Pedogenesis–Terrain Links in Zero-Order Watersheds after Chaparral to Grass Vegetation Conversion

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ABSTRACT

Four decades after conversion from chaparral to grass, zero-order watersheds were compared to identify differences in topography and its relation to soil characteristics. Three watersheds of each vegetation type were topographically mapped and sampled at random points for depth to weathered bedrock and soil water content. Stepwise regression was used to explain spatial variability in terms of terrain variables. In chaparral watersheds, convex slopes result in widespread infiltration and significantly higher storage of water on the slopes. Topography of watersheds converted to grass is more concave, resulting in higher upslope contributing areas. This favors water convergence in the subsurface and results in significantly lower soil water content in grass watersheds. In chaparral watersheds, upslope average slope gradient best explains variability in depth to weathered bedrock. In contrast, slope gradient best explains depth to weathered bedrock in grass watersheds, suggesting that the uniform plant distribution localizes erosional processes. Soil water content is explained by depth to weathered bedrock and slope aspect in both vegetation types; however, a positive relation with profile curvature is the third indicator in chaparral watersheds, compared with an inverse relation with upslope average slope gradient in grass watersheds. The result is that grass watersheds drain water downslope, creating similar processes and forms in watersheds of various sizes. For both depth to weathered bedrock and soil water content, prediction using the regression models is only successful in grass watersheds. Thus terrain variables may be ineffective predictors of soil characteristics in shrublands where a dense canopy hides a nonuniform erosional environment.

What was once perceived as random soil variability has now been linked to our incomplete understanding of the relation between pedogenesis and landscape development (Daniels et al., 1985; Kachanoski, 1988). Soil characteristics vary across the landscape, interacting with hydrologic, geomorphic, and biologic processes. Terrain analysis enables the modeling of the spatial variability of these processes, and their interactions with soils, by providing a means to integrate topography with attribute data observed in the field (Moore et al., 1991; McSweeney et al., 1994; Slater et al., 1994; Evans, 1998; Montgomery et al., 1998). The ability to link data spatially allows an iterative analysis of landscapes, integrating regional data on geology, climate, and other landscape parameters with field and lab analysis at the meso- and microscale (McSweeney et al., 1994). Integration of topography with attribute data is most effective when small catchments and slopes are the basic unit of study (Kachanoski, 1988; Dietrich et al., 1995), providing the opportunity to focus on discreet hypotheses that relate topographic form to landscape process (Montgomery et al., 1998).

Primary and secondary terrain attributes are recognized as standard means of linking topographic form to watershed process (Table 1; for complete reviews, see Moore et al., 1991; McSweeney et al., 1994; Montgomery et al., 1998). Primary attributes are calculated directly from a digital elevation model (Gallant and Wilson, 1996) and describe characteristics that control slope hydrology (Selby, 1982). Secondary attributes are derived from a combination of two or more primary attributes, and characterize the spatial variability of specific landscape processes (Gallant and Wilson, 1996). A secondary attribute used in many studies to compare soil physical and hydrologic characteristics to local topographic form is $\ln(A_S/\tan S)$, where A_S is the upslope contributing area, or the *compound topographic index* or CTI, and S is slope (Table 1). The CTI, also known as the *topographic wetness index*, has been combined with primary topographic attributes to explain patterns in A-horizon thickness, solum depth, and soil water content (Sinai et al., 1981; Hanna et al., 1982; Gessler et al., 2000; Chamran et al., 2002).

Soil and watershed development are commonly explained by the interaction of environmental factors, including topography, parent material, vegetation and other organisms, climate, and time (Horton, 1932; Jenny, 1941). Vegetation is a factor that reflects local geology and climate, but is not normally an independent component of the landscape. Vegetation effects on soil genesis include increasing organic matter in the soil, controlling subsurface water via evapotranspiration and preferential flow, and physical disruption of bedrock structure (Joffre and Rambal, 1993; Canadell et al., 1996; Martinez-Meza and Whitford, 1996; Quideau et al., 1998). Effects of vegetation on landscape processes include protection of the surface from erosion by vegetative canopy and plant litter and increasing slope stability due to root cohesion (Schumm and Lichty, 1965; Reneau and Dietrich, 1987). In the USA, >1500 nonnative vegetation species have been established (Vitousek et al., 1996). Some of these species were introduced into natural ecosystems as part of land management practices. In areas of vegetation conversion, vegetation effects can be studied without being compounded by changes in geologic parent material or climate that might occur with different geographic locations.

The SDEF (San Dimas Experimental Forest) provides an opportunity to evaluate the effect of vegetation conversion on terrain and soil characteristics. After a widespread fire in 1960, vegetation was manually con-

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Table 1. Explanations and hydrologic significance of selected terrain attributes.

Terrain attributes	Symbol	Explanation and comments	Hydrologic significance‡
Slope aspect	ψ	Slope azimuth	Solar irradiation
Slope	S	The slope angle is arctan(slope/100)	Overland and subsurface flow and runoff rate
Upslope average slope	S'	Mean slope of upslope cells	
Contour curvature	K_c	Curvature perpendicular to slope profile	Converging–diverging flow, soil water content
Upslope average contour curvature	K_c'	Mean contour curvature of upslope cells	(+ = convex, divergent; − = concave, convergent)
Profile curvature	K_p	Slope profile curvature	Flow acceleration, sediment erosion–deposition
Upslope average profile curvature	K_p'	Mean profile curvature of upslope cells	(+ = convex, erosion; − = concave, deposition)
Upslope contributing area	A_S	Area draining out of each cell	Runoff volume, steady-state runoff rate
Compound topographic index or ln(A_S/tan$S$)	CTI	Potential for water accumulation at a point and tendency of that water to move down slope	Flow accumulation and path

‡ After Moore et al. (1991).

verted in some watersheds from native chaparral to perennial grass. As a result, these chaparral and grass watersheds share similar disturbance records. While the new vegetation was being established, the native vegetation was undergoing fire recovery. The nature of the vegetation conversion enabled our research to focus on several zero-order watersheds of each vegetation type (chaparral and grass), allowing replication that is commonly missing from terrain analyses. This decreased the potential for hydrologic and topographic factors specific to individual watersheds to undermine this replicate watershed study (Montgomery et al., 1998); variability in watershed physical properties would have been overshadowed by the commonality of vegetation. The effect of vegetation on topographic form should be the discerning factor, revealing the influence of vegetation as an independent factor.

