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Impact of small mammal disturbances on sediment yield from grassland and shrubland ecosystems in the Chihuahuan Desert

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Abstract

This study examines water and sediment movement on Summerford bajada in the Jornada Basin, N.M. Forty-five rainfall simulation experiments were conducted on 1- and 2-m^2 runoff plots in grassland, degraded grassland, and shrubland communities. Within the shrubland community separate experiments were conducted in shrub and intershrub environments. Regression analyses indicate that for a 30-min rainfall at approximately 130 mm h^{-1}, water yields on these environments are negatively related to the percentage of ground covered by vegetation and/or litter. In the degraded grassland and intershrub environments, sediment concentration is positively correlated with the average diameter of small mammal disturbances, suggesting that animal digging is an important factor controlling rates of erosion in these environments. Sediment concentration is not correlated with any surface property in the grassland or shrub environments. An analysis of water yields and sediment concentrations at 5-min intervals during the 30-min simulated rainfall experiments reveals that the influence of the above-mentioned factors on runoff and erosion is established during events as short as 10–15 min. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Animal disturbance; Sediment yield; Zoogeomorphology; Desert hillslopes; Surface runoff; Biopedturbation

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1. Introduction

Many animals excavate burrows or dig for and cache food in the soil. These activities are likely to directly affect runoff and erosion by altering soil infiltration rates and/or the availability of loose sediment. In environments where animal disturbances are manifest, account must be taken of these processes, otherwise significant errors may be incurred in estimating the rates and spatial and temporal variability in runoff and sediment yields (Yair and Rutin, 1981).

Badgers, grizzly bears, wild pigs, echidnas and mountain goats are examples of animals whose habits impact geomorphic systems in temperate regions by providing transportable sediment to overland flow (Morcombe, 1968; Vroom et al., 1980; Tisdell, 1982; Long and Killingley, 1983; Lyman, 1988; Butler, 1995). Imeson (1976) and Imeson and Kwaad (1976) concluded that material deposited on hillslopes by burrowing animals served as important sources of sediment in the forested Luxembourg Ardennes. They suggested that animal diggings may even have played a role in the development of regional slope convexities. Roose (1976) found that the volume of material excavated by termites and earthworms in a tropical forest far surpassed that generated from other processes.

Although most studies of the impacts of animal activities on hillslope processes have been conducted in humid and tropical environments such impacts are likely to be far more significant in arid and semiarid regions where Horton overland flow is widespread and soil surfaces are unprotected by vegetation. In their review of the impact of biopedturbation by mammals in deserts, Whitford and Kay (1999) showed that mammals contribute significantly to the development and maintenance of heterogeneity in arid ecosystems. Biopedturbation across a range of temporal and spatial scales increases soil porosities and infiltration rates, enhances soil nutrient levels, and improves soil structure. At Seder Boqur in the Negev desert, Israel, Yair et al. (1978) found that hillslope surface properties, such as slope length and gradient, failed to account for variations in sediment yields. Instead the extensive diggings and burrowings of porcupines and isopods were identified as the source of loose soil material which was then transported downslope by overland flow (Yair and Rutin, 1981). Yair (1995) also found that bioturbation by isopods contributed to the spatial redistribution of soil, water, and salts at Seder Boqur.

Elkins et al. (1986) examined the influence of subterranean termites on rates of infiltration and sediment production within a Chihuahuan desert ecosystem. These authors found that on plots with low vegetation covers ($< 5\%$), infiltration rates were higher and runoff volumes and bedloads were lower when termites were present than when they were not. Chew and Whitford (1992) and Whitford (1993) studied the impact of the banner-tailed kangaroo rat (*Dipodomys spectabilis*) on the desertification of Chihuahuan desert grasslands. They found that the mounds produced by these animals, which serve as their burrows, are nitrogen rich and have reduced bulk densities and better drainage than the adjacent soils (Moorhead et al., 1988; Mun and Whitford, 1990).

Brown and Heske (1990) and Heske et al. (1993) studied the role of kangaroo rats (*Dipodomys* spp.) in desert ecosystems in southeastern Arizona. They showed that where kangaroo rats were excluded from field plots there was an increase in the density of a particular grass species. Thus, these animals appear to be driving the desertification of grasslands in this region through their feeding habits.

