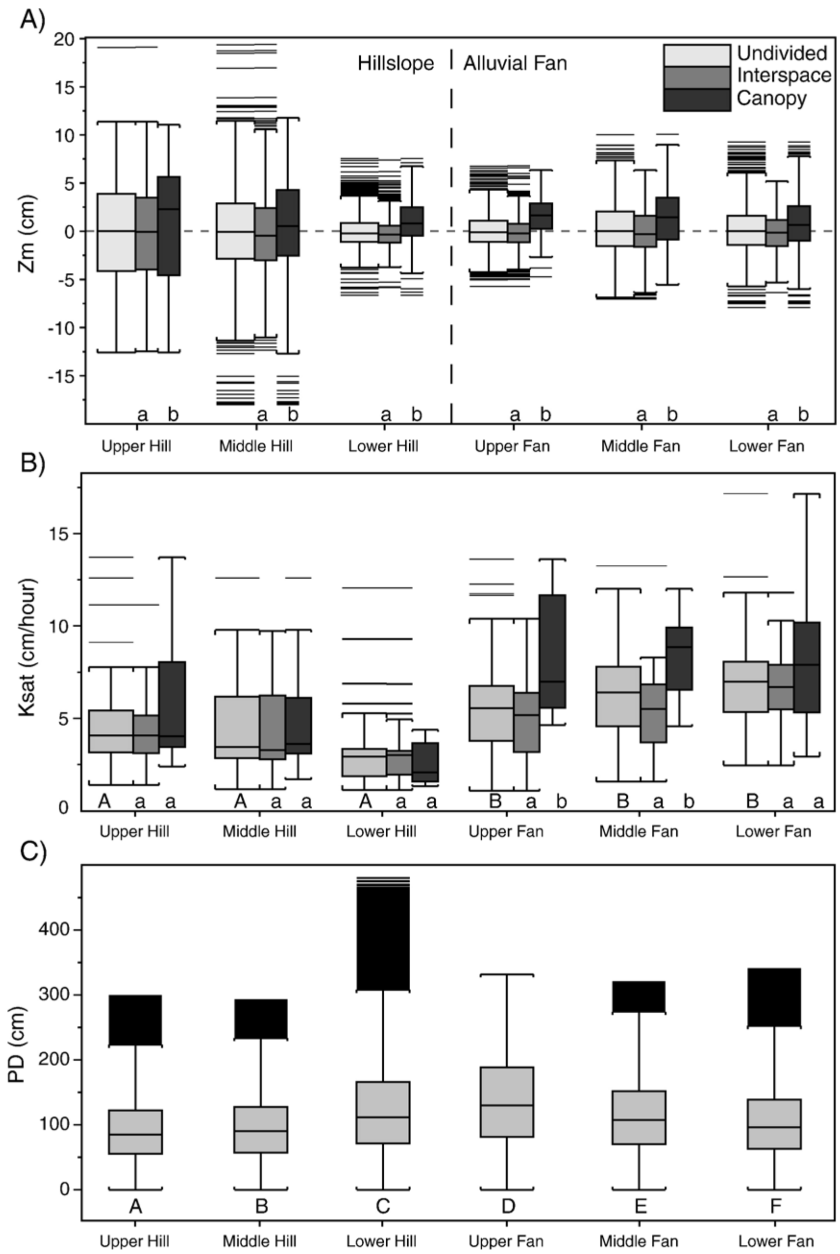

Fig. 4. Box plots of ecohydrologic properties divided by plot and mosaic component. A) Microtopography (Zm), saturated conductivity (Ksat), and distance from plant center (PD). Letters denote significant differences of means at 95% confidence; large letters denote differences between plots, and lowercase letters denote differences between mosaic components. Boxes denote sample 25% and 75% quartiles, line within box is the mean, whiskers are 5% and 95% percentiles, and horizontal lines outside whiskers are outliers. For A, the dashed line in the background is the mean (0) value.

averages (Pardo-Iguzquiza and Dowd, 2001; Pelletier et al., 2004; Zimmerman and Zimmerman, 1991). Pardo-Iguzquiza and Dowd (2001) claim that WLS is too crude to use for calculating confidence intervals of variogram parameter, however there currently is no method for assessing cross-variogram uncertainty with GLS in the literature we found. Other authors have found that while GLS methods perform best, WLS is often sufficient, particularly for simple variogram parameters such as the range and sill particularly when WLS weights were determined from the number of pairs or sampling variance in each lag (Pelletier et al., 2004; Zimmerman and Zimmerman, 1991).