Our hypothesis was that changes in hydrologic, pedogenic, and erosional processes resulting from the vegetation conversion would be manifested as differences in topographic form and differences in the relation between topography and soil characteristics. The objective of this research was to determine the 37-yr effect of vegetation conversion on the terrain of zero-order watersheds and on the relation between topography and variability in soil characteristics. This objective and hypothesis are based on the assumption that slope form and process in all six watersheds were similar before the fire event and that the decadal effects of different vegetation types, not the conversion process itself, are responsible for differences in current watershed form.

MATERIALS AND METHODS

Environmental Setting

The SDEF is a 7000-ha area on the southern flank of the San Gabriel Mountains. The SDEF is representative of this part of southern California where dry ravel (downward movement of dry sediment due to the steepness of slopes) equals or exceeds surface water induced erosion (Kraebel and Sinclair, 1940; Sinclair, 1953; Anderson et al., 1959; Wohlgemuth, 1985). Typic Xerorthents are the predominant soil type (Ryan, 1991), but Typic Haploxeralfs are also common (Williamson and Graham, 1998). Bedrock is a mixture of highly weathered banded gneiss and granitics (Nourse, 1998). Krammes (1969) reported that the soil and bedrock are similar hydrologically, with ~70% of the porosity being noncapillary. The Mediterranean climate provides cool, wet winters and hot, dry summers with an annual temperature range of about −4 to 38°C (Dunn et al., 1988). Most precipitation occurs as rain. Historically, annual precipitation varied from 258 to 1595 mm, with a mean of 678 mm (Dunn et al., 1988). Native vegetation is chaparral.

Chaparral

Chaparral is a 1- to 3-m-tall, dense-canopy, sclerophyllous vegetation community. On the SDEF, chaparral species include chamise (*Adenostoma fasciculatum*), scrub oak (*Quercus dumosa* Nutt.), hoary-leaf ceanothus (*Ceanothus crassifolius* Torr.), black sage (*Salvia mellifera* Greene), bigberry manzanita (*Artcostaphylos* spp.), California buckwheat (*Eriogonum fasciculatum* Benth.), and yerba santa (*Eriodictyon* spp.). Fire is critical in chaparral ecosystems because it prepares seeds for germination, removes dead wood, and recycles nutrients (Hellmers et al., 1955; Barro and Conard, 1991). After fire, chaparral species reestablish dominance after 2 to 5 yr and outcompete initial blooms of native annual and perennial herbs (Keeley et al., 1981). During reestablishment of chaparral, up to 40% of rainfall is converted to overland flow, compared with approximately 1% in unburned watersheds (Rice, 1974).

Vegetation Conversion

After the 1960 fire that burned >96% of the SDEF, large areas were rehabilitated using a combination of manual vegetation removal, herbicide application, and hand seeding (Dunn et al., 1988). One such rehabilitation method involved high-density seeding of perennial grasses in watersheds that were also stabilized by planting barley (*Hordeum vulgare* L.) along contours in 0.6-m intervals, hereafter called the HDPB treatment (Corbett and Green, 1965; Rice et al., 1965). Hand seeding was first done in November 1960 (Fig. 1). Rain during the 1960–1961 season was the lowest on record (258 mm), so the watersheds were reseeded in October 1961. By the end of spring 1964, control areas of native chaparral had reestablished >50% ground cover, compared with only 33% ground cover under the HDPB treatment (Corbett and Green, 1965). The barley provided up to 10% of the HDPB cover, but did not persist after 1964 (Corbett and Green, 1965; Rice et al., 1965).

The first year after the fire, erosion was low and plant growth slow due to the low rainfall. The second year after the conversion, erosion was decreased by 70% in HDPB areas relative to chaparral control watersheds (Rice et al., 1965). Aerial photographic analysis after the 1965 storms measured slope across 140 ha of each vegetation type and showed average slopes of 59.2% under chaparral and 56.8% under grass (Rice et al., 1969). Soil slips following these storms were limited to areas with >80% slope, but there was five times more slippage in areas with perennial grass than in chaparral (Rice et al., 1969).

Veldt Grass

Perennial veldt grass (*Ehrharta calycina* Sm.) was only 15% of the original HDPB mixture (Bentley, personal communication, 1960). Sometime after 1964, veldt grass became the predominant species in areas that had been part of the HDPB treatment. Veldt grass has been used internationally for erosion control (Mulroy et al., 1992) because of its adaptability to mountainous regions with sandy soils and a Mediterranean climate (Tothill, 1962). Veldt grass commonly occurs in association with other sclerophyllous vegetation types, including the heath of South Australia (Tothill, 1962).

Field and Lab Methods

Research was conducted in six zero-order watersheds—three with chaparral and three with veldt grass (Table 2). Zero-order watersheds in the SDEF drain into larger streams that are visible on a 1:24 000 map. These zero-order watersheds range in elevation from 830 to 920 m above mean sea level and all have easterly aspects. Relief of individual watersheds ranges from 9 to 15 m. Watersheds were chosen as close together as possible, within 0.1 km^2, to reduce potential differences in basin morphometry that might be caused by regional geologic structure or base-level changes. There was no evidence of active gullying in any of the watersheds. Two of the watersheds have a steep drop (~2 m) at their base due to a combination of road building and the resultant water management; however, this management is outside of the watersheds. Except for the vegetation conversion, there was no observational or historical evidence that the interior of these zero-order watersheds was altered.