These investigations all indicate that animal activities can have a significant influence on abiotic processes, especially in arid and semiarid environments. This study aims to contribute to the literature on animal impacts on geomorphic processes by using rainfall simulation experiments to estimate the effect of small mammal activities on sediment yield in a Chihuahuan desert ecosystem in the American southwest.

2. Study area

This study was conducted in the Jornada del Muerto Basin in southern New Mexico, USA. The Jornada Basin is situated within the Mexican Highland section of the North American Basin and Range physiographic province and is bordered by erosional mountain slopes that provide the major sources of present-day runoff and sediment (Gile et al., 1981; Wondzell et al., 1987). Coalescing alluvial fans (i.e. bajadas) extend from the mountain ranges down to the essentially level basin floor.

The climate of the basin is warm and semiarid (Gile et al., 1981). The highest and lowest maximum monthly temperatures of 36°C and 13°C occur in June and January, respectively (Gibbens and Beck, 1988). The average annual precipitation is 230 mm, 64% of which occurs as localized high intensity, short duration convective events in the summer months of July through October. These storms produce significant volumes of surface runoff. In contrast, precipitation during the winter months of November through March is generated by longer lasting, low-intensity frontal storms that originate over the Pacific Ocean (Gibbens and Beck, 1988). Winter precipitation accounts for 23% of the annual total, but its intensity is generally low—so low in fact that most of the rainwater infiltrates into the soil. The remaining 12% of the annual precipitation is received during the spring months of April through July.

In the Jornada Basin, species such as pocket mice (*Perognathus* spp.), rabbits (*Sylvilagus audubonii* and *Lepus californicus*) and kangaroo rats (*Dipodomys* spp.) have been observed to make numerous excavations in the soil, predominantly in search of buried seeds or caches (Steinberger and Whitford, 1983). These activities can result in considerable disturbance to the soil surface (Fig. 1). Surveys revealed that in excess of 20% of the ground surface in the study site could be disrupted by small mammals. The average depth of these disturbances is typically between 20 and 30 mm. However, holes up to 200 mm deep have been observed. Steinberger and Whitford (1983) noted that rates of disturbance in the Jornada Basin are most intense in the late spring through mid-summer. Where these disturbances are extensive, runoff and erosion processes are likely to be affected.

The present study was carried out on a bajada surface adjacent to Summerford Mountain on the western edge of the Jornada Basin (Fig. 2). This bajada, hereafter called the Summerford bajada, extends approximately 2.5 km from the foot of Summerford Mountain to the basin floor and has an average slope of 4%.

Two distinct vegetation communities can be identified on Summerford bajada. A grassland dominated by black grama (*Bouteloua eripoda*) is found at the base of

Fig. 1. Small mammal disturbances on a bare surface in the Jornada Basin.

Summerford Mountain. The remainder of the surface is a shrubland dominated by creosotebush (*Larrea tridentata*).

The intention of this study is to investigate the controls of sediment yield in the grassland and shrubland communities on Summerford bajada. Accordingly, field sites were selected that are typical of each community. The grassland field site is located at the foot of Summerford Mountain. The vegetation at this site is predominantly black grama (*B. eripoda*) grass with the occasional mesquite (*Prosopis juliflora*) and mormon tea (*Ephedra trifurca*) bush.

The shrubland field site is situated approximately 300 m downslope from the grassland site. Creosotebush (*L. tridentata*) is the dominant vegetation. Several grass and herb species are also present, but these are typically located beneath the shrubs.

A third field site, hereafter called the degraded grassland site, is located about 300 m north of the shrubland site. The degraded grassland has a lower total vegetation cover than either of the other sites. The flora is a mixture of black grama grasses and scattered creosotebush shrubs. This community represents the transition from an established black grama community to a creosotebush community.