We fit theoretical variogram and cross-variogram models with WLS techniques and assign lag weights using the lag sampling variance. We calculate the variance of a semivariogram lag according to Cressie (1985):

$$\mathrm{Var}[\gamma(h)] = \frac{2[2\gamma(h)]^2}{N(h)} \tag{6}$$

where $\gamma(h)$ and $N(h)$ are calculated from Eq. (3). For variance of cross-variogram lags, we take the approach of Pelletier et al. (2004) and calculate the variance according to:

$$\mathrm{Var}[\gamma_{ZY}(h)] = \frac{{\gamma_{ZY}}^2 + [\gamma_Z(h) * \gamma_Y(h)]}{N(h)} \tag{7}$$

where $\gamma_{ZY}(h)$, is calculated from Eq. (4), and γ_z and γ_y are calculated for each variable z and y with Eq. (3).

Inspection of our experimental variograms suggested that spherical, nested spherical with hole effect, and Gaussian models are likely most appropriate for experimental models. Hole effects are typical when properties have repetitive or cyclic structure such as vegetation patches. For consistency, we use a simple spherical model for fitting all of our data. Spherical variograms are modeled with:

$$\gamma(h) = \left\{ \begin{array}{l} C_0 + C_1^* \left[1.5 \dfrac{h}{\text{range}} - 0.5 \left(\dfrac{h}{\text{range}} \right)^3 \right], h < \text{range} \\ C_0 + C_1, h \geq \text{range} \end{array} \right\} \tag{8}$$

where C_0 is the nugget effect, C_1 is the spatially structured variance, and h is as above (Deutsch and Journel, 1998). The sill is the sum of C_1 and C_0.

We fit our models using the package NLME version 3 (Pinheiro and Bates, 2000) in S-plus version 6 (Insightful Corporation, 2001). We also calculated simultaneous standard errors on model parameters to assess parameter uncertainty with NLME.

We determined the spatial scale of ecohydrologic properties with the semivariogram range, and use its standard error to discuss its uncertainty and differences. We determine the correlation length scales between vegetation pattern and soil properties as the range of the soil property-PD cross-variogram.

3. Results

3.1. Vegetation measurements

We found that shrubs are significantly smaller on the hillslope than on the alluvial fan (Table 1). There are no clear patterns of differences between individual plots on a landform, suggesting that landform type is a key determinant of vegetation characteristic at our site. However, the general trend of plant measures was for them to increase down the hillslope–alluvial fan transect. Qualitatively, we also found that there is more variety of species on the hillslope, including a wider diversity of sub shrubs.

PD, our measure of distance to the nearest plant center is significantly different between all of the plots at the 99% confidence level (Table 2, Fig. 4). However, we caution that differences in PD on the order of 10 cm are likely not ecologically significant (i.e. differences between Upper and Middle Hill are not strong). Mean PD generally increased down the hillslope, with smallest values at the steepest middle plot, showing that plants are getting more spread apart, potentially in response to slope. Conversely, PD decreased down the alluvial fan transect, showing that plants are getting closer and/or larger.

3.2. Zm relations to vegetation and landform

We found that microtopography, Zm, is on average 133% higher under vegetation canopy than in interspace, showing the presence of shrub mounds (Table 2 and Fig. 4). Despite plot surfaces being overall fairly rough, shrub mounds are present on all plots regardless of landforms and positions within landform.

The average difference between mean interspace and canopy Zm across all plots is 1.2 cm. The mean difference varies across plots, from 0.7 to 1.7 cm. Mean Zm under canopy is not a good indicator of shrub mound height. On a per-plant basis, the shrub mound height would be the maximum Zm value, but our data does not allow this determination. Therefore we consider the upper, 3rd, quartile of our Zm measurements under canopy as an indicator of the magnitude of plot-average shrub mound height. Overall, the average height of shrub mounds is 3.3 cm, but on hillslopes the average is 3.9 cm and 2.9 cm on alluvial fans (Table 2, Fig. 4). We determined roughness via the variance of Zm. Zm under shrub canopy is always more rough than interspaces within a plot. In addition to microtopography being higher under shrub canopy, we also found that plot-wide microtopography was significantly rougher on the hillslope than the alluvial fan (Table 2).

These results suggest that vegetation, landform type, and position within landform are strong determinants of microtopography. We observed mounds under shrubs on all plots; hillslopes are rougher and have tall and rough shrub mounds.