Each watershed was mapped at a resolution of ~1 m in an irregular point coverage using a Spectra-Physics Geodolite Constructor-DC5 (Spectra-Physics, Mountain View, CA) during July and August 1997. Base points for each watershed were located with a Trimble GPS Pathfinder Basic+ (Trimble, Sunnyvale, CA). Topographic maps were produced in Arc/Info (ESRI, Redlands, CA). The terrain in the SDEF presented problems with accurately locating base points for two watersheds, so slope aspect data derived in Arc/Info were checked and corrected by comparison to field measurements. Regolith and surface properties (described in Williamson et al., 2004) are summarized in Table 3 for each vegetation type. Analysis of soil characteristics showed that the soil A horizons significantly differ between the two vegetation types and that vegetation cover, measured along line transects, is distributed significantly differently.

Topographic analysis was completed using TAPES-G and UPSUM-G (Gallant and Wilson, 1996). Seven primary terrain attributes and the CTI were selected because of their relation to pedogenesis and hydrology. Grids of 1 m^2 were produced for each terrain attribute and clipped for the catchment area of each watershed. Probability density curves of these grid data will be discussed using the terminology of Evans (1998); these curves illustrate the relative distributions, but no statement of magnitude can be made.

Depth to weathered bedrock was sampled to compare surface topography to subsurface variability. Depth to weathered bedrock was sampled by auger at ≥20 randomly chosen points in each watershed, totaling $n = 72$ for chaparral and $n = 84$ for grass, during March to August 1997. Terrain attribute grids were sampled at these same points to evaluate depth to weathered bedrock as a dependent variable in correlation and stepwise regression analyses with a default significance level of 0.15 (SAS Institute, 1999). Natural-log transformations of positive, continuous variables were included in the regression. A power transformation (x^2) was also considered for all continuous variables. Data from the largest and smallest watersheds of each vegetation type (Chaparral 1 and 3 and Grass 2 and 5 in Table 2) were used to develop the regression equations; all variables left in the model are significant at ≤0.01 level. Variables are listed in the order in which they were added to the model. Data from the largest and smallest watersheds were combined to enable incorporation of the largest variability in form and process. These models were then validated using data from the intermediate-sized watersheds (Chaparral 2 and Grass 3 in Table 2). Consequently, ~40% of the data were used to validate the model while still maintaining an entire watershed as the experimental unit. Depth to weathered bedrock data were also Gaussian kriged using Arc/Info to produce a 3-m grid for each watershed.

Soil water content after the 9 Feb. 1999 storm was chosen for comparison to terrain attributes. Four storms had produced 89 mm of precipitation in the previous 30 d, including 32 mm for the 9 February event (Larson, 1999). All sites were sampled on the day following the storm to minimize effects due to evapotranspiration and to allow percolation and redistribution. Soil water data from the 9 Feb. 1999 storm significantly correlate to those from other storms when values from each sample point are Spearman ranked, suggesting that data from this storm are representative of those from other storms

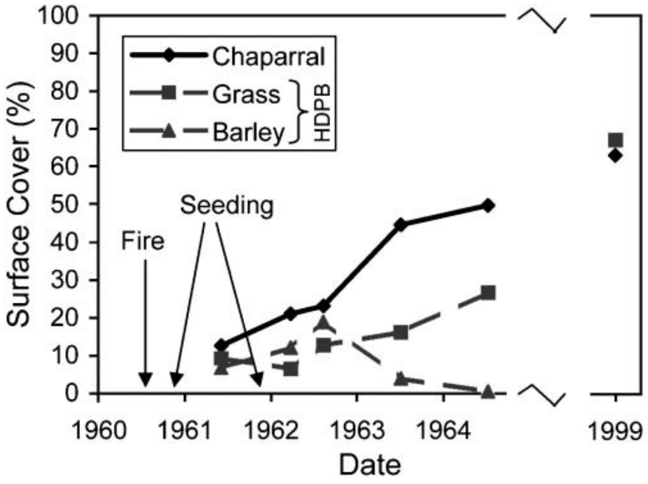


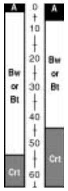
Fig. 1. Development of surface cover after the 1960 fire in watersheds with native chaparral vegetation and those that underwent the high-density perennial and barley (HDPB) treatment. Canopy surface cover was measured from 1961 through 1964 (Corbett and Green, 1965). Chaparral provided more cover in the years immediately after the fire. The barley from the HDPB treatment did not return after the fourth year. Surface cover data averaged for watersheds examined in this study show that canopy cover for each vegetation type reached ~65% (Williamson et al., 2004).

Table 2. Characteristics of the watersheds studied.†

Watershed	Area	Relief	Average slope		Aspect
	m^2	m	%		
Chaparral 1	682	13.4	41		ESE
Chaparral 2	264	9.8	40	46 ± 2	ENE
Chaparral 3	203	9.4	51		E
Grass 2	559	10.8	52		ESE
Grass 3	370	13.5	33	45 ± 2	SE
Grass 5	310	15.0	37		ESE

† Average watershed characteristics were computed using TAPES-G and Arc/Info. Area reported is plan area.

Table 3. Summary of surface and soil characteristics for watersheds.†

Chaparral							Grass					
Surface cover‡	Textural class	Roots§	K_{sat}¶	Plant-available water¶	ρ_b¶	Mean morphologic profile	Surface cover‡	Textural class	Roots§	K_{sat}¶	Plant-available water¶	ρ_b¶
%		no. dm^{-2}	cm min^{-1}	m^3 m^{-3}	Mg m^{-3}	cm	%		no. dm^{-2}	cm min^{-1}	m^3 m^{-3}	Mg m^{-3}
88 ± 6	sandy loam	80 vf 2 f–c	3.0#	0.06 ± 0.02	0.46 ± 0.06		92 ± 1	sandy loam	140 vf	1.3 ± 0.39	0.07 ± 0.02	1.08 ± 0.10
	sandy loam	20 vf 6 f–c	0.32 ± 0.09	0.12 ± 0.01	1.35 ± 0.05			sandy loam	50 vf	0.94 ± 0.45	0.09 ± 0.02	1.46 ± 0.05
	sandy loam	10 vf 2 f–vc	0.22 ± 0.06	0.09 ± 0.01	1.66 ± 0.02			loamy sand	20 vf	1.6 ± 0.70	0.06 ± 0.02	1.71 ± 0.04

† Data summarized from Williamson et al. (2004). All data are reported with standard error.
‡ Surface cover includes stems and tussocks, canopy, litter, and mineral material >2-mm diameter.
§ Mean root quantities are estimated from soil description data; v = very, f = fine, c = coarse.
¶ K_{sat} = saturated hydraulic conductivity; ρ_b = bulk density; plant-available water calculated by difference in retention at −0.01 and −1.5 MPa.
# Only one A horizon was sampled; for all other values, $n \geq 4$.