3. Materials and methods

3.1. Causal model

Small mammal disturbances usually consist of an excavated hole with an accompanying mound of loose material (Fig. 1). These two features may affect sediment yield in

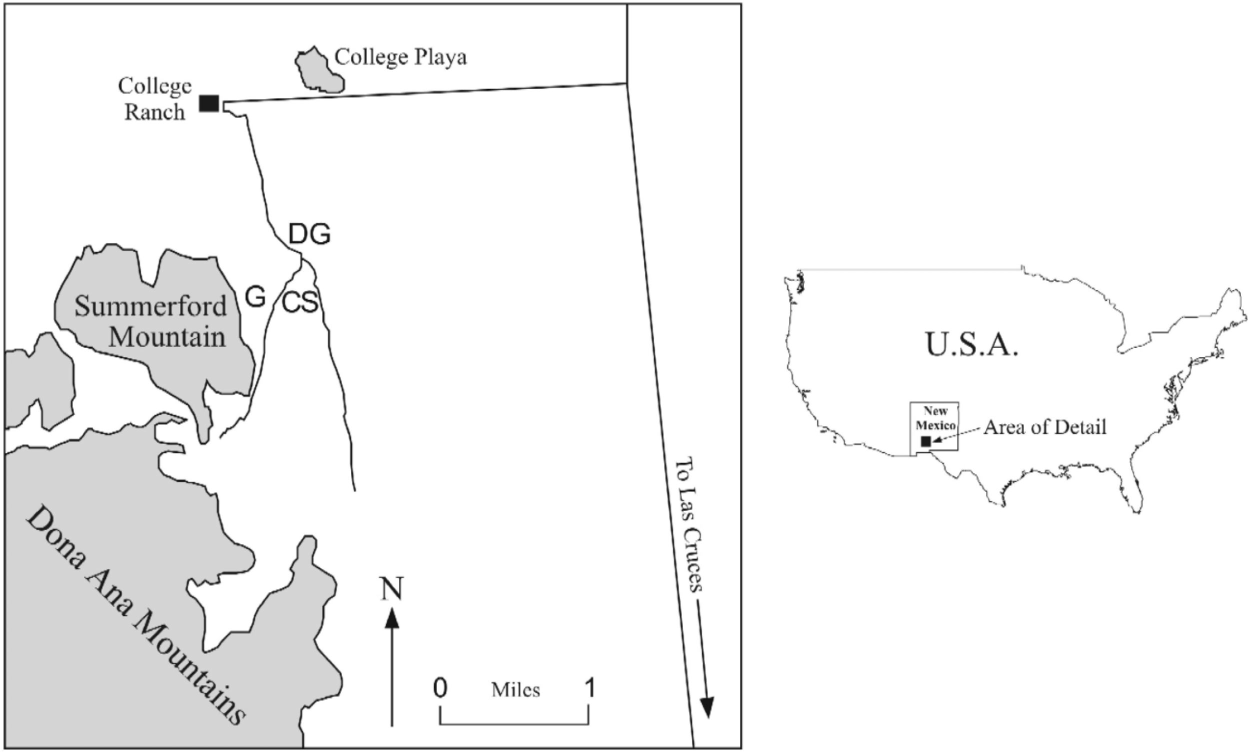


Fig. 2. Approximate location of study sites on the Summerford bajada. G = black grama grassland. DG = degraded black grama grassland. CS = creostebush shrubland.

different ways. A hole may serve as a site for surface water retention and infiltration and may, therefore, reduce overland flow and, hence, lower sediment yield. A mound, on the other hand, may serve as a discrete sediment source that increases the sediment concentration in overland flow and, hence, increases sediment yield. This study investigates the controls of sediment yield with the aid of a causal model (Fig. 3). Inasmuch as sediment yield (S_Y) is the product of water yield (W_Y) and sediment concentration (S_C) a closed causal relationship exists in which W_Y and S_C alone determine S_Y. Thus, a multiple regression between the dependent variable of S_Y and the independent variables of W_Y and S_C will have a multiple coefficient of determination $R^2 = 1.00$. In the model, a ground surface property may affect S_Y through its influence on W_Y or S_C, or both. The surface properties that influence W_Y and S_C are identified by performing regression analyses with W_Y and S_C as the dependent variables and a variety of surface properties as the independent variables.

The causal model is presented in the form of a flow diagram (Fig. 3) in which an arrow indicates the existence of a statistically significant ($\alpha = 0.10$) causal relation between a dependent and an independent variable. The head of the arrow points toward the dependent variable. The strength and direction of the relation is indicated by the standardized partial regression (beta) coefficient listed beside each arrow (Clark and Hosking, 1986). The r^2 value for the relations between either W_Y or S_C and the surface properties is reported beside the flow diagram.