Table 3
Summary statistics and statistical differences for Ksat between landforms, plots and mosaic components

Ksat (cm hour−1)	n	Mean	Different variance (F-test)1	Different mean (Anova)[1]	Percent difference (interspace vs canopy)
Interspace	263	4.86±2.82	A	A	
Canopy	97	6.54±3.66	A	B	35
Hillslope	172	4.02±2.34	A	A	
Interspace	127	3.84±1.98	a[2]	a[2]	
Canopy	45	4.56±3	a[2]	a[2]	19
Alluvial Fan	188	6.48±3.36	A	B	
Interspace	136	5.76±3.12	a[2]	a[2]	
Canopy	52	8.28±3.3	a[2]	b[2]	44
Upper Hill	58	4.62±2.4	–	A	
Interspace	45	4.26±1.74	a[2]	a[2]	
Canopy	13	5.88±3.84	a[2]	a[2]	38
Middle Hill	65	4.44±2.4	–	A	
Interspace	42	4.2±2.16	a[2]	a[2]	
Canopy	23	4.86±2.82	a[2]	a[2]	16
Lower Hill	60	3.12±1.86	–	A	
Interspace	48	3.24±1.98	a[2]	a[2]	
Canopy	12	2.52±1.14	a[2]	a[2]	−22
Upper Fan	60	5.58±2.64	–	B	
Interspace	45	4.8±2.04	a[2]	a[2]	
Canopy	15	7.98±2.82	a[2]	b[2]	66
Middle Fan	64	6.3±2.58	–	B	
Interspace	43	5.34±2.22	a[2]	a[2]	
Canopy	21	8.22±2.16	b[2]	b[2]	54
Lower Fan	62	7.56±4.26	–	B	
Interspace	46	7.2±4.08	a[2]	a[2]	
Canopy	16	8.58±4.74	a[2]	a[2]	19

Comparisons with different letters are significantly different: Large letters denote differences between plots, and small letters denote differences between mosaic components.

[1] Different letters denote differences at 95% confidence level.

[2] Within-plot differences.

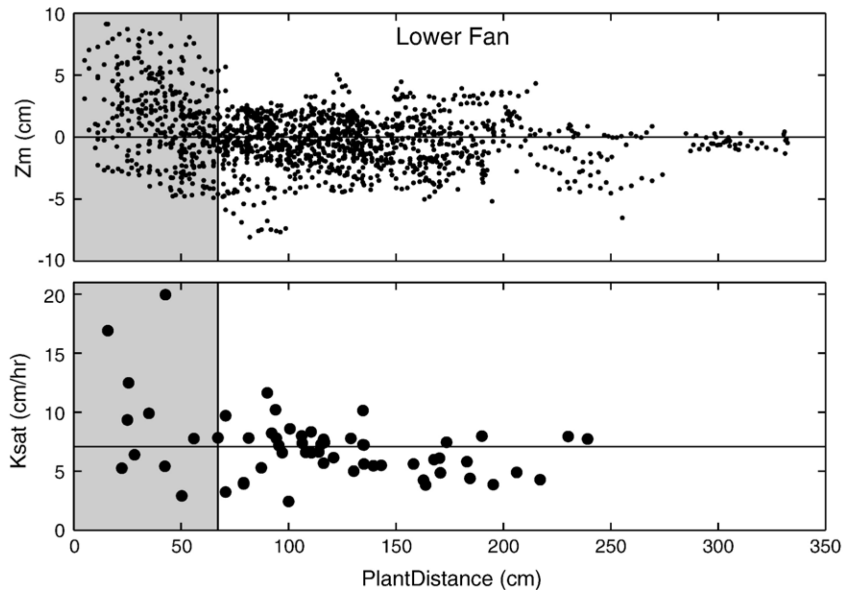

Fig. 5. Relationships of Zm and Ksat to distance from plant center (PD) for the Lower Fan plot. Shaded area represents average shrub radius, horizontal lines portray the mean value.

Alluvial fans are overall smoother and much of the microtopography is under shrubs.

3.3. Ksat relations to vegetation and landform

We found that Ksat is significantly higher (by 35%) under shrub canopy (Table 3, Fig. 4) when all of the data is subdivided only by interspace-canopy. This relationship only statistically holds true on alluvial fan plots, where Ksat is 19–66% higher under canopy. However, on hillslope plots, Ksat is slightly higher under canopy but statistically equal. At the Lower Hill plot, Ksat was actually ~22% lower under canopy.

Pooled by landform, plot-averaged Ksat is ~60% greater (significant at 95%) on alluvial fan plots than on hillslope plots (Table 3). The mean Ksat rate is not statistically different between all plots, suggesting that the landform is a strong determinant of plot-averaged Ksat (Table 3, Fig. 4). Despite the lack of significant differences of mean Ksat values within a landform, there are subtle trends with respect to position within landform. In general, mean Ksat rates decreases down the hillslope and slightly increases down the alluvial fan, from head to toe. In short, hillslopes have lower mean Ksat rates, and alluvial fans have higher mean Ksat rates. We detected no significant difference in mean Ksat rate as a function of position within landform.