(Williamson, 1999). A Trase portable time domain reflectometer (Soil Moisture, Santa Barbara, CA) was used to measure volumetric water content in the upper 15 cm of the soil, adjacent to points where depth to weathered bedrock was measured (n = 62 for chaparral and n = 75 for grass). In some cases, the soil plus weathered bedrock was too thin to allow measurement with the TDR. Under chaparral vegetation, the TDR data mostly reflect the water content of the B horizon because the A horizon is relatively thin (Table 3). Under grass, the similar water-holding characteristics of the A and B horizons means that the 15-cm thickness could be sampled as a single layer. Soil water content was treated as a dependent variable and stepwise regression analyses were completed using terrain attributes and depth to weathered bedrock as independent variables. As with the depth to weathered bedrock analysis, data from the largest and smallest watersheds were used to build the model; data from the intermediate-sized watersheds were used to validate the model. Soil water data were also Gaussian kriged using Arc/Info to produce a 3-m grid for each watershed.

All data are reported with standard error. Differences in means were tested using a two-tailed t-test for samples with unequal variance. Differences in variability were tested using a one-tailed F test. Models were validated using a t-test of measured vs. predicted values; R^2 for the measured vs. modeled data are also reported. All statements of significance indicate $p \leq 0.05$.

RESULTS

Topographic Form

Eight terrain attributes were chosen to identify differences in topographic form between areas with native vegetation and those that underwent conversion to grass (Fig. 2, Table 4). A comparison of local slope and upslope average slope gradient for the two vegetation types shows little difference between chaparral and grass watersheds. The probability density plots for curvature show a preponderance of convex topography (positive, erosional curvature) in the watersheds sampled. In most cases, however, the grass probability densities are leftward toward concavity relative to plots for native vegetation. For average upslope profile curvature, the chaparral plots are skewed toward increasingly convex curvature in order of decreasing watershed area. Curves from the grass watersheds are similar to each other and show no trend relative to watershed area or to the chaparral watersheds.

The CTI reflects water accumulation based on surface topography. The natural log of upslope contributing area, ln(A_S), is presented to ease comparison to the CTI since higher upslope contributing areas indicate a watershed in which flow paths are better integrated. Both ln(A_S) and CTI data show a trend for chaparral watersheds, where values increase with increasing watershed size. In contrast, no relation to watershed area is evident for grass, where ln(A_S) and CTI values are similar for all three watersheds, regardless of size. Mean values of both ln(A_S) and CTI are significantly higher in converted watersheds (Table 4).

Topography and Soil Characteristics

Hydrology is not solely dependent on surface topography, but includes water movement through soil