3.2. Surface sealing

Poesen (1992) found that soil texture was an important factor determining whether or not a soil will develop a surface seal. In particular, he concluded that loamy sands were very susceptible to sealing. Surface sealing reduces soil permeability, thereby increasing overland flow discharge (Mauchamp and Janeau, 1993). Consequently, it was important to assess the sealing potential of the soils examined in this study.

Field observations revealed that soils of the Summerford bajada often develop a sealed surface layer, 3–6 mm thick, that is denser than the material immediately below it. Penetrometer readings taken in the intershrub environment confirm that soil resistance varies considerably depending upon the presence or absence of a sealed surface layer (Table 1).

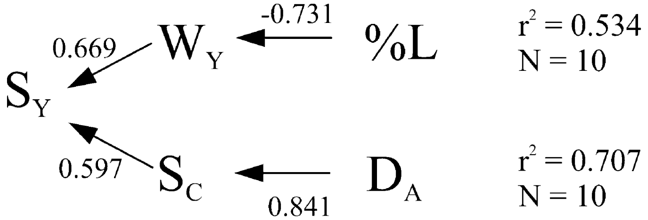


Fig. 3. An example of a causal model. S_Y = sediment yield. W_Y = water yield. S_C = sediment concentration. %L = percentage of the ground covered in litter. D_A = mean diameter of animal disturbance.

Table 1
Average soil penetration resistance values for soils adjacent to three intershrub plots

Plot	Average penetration resistence (kg cm^{-2})	
	Sealed	Unsealed
CI31	0.186	0.089
CI33	0.171	0.084
CI35	0.188	0.087
Combined	0.182	0.087

A Mann–Whitney *U*-test was employed to assess the significance of a difference between the penetration resistance of the soils in their sealed and unsealed states. The results of this test allowed the null hypothesis of no difference to be rejected ($P = 0.001$) in favor of the alternative hypothesis that the penetration resistance of the sealed population of soils is greater than that of the unsealed population (Ebdon, 1985).

3.3. Rainfall simulation experiments

Estimates of runoff and sediment yield from each ecosystem were obtained using rainfall simulation experiments. Eight runoff plots were established on the grassland, 10 on the degraded grassland, and 27 on the shrubland. Of the shrubland plots, 14 were located beneath shrub canopies, and are hereafter referred to as shrub plots, while 13 were located in intershrub areas, and are hereafter referred to as intershrub plots.

In the remainder of this paper, the terms ecosystem and community are used interchangeably to refer to the grassland, degraded grassland, and shrubland. On the other hand, the term environment is used to refer to the four types of surface on which the rainfall simulations were performed, namely grassland, degraded grassland, shrub, and intershrub.

The rainfall simulation experiments were undertaken in late June and early July of 1995 and 1996, prior to the onset of the summer rains. All the experiments were run on dry surfaces with soil water contents in the order of 2%. Particle size analyses indicate that the soils in the intershrub, grassland, and degraded grassland environments are sandy loams. The soils in the shrub environment are loamy sands.

Rainfall simulation experiments were performed on runoff plots that were generally 1 m wide and 2 m long. An exception was made in the case of the shrub plots. These were 1 m wide and 1 m long to ensure that the entire plot lay beneath a shrub canopy. The rainfall simulator was based upon a design by Luk et al. (1986) and delivered rainfall to each plot at an average intensity of 133 mm h^{-1} for 30 min.

Short-term rainfall intensity data collected within the Jornada Basin indicate that storm intensities of 133 mm h^{-1} or higher are not uncommon. However, such intensities are rarely maintained for 30 min (recurrence interval of > 100 years). Nonetheless, the simulated rainfall experiments were run for 30 min for two reasons. First, data collected during a 30-min storm can be analyzed for shorter durations (see below). Second, it was anticipated that equilibrium runoff would be achieved by the end of a 30-min storm.

Table 2
Average surface properties of the rainfall simulation plots

Environment	Fines (%)	Gravel (%)	Vegetation (%)	Litter (%)	Canopy (%)	Proportion of surface disturbed (%)	Average diameter of animal disturbance (mm)
Grassland	17	29	34	21		7	466
Degraded grassland	39	29	18	14		12	447
Shrub	22	13	35	31	66	1	77
Intershrub	45	35	12	9		16	300

Timed volumetric samples of the runoff of water and sediment