Our Ksat measurements have a range of ~15× (from 1.08 to 16.80 cm/h), which is a relatively small range compared to published Ksat values, such as in Rawls et al. (1983), which range from 0.03 to 11.78 cm/h, a factor of over 500×. These results show that for related landforms, there is an overall small range of Ksat. Yet within that range, there is random variability in addition to variability described by the presence of shrub canopy.

In summary, plots on hillslopes have small plants with low cover, rough microtopography and low Ksat rates. Shrub mounds are tall and there is no significant difference in Ksat under shrubs versus interspace. Plots on the alluvial fans have taller, wider shrubs, with more cover, smooth, low-amplitude interspace microtopography, and higher Ksat rates. Shrubs on alluvial fans have taller mounds, and also have higher Ksat rates relative to interspaces beneath them.

3.4. Spatial patterns

We found that soil properties are strongly related to the pattern of vegetation, and that the effect of vegetation on soil properties extends beyond vegetation canopy. For example, Fig. 5 shows that both Zm and Ksat are high under shrub canopy (shaded area) and tend to decrease with distance away from shrubs (increasing PD). This decrease with distance and the magnitude of differences vary by landform and vegetation characteristics, which we show with geostatistics.

We fit variogram models to quantify the distance over which ecohydrologic soil properties are spatially structured, equal to the range. Examples of our variograms are displayed in Fig. 6. Despite a simple variogram model, most data were fitted well. Ksat variograms, however, were generally not fitted very well. This is largely due to two factors: sparse sampling, and likely large amounts of random variability. All Zm variograms show clear variogram features such as a sill and range, with the exception of the Upper Hill plot. Zm variograms from this plot do not show a strong sill feature, indicative of a trend in the data. We interpret that this trend arose from cross-slope curvature of the plot surface that was not accounted for in our measurements, yet is visually apparent in the field. Because of this trend, we expect range estimates for this plot to be inaccurate and represent the trend as opposed to the scale of the local variability. We feel a better estimate of the range for the Upper Hill plot is slightly less than 2 m, but present all results with the fitted values. We estimated the