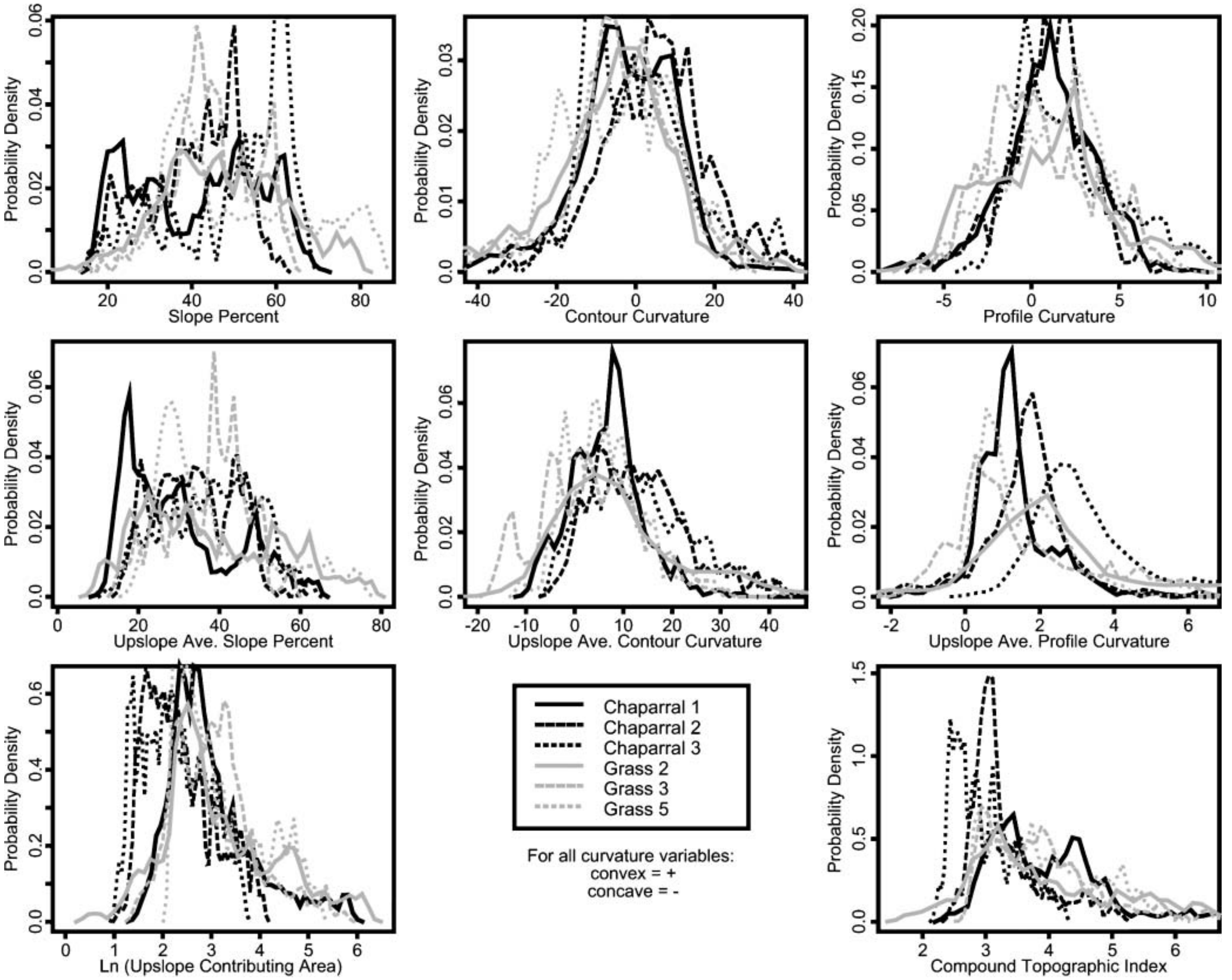


Fig. 2. Probability density diagrams for primary and compound terrain attributes for each watershed. The most consistent difference between chaparral and grass is that grass watersheds have higher densities of concave (negative) curvature. Watersheds for each vegetation type are listed in order of decreasing size (Table 2). In chaparral watersheds, several attributes show a link to watershed size. Topography in grass watersheds is similar regardless of watershed size.

and weathered bedrock (McDonnell et al., 1996). Consequently, depth to weathered bedrock was sampled in each watershed as an indicator of the accumulated, longer term effects of landscape processes. Data are summarized in Table 5 for each vegetation type and grid maps for two watersheds are shown in Fig. 3. In general, depth to weathered bedrock, or solum thickness, is largest at the summit and decreases toward the outlet of the watershed. Mean depth to weathered bedrock is not statistically separable between the two vegetation types; however, the variability in depth to weathered bedrock is significantly lower in watersheds with grass relative to chaparral.

Depth to weathered bedrock was linearly correlated with terrain attributes (Fig. 4). Upslope average slope gradient explains the highest amount of variability for both vegetation types. Both upslope average slope gradient and the similarly correlated slope gradient are inverse relations. Stepwise regression was used to explain the spatial variability in depth to weathered bedrock using data from the largest and smallest watersheds (Table 6). Neither regression explains more than 37% of

Table 4. Mean values of terrain attributes.†

Vegetation	Slope	Upslope average slope	ln(upslope contributing area)	Contour curvature	Upslope average contour curvature	Profile curvature	Upslope average profile curvature	Compound topographic index
	%		$m^2\ m^{-1}$	$(100\ m)^{-1}$		$(100\ m)^{-1}$		
Chaparral	46.1 ± 1.57	35.4 ± 1.36	2.64 ± 0.102*	0.0964 ± 1.67	10.1 ± 1.10	0.996 ± 0.295	1.88 ± 0.140	3.47 ± 0.0960*
Grass	45.1 ± 1.63	36.3 ± 1.51	2.97 ± 0.107	−1.19 ± 3.70	10.0 ± 3.33	0.590 ± 0.409	1.94 ± 0.280	3.84 ± 0.109

† $n = 72$ for chaparral and $n = 86$ for grass.
* Significant difference ($p < 0.05$) between the two vegetation types.

Table 5. Mean values of depth to weathered bedrock.

Vegetation	Mean depth	SE*	*n*
	cm		
Chaparral	**30.7**	**3.3**	**72**
Grass	**27.3**	**2.3**	**84**

*** Significant difference ($p < 0.05$) between variability in depth to weathered rock under the two vegetation types.**

these data and no additional attributes help the regression analyses at the 0.01 or 0.05 level; although these coefficients of interpretation are low, they are significant due to the large sample size. These regression equations were validated using data from the intermediate-sized watersheds. The R^2 of the measured vs. modeled data was <0.1 for both vegetation types. In watersheds converted to grass, however, model data did not significantly differ from measured data (Table 6).

Following the work of other researchers (e.g., Moore et al., 1988, 1993; Gessler et al., 1995), near-surface soil water content was identified as a dependent variable and compared with the terrain attributes. Soil water content is indicative of short-term effects (i.e., seasonal and annual) of water redistribution in the landscape. Mean soil water content was significantly higher in chaparral watersheds relative to grass watersheds (Table 7). Based on the correlation analysis (Fig. 4), depth to weathered bedrock (D) was included as an independent variable for explanation of spatial variability in water content. Depth to weathered bedrock was valid as an independent variable because it was measured in the field.

Soil water content after the 9 Feb. 1999 storm best correlates to profile curvature in chaparral watersheds and to depth to weathered bedrock in grass watersheds. For both vegetation types, soil water content shows a significant inverse correlation to both slope variables and $\ln(A_S)$, as well as a significant positive correlation to depth, profile curvature, and upslope average contour curvature. Using data from the largest and smallest