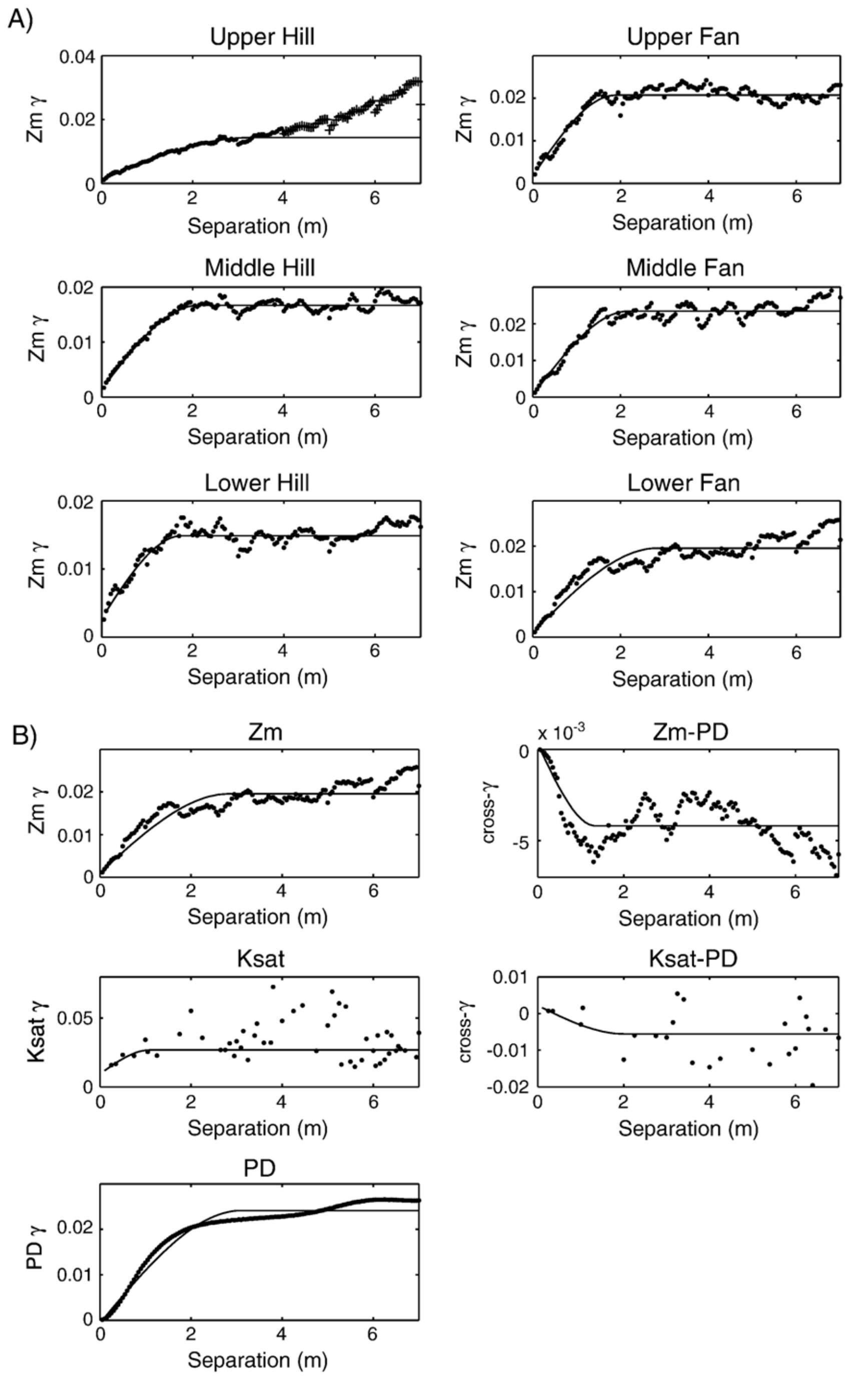

Fig. 6. A) Example variograms of Zm from all plots. Dots denote variogram lags used to fit the variogram model, shown as a line; crosses denote data not used in the fitting. B) Zm, Ksat, PD variograms and Zm-PD, Ksat-PD cross-variograms from Lower Fan plot.

Upper Hill Zm range at<2 m from a slight flattening of the variogram that may indicate a sill in the absence of a trend (Fig. 6).

We found that all of the properties show spatial patterns commonly ~1.5–3 m in scale (Table 4 and Fig. 7), whereas the average shrub radius is<1 m (Table 1). These patterns were strongly related to the vegetation pattern, and extended 3–4 times beyond the edge of vegetation canopy. The average range of all variograms is 2.5 m. As Fig. 7 shows, range parameters for most of our variograms change with respect to landform type, and for some data with position on the landform. Assuming that the range for Zm on the Upper Hill is less than 2 m, the ranges for Zm, Ksat, and PD tend to be smaller on hillslopes than on fans.

The average range of cross-variograms, representing the scale of co-variability, is 1.6 m (Fig. 7). Small standard errors on cross-variograms for Zm-PD suggest that there is a strong

Table 4
Fitted variogram and cross-variogram model parameters for ecohydrologic properties

Plot	Zm	Ksat	PD	Zm-PD	Ksat-PD
Upper Hill	3.3±0.1	**0.9±0.7**	2.3±0.1	**1.2±0.9**	**1.5±3.1**
Middle Hill	2.1±0.1	**0.4±0.7**	2.4±0.1	1.5±0.4	**0.7±3.1**
Lower Hill	1.8±0.1	**1.6±1.6**	3.9±0.1	2.0±0.2	**2.1±2.4**
Upper Fan	1.9±0.1	5.0±2.2	3.7±0.1	3.0±0.2	**1.2±1.2**
Middle Fan	2.2±0.1	**4.5±2.3**	2.7±0.1	1.3±0.2	**1.4±0.7**
Lower Fan	2.8±0.1	**1.1±1.2**	3.1±0.1	1.3±0.1	**2.0±3.1**
Mean Hill	2.4	1.0	2.9	1.6	1.4
Mean Fan	2.3	3.5	3.2	1.9	1.5
Mean	2.4	2.3	3.0	1.7	1.5

Note: bold values are not significant at 95% confidence.

Table 5
Percentages of plot area showing spatial structure associated with vegetation pattern

Plot	Zm (%)	Ksat (%)
Upper Hill	73	61
Middle Hill	84	32
Lower Hill	86	87
Upper Fan	99	49
Middle Fan	66	67
Lower Fan	72	93

Proportions defined as the aerial percent of PD measurements within the range of the cross-variogram for each property.

spatial correlation between these two variables. This is also supported by the ranges for Zm-PD to mimic those of PD, roughly by a factor of one-half those of PD. Cross-variograms for Ksat-PD have large standard errors again, due to a combination of small Ksat sample numbers, simple variogram model, and apparent random variability in Ksat. However, the average Ksat-PD range is 1.5 m, suggesting that this may be a common correlation distance for these soils.

We found that the scale of ecohydrologic properties was similar in magnitude to the scale of vegetation-associated patterns (i.e. the range of Zm is similar to the range of Zm-PD). From this we conclude that the pattern of soil properties is dependant on the vegetation pattern. This is further supported by smaller standard errors on variograms and their parameters.

It is also important to note that the scale of soil variability associated with shrub canopies is much larger than the scale of the shrub canopy itself. This is illustrated in two ways. First, we compare the proportion of space covered by vegetation canopy cover, to the range of canopy-associated variability. We used our maps of PD to calculate the proportion of plot area within the range of cross-variogram parameters. Table 5 and Fig. 8 show that the proportion of space exhibiting spatial structure of Zm and Ksat vary with landform and position within landform, although not in an apparent systematic way. Second, we compare the size of shrubs to the size (scale) of shrub-associated variability: the percent space affected by shrubs is larger than the space occupied by shrubs. The average space exhibiting spatial variability is ~75%, while the average cover is 16% and the maximum is 30% (Table 1). This is further demonstrated by pointing out that the average radius of shrub canopy is ~56 cm, while the range of spatial variability associated with shrubs is

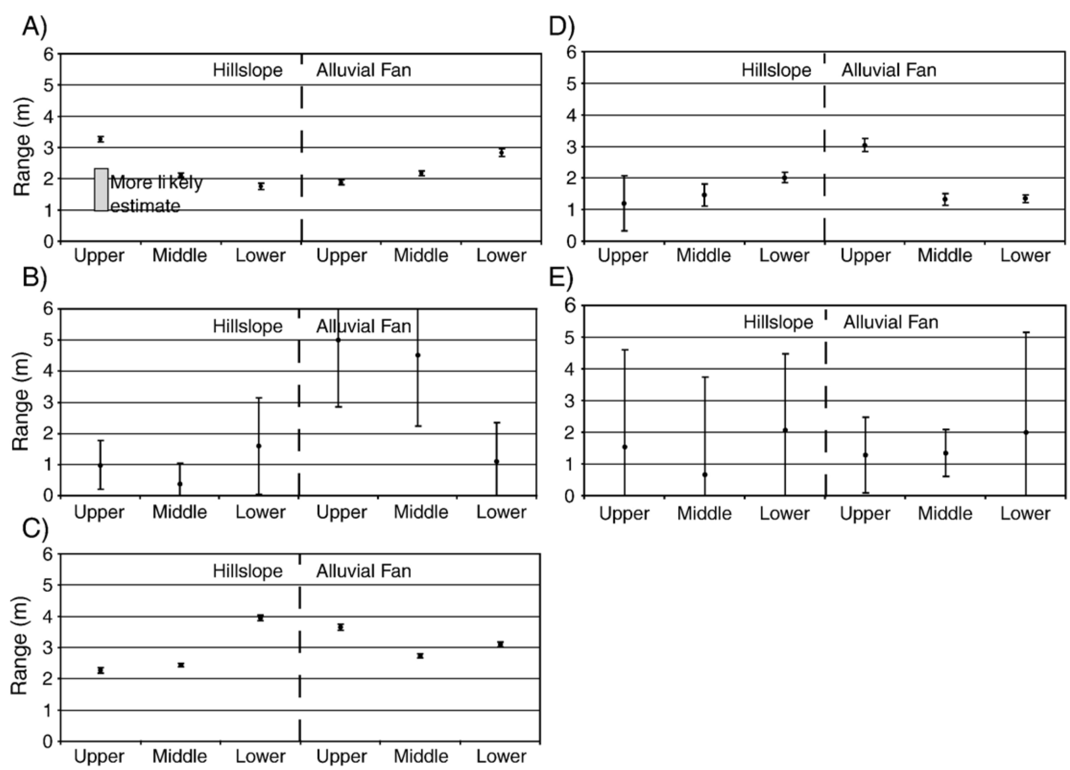

Fig. 7. Range and standard error of fitted variogram and cross-variogram models. A) Zm, B) Ksat, C) PD, D) Zm-PD, E) Ksat-PD.