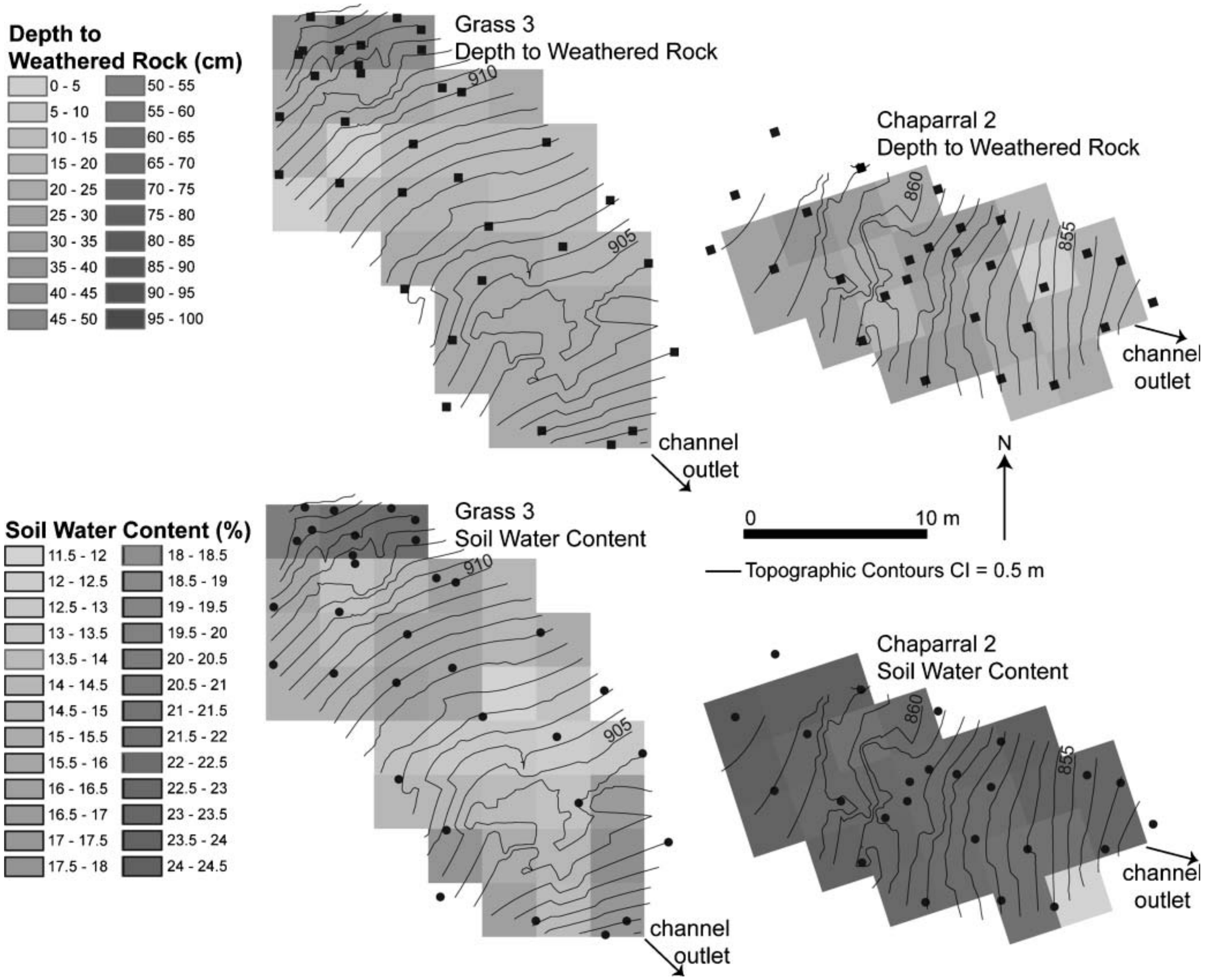


Fig. 3. Depth to weathered rock and soil water content in two zero-order watersheds. These examples are from the Grass 3 and Chaparral 2 watersheds. Both soil characteristics are shown as a 3-m grid, overlain by a topographic map of each watershed; points indicate measurement locations. In the six zero-order watersheds examined, depth to weathered rock generally is thickest at the summit and thins toward the outlet of the watershed. In all watersheds, soil water content reflects depth to weathered rock; however, this relation is strongest in grass watersheds.

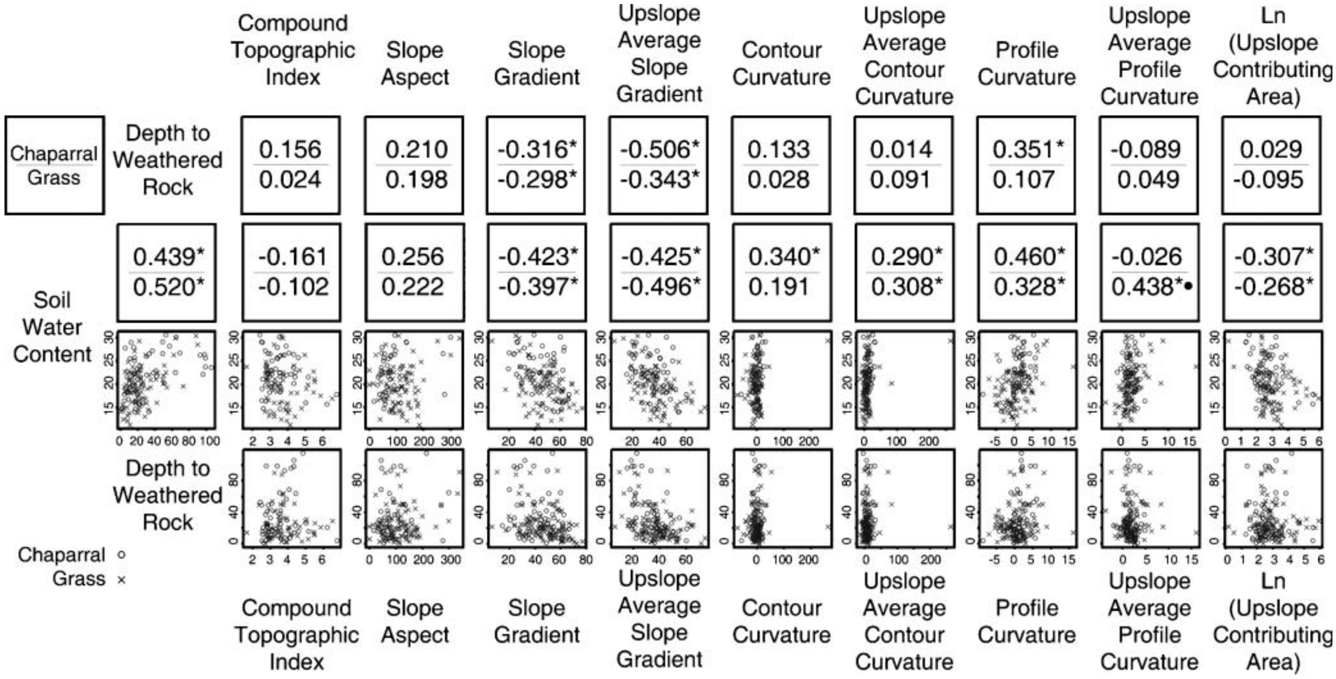


Fig. 4. Scatterplots and correlation coefficients between terrain attributes and soil characteristics. For each set of correlation coefficients, values for chaparral are above the line and grass below. *Significant correlation ($p \leq 0.05$). •Significant difference between chaparral and grass ($p \leq 0.01$).

watersheds, stepwise regression showed that different attributes are most indicative of soil water content for the different vegetation types (Table 8). The resultant models explain >65% of the variability in soil water content in watersheds of each vegetation type. As with depth to weathered bedrock, these regressions are significant due to the large sample size. No other indicators are significant at the 0.05 level. The models were validated using data from the intermediate watersheds. For grass, there is no significant difference between measured and modeled data; the mean difference between measured and modeled data is also significantly lower for grass (Table 8).