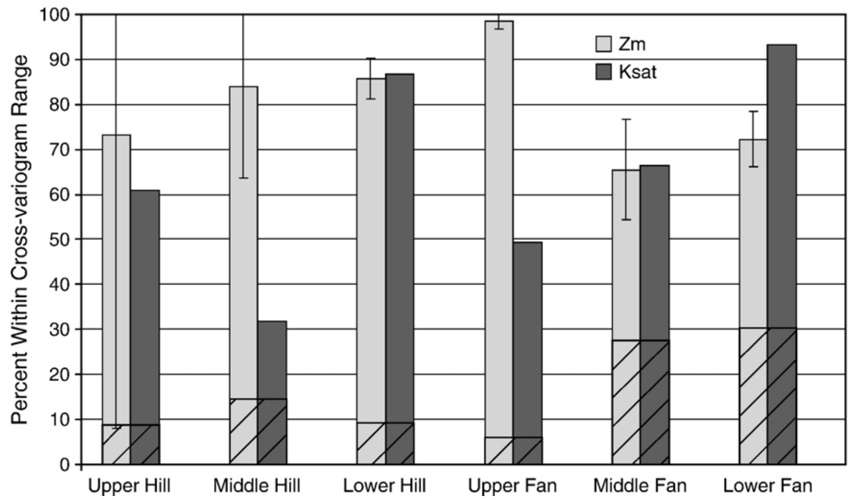

Fig. 8. Proportions of PD plot area within the range of cross-variogram parameter, representing the percent space affected by shrub-related ecohydrologic properties. Crosshatches denote canopy cover in percent.

commonly 1.5–2 m, roughly 3–4 times the size of shrub canopy.

4. Discussion

We found that there are differences between hillslope and alluvial fan landforms with respect to vegetation and associated patterns of soil ecohydrologic properties, summarized in Fig. 9. Hillslope plots have smaller shrubs. On hillslopes, shrub mounds are taller than those on alluvial fans, but relatively small compared to the large roughness that exists in hillslope interspaces. There are no statistical differences between canopy and interspace Ksat on the hillslope. Microtopography is higher and rougher, and Ksat lower, on hillslopes than on alluvial fans. Alluvial fan plots have larger shrubs with more cover. The shrub mounds are tall compared to the relatively low-relief interspaces. High Ksat rates under shrubs decrease away from plant centers and extend much farther than the canopy. Our data also suggest that vegetation more strongly affects ecohydrologic properties on alluvial fan plots than on hillslope plots. This is shown for Zm in that higher microtopography is more often found under shrubs on alluvial fans, as well as the majority of alluvial fan roughness occurring under shrub canopy. We also only found significantly higher Ksat under shrub canopy on alluvial fan plots.

Our findings are similar to those in many other semi-arid landscapes. We observed microtopography under shrubs (shrub mounds) on the order of 3–4 cm, which are similar in height to shrub mounds in southern New Mexico (Gile et al., 1998), Arizona (Parsons et al., 1992), Australia (Dunkerley, 2000), and south-eastern Spain (Bochet et al., 2000). The similarity or microtopography across regions is likely a result of the same processes interacting with morphologically similar vegetation. In most of these examples mound formation was determined to be from differential rainsplash and/or overland flow erosion. Furthermore, in SE Spain there was nearly twice as much runoff from erosional hillslopes than constructional alluvial fans (Nicolau et al., 1996). This suggests that given the same governing processes, the effects are moderated by vegetation and landform characteristics. However, these results show that mounds under morphologically similar plants can be expected to be similar given similar soil and climate contexts. This is because they develop due to a dynamic interaction between landforms, rainfall, vegetation, diffusive rainsplash, and overland flow erosion.

Infiltration rates have been widely observed to vary between sub-vegetation and non-vegetated interspaces. Most studies have

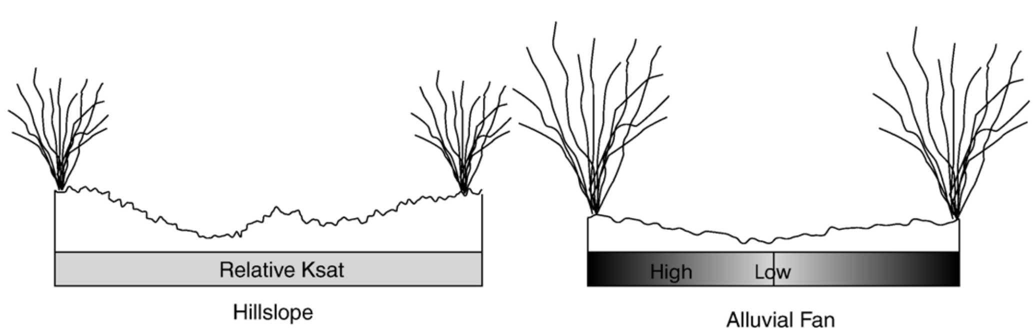

Fig. 9. Sketch showing the relative magnitudes of microtopography and Ksat in relation to vegetation on common arid land landforms at our study site. On hillslopes there is vegetation-related microtopography in the form of shrub mounds as well as significant microtopography in the interspaces. On hillslopes there is no significant increase in Ksat under or near shrubs. On alluvial fans, both microtopography and Ksat are high under shrubs and decrease with distance away from shrubs such that nearly the entire interspace area is affected by the pattern of vegetation.