DISCUSSION

Topographic Form and Watershed Behavior

Evaluation of watershed topography showed that differences due to vegetation conversion are slight, but consistent. There are no differences in slope gradient between the vegetation types (Fig. 2, Tables 2 and 4). This change from the findings of Rice et al. (1969) may be due to the different resolution of measurement (1-m^2 grid cells vs. random points on 1:5000 aerial photographs), the smaller total area considered (0.24 vs. 288 ha), or a resultant equilibrium now that both vegetation communities have reached ~90% surface cover.

The curvature analyses show that convex topography is prevalent in these zero-order watersheds. Interestingly, soil water content was positively correlated to both contour and profile curvature (Fig. 4), indicating that this convexity results in widespread infiltration and retention of water on the slopes. This convexity results in water distribution along the slopes where the average infiltration capacity of 2.0 ± 0.4 cm min^{-1} exceeds recorded rainfall rates for the SDEF (Williamson et al., 2004), thus enabling storage of soil water on the slopes. Correlation between convexity and soil water content is higher in chaparral watersheds, where small rills create many separate flow pathways, many of which do not reach the base of the watershed; this further increases the opportunity for infiltration on the slopes. Any subsurface flow that follows surface topography in these watersheds has little opportunity for concentration and

Table 6. Regression of depth to weathered rock.†

			n		Measured vs. modeled data¶		
Vegetation type	Equation‡	R^2§	Model§	Validation¶	Mean difference	p value	R^2
					cm		
Chaparral	$D = 218.06 - 52.05[\ln(S')]$	0.373	45	27	−12.4 ± 3.2	0.001#	0.049
Grass	$D = 43.65 - 0.01S^2$	0.205	49	35	−5.22 ± 3.5	0.121	0.038

† Regressions reported are at $p \leq 0.01$.

‡ D = depth to weathered rock (cm), S = slope (%), S' = upslope average slope (%).

§ All regression equations are based on data from the largest and smallest watershed of each type; the R^2 refers to these data and the resulting equation.

¶ Models validated using data from intermediate-sized watersheds; the mean difference, p value, and R^2 refer to the comparison of measured and modeled data for these intermediate watersheds.

Significant difference between the measured data and those predicted by the model.

Table 7. Mean values of soil water content.

Vegetation	Mean soil water content	SE	n
	%		
Chaparral	**22.0**	**0.53**	**62**
Grass	**19.3*****	**0.50**	**75**

*** Significant difference ($p < 0.001$) between the two vegetation types.

resultant saturation overland flow, an effect that becomes more significant with decreasing watershed size.

Watersheds converted to grass have a higher probability of concave slope curvature relative to chaparral watersheds (Fig. 2). More concave curvature translates to a more convergent (contour) and depositional (profile) environment in grass relative to chaparral (Moore et al., 1991; Montgomery et al., 1998). Consequently, overland and subsurface flow should be concentrated downslope, not distributed across the slopes, in grass watersheds to a greater degree than in chaparral watersheds. In grass watersheds, higher upslope contributing areas, reflected by significantly higher $\ln(A_S)$ and CTI values, result in direction of flow toward centralized, downslope areas (i.e., the channel), regardless of watershed size (Fig. 2, Table 4).

Spatial Variability of Soil Characteristics

Depth to weathered bedrock is significantly less variable in converted watersheds (Fig. 3, Table 5). A potential explanation for this decreased variability is that sediment movement is different between the two vegetation types. Although ~90% total surface cover was measured for both vegetation types, the bases of grass tussocks provide a significantly increased and more uniform distribution of cover relative to chaparral stems (Table 3). An additional difference is that the grass canopy commonly rests on the surface, unlike the canopy of several chaparral shrubs. A potential effect of these differences in cover is that sediment produced in grass watersheds, by burrowing animals for example, will not move far because of the physical presence of grass plants. Wohlgemuth (personal communication, 1997) saw that sediment movement in SDEF perennial grass watersheds was one to two orders of magnitude lower than in chaparral watersheds. He related this to differences in the growth habit of the vegetation.

The significant relation between depth to weathered bedrock and upslope average slope gradient, an attribute that indicates the potential energy of overland and subsurface flow (Moore et al., 1991; McSweeney et al., 1994; Montgomery et al., 1998), suggests that depth to weathered bedrock reflects water flow paths in both vegetation types. Depth to weathered bedrock is largest at the upper divide of the watersheds, reflecting the landscape stability along the relatively flat interfluves relative to the steeply sloped interior of the watersheds from where water and sediment are carried to larger order stream systems. Upslope average slope gradient is the most indicative terrain attribute for depth to weathered bedrock in chaparral watersheds (Table 6). This is an inverse relation, suggesting that, as the slope gradient of the contributing area increases, there is less opportunity for development of a thick soil. These watersheds also experience dry ravel, so this slope-gradient influence would occur even in the absence of surface flow. In grass watersheds, the regression showed local slope gradient to be the best indicator of depth to weathered bedrock, suggesting that if the same erosional processes are in action, whether from surface water flow or dry ravel, the presence of the grass tussocks localizes this effect.

There is further evidence that the relation between topography and depth to weathered bedrock is different in converted watersheds. Under grass, depth to weathered bedrock generally shows a lower correlation to topographic attributes, relative to chaparral (Fig. 4). Under grass, variability in soil water content best correlates with depth to weathered bedrock, not topographic attributes. Evidently, the uniform surface cover in converted watersheds, combined with the stabilizing influence of large grass tussocks on sediment movement (Wohlgemuth, personal communication, 1997; Williamson et al., 2004), results in depth to weathered bedrock acting as an independent variable that is no longer controlled solely by topography.

The effects of pedogenic processes on depth to weathered bedrock accrue during multiple years. In contrast, soil water content is a snapshot of current controls on water redistribution. These controls include the contact, at ~30-cm depth (Table 5), between the soil and the weathered bedrock, making it an important indicator of soil water content in both vegetation types (Table 8). Slope aspect is also an important indicator of soil water

Table 8. Regression of soil water content.†

Vegetation type	Equation‡	R^2§	n		Measured vs. modeled data¶		
			Model§	Validation¶	Mean difference	p value	R^2
					%		
Chaparral	$\theta_v = 9.77 + 2.05[\ln(D)] + 0.80K_p + 0.06\psi$	**0.675**	**35**	**17**	**2.87 ± 0.78**	**0.003#**	**0.005**
Grass	$\theta_v = 28.02 - 3.06[\ln(S')] + 0.0001\psi^2 + 0.001D^2$	**0.752**	**39**	**31**	**−0.99 ± 0.64*****	**0.306**	**0.359**

† Regressions reported are at $p \leq 0.01$.

‡ θ_v = soil water content (%), D = depth to weathered rock (cm), K_p = profile curvature (per 100 m), ψ = slope aspect (°), S' = upslope average slope gradient (%).

§ All regression equations are based on data from the largest and smallest watershed of each type; the R^2 refers to these data and the resulting equation. Some data points were not used because of missing depth or aspect data.

¶ Models validated using data from intermediate-sized watersheds; the mean difference, p value, and R^2 refer to the comparison of measured and modeled data for these intermediate watersheds. Some data points were not used because of missing depth or aspect data.

Significant difference between the measured data and those predicted by the model.

*** Significant difference between the two vegetation types at $p < 0.001$.

content for both vegetation types because of its effect on evapotranspiration. In chaparral watersheds, however, increased profile curvature is linked to increased soil water content, again indicating that increased convexity leads to widespread infiltration as opposed to channelization of water down, away from the slopes. In contrast, grass watersheds show what might be a more expected inverse relation between increased average upslope slope gradient and the resultant decrease in soil water content as water is given a method of drainage from the slopes.

Although CTI significantly differed between vegetation types, CTI did not significantly correlate with depth to weathered bedrock or soil water content for either vegetation type. Several researchers have shown a relation between CTI and soil characteristics (Sinai et al., 1981; Hanna et al., 1982; Moore et al., 1988, 1993; Gessler et al., 1995). Each of these analyses was done in a crop or pasture environment, however, with uniform vegetation and slopes <15%. Chamran et al. (2002), working in a zero-order, mediterranean-climate watershed, found that CTI was an adequate predictor of soil water; however, the significance of this predictor increased as the total soil water content increased and lateral flow paths became active. The link between CTI and soil characteristics is dependent on the relation between subsurface water paths and surface topography. In the SDEF, 99% of precipitation infiltrates into the highly permeable soil, where it is redistributed by the regolith (Krammes, 1969; Rice, 1974); <1% of precipitation contributes to overland flow. Previous researchers identified two sources of error in the estimation of soil water patterns. The first is a spatial variability in the transmissivity of the surface and subsurface (Lamb et al., 1998). The second is the fact that, in many instances, flow pathways modeled by surface topography do not necessarily model flow pathways as defined by subsurface patterns due to lithology or stratigraphic layers (Jones, 1986; McDonnell et al., 1996; Lamb et al., 1998). Both of these are potential sources of unexplained variability in the SDEF watersheds, where the soil–weathered bedrock contact is irregular and relatively close to the surface.

Based on the validation of the regression equations, the ability to predict both depth to weathered bedrock and soil water content is more successful in grass watersheds (Tables 6 and 8). There are two potential reasons for this. First, process and topographic form of chaparral watersheds changes based on watershed size; there is no evidence that this occurs in grass watersheds. Second, the less uniform plant environment in chaparral watersheds creates localized concentrations of moisture. For example, in the Chaparral 2 watershed, the three points with the highest average soil water content for January and February 1999 were located adjacent to buckwheat stems (Williamson, 1999). In contrast, the more uniform coverage of grass plants distributes rainfall to a greater portion of the surface. Stem flow along grass leaves is partially directed downgradient to adjacent, touching plants, not only to the plant base, distributing rainfall throughout the watershed (Williamson, 1999). Vegetation effects on rainfall disposition suggest that if topography and soil characteristics are to be assessed at a resolution of 1 m^2, assessment of plant distribution, not simply canopy cover, might improve our understanding of soil water patterns. This analysis also suggests that terrain variables may be ineffective predictors of soil characteristics in dense shrublands where a complete canopy cover hides a nonuniform erosional environment.

CONCLUSIONS

The relation between terrain and soil characteristics changed in the four decades after vegetation conversion in zero-order watersheds. This interpretation is based on the understanding that slope form and process in all six watersheds were similar before the fire event and that the decadal effects of different vegetation types, not the conversion process itself, are responsible for differences in current watershed form and soil characteristics. The overwhelming convexity in chaparral watersheds results in storage of water on the slopes and a change in process and form as watershed size increases. Compared with chaparral watersheds, grass watersheds experience a combination of incisional, erosional, and depositional processes that result in a larger proportion of concave topography, a significantly higher upslope contributing area and CTI, and a significantly higher soil water content. The result is that grass watersheds drain water downslope, creating similar processes and forms in watersheds of varying sizes. For both depth to weathered bedrock and soil water content, prediction using the regression models was only successful in the grass watersheds. This analysis suggests that vegetation can act as an independent landscape component, altering the interactions of other environmental factors. Attempts to predict spatial variability of soil characteristics must not overlook vegetation influences on landscape processes.

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