Table 6
Mean canopy to interspace infiltration ratios for a variety of patchy vegetation ecosystems

Source	Vegetation type	Canopy:interspace ratio
This report	Larrea	1.3
Bhark and Small	Larrea only	1.2
Bhark and Small	Larrea and grass	1.6
Cerda 1997	*Stipa tenacissima*	2.2
Eckert and others	Larrea	2.6
Lyford and Qashu	Larrea and paloverde	3.1
Dunkerley 2002	Mulga groves	5.1
Dunkerley 2000	Maireana shrubs	5.3

focused only on the magnitude of infiltration differences between vegetation sub-canopy and interspace, and our results are similar to other small-scale infiltration measurements in a wide variety of ecosystems (Table 6). These data show that infiltration under vegetation is ~30–500% greater than in interspaces. Our measurements are very similar to the measurements of Bhark and Small (2003) made ~5 km away, as well as tussock grass in Spain (Cerda, 1997). *Larrea* shrublands in the Mojave Desert have 250–300% higher infiltration rates under shrubs than interspaces (Eckert et al., 1979; Lyford and Qashu, 1969), and isolated shrubs and vegetation groves in Australia have ~500% higher infiltration under vegetation (Dunkerley, 2000; Dunkerley, 2002). We interpret the relatively low differences in values found at the Sevilleta to be a result of the relatively recent encroachment of shrubs into the region. However, it is still unknown what the time scales are of infiltration modification associated with shrubs, and particularly if the development of high infiltration under and near shrubs will continue to progress on somewhat stabilized (i.e. alluvial fan) landforms. On our steep hillslope, the effects of vegetation on infiltration are likely moderated by the down-slope movement of sediments.

While most authors have focused only on the differences in Ksat between vegetation canopy and interspaces, Dunkerley (2000), and Lyford and Qashu (1969) showed that infiltration rates, while high under shrubs, decay as a function of distance from shrub stem center. Their results agree with our findings that Ksat is closely related to distance from plant centers, especially for alluvial fan landforms. Dunkerley (2000) found that zones of high Ksat extended 3.3 times farther than plant canopy edges. We found that for both Ksat and Zm, the extent of influence of shrub canopy is 2–4 times the canopy radius. These results are important to note because they suggest that for many semi-arid landscapes, determining soil properties based on vegetation cover alone will underestimate the actual areal extent of vegetation-like soil properties.

Our results show that given similar soil characteristics, landform type and vegetation pattern are strong determinates of small-scale variability in soil properties. This is likely a response to differing magnitudes of surface processes that occur on these landforms. Hillslopes have steep slopes and likely have sediment fluxes across the surface over reasonably short time scales. This will likely result in the erasure of the effects that vegetation has on surface processes. Conversely, gently sloping alluvial fan surfaces likely remain constructional through time as a result of relatively low net sediment fluxes (i.e. local redistribution of sediment). The relative stability of alluvial fan surfaces allows the feedbacks associated with vegetation canopy to progress, resulting in stronger vegetation-dependant soil properties.

These results have repercussions on the geomorphological and ecological dynamics of these landforms. We have shown that vegetation size and amounts, as well as the variability of soil properties, are dependent on the type of landform, and may be dependant on position within the landform. This suggests that landforms, and potentially different landform positions, will respond differently to rainfall events. This has strong implications for the long-term dynamics of sediment across them, and therefore landform evolution, as has been theorized and modeled (e.g. Collins et al., 2004; Istanbulluoglu and Bras, 2005). Furthermore, our results show that landform-dependant processes may affect the local redistribution of water and sediment. Redistribution has been attributed to the creation and maintenance of patterned mosaic vegetation on hillslopes in a variety of environments (Bergkamp, 1998; Bergkamp et al., 1996; Ludwig et al., 2005; Puigdefabregas, 2005; Sanchez and Puigdefabregas, 1994; Wilcox et al., 2003). Breshears (2006) also hypothesized that environments with moderate canopy cover may be more susceptible to landscape change, and our results suggest that hillslope environments, because of relatively low to moderate cover and relatively little modification of the soil beneath canopy, may be more susceptible to landscape change. Despite the apparent role of redistribution in concentrating resources, a key part of arid land ecologic functioning, the processes driving redistribution processes have generally not been studied, and it remains to be determined under what conditions, and to what extent, redistribution occurs.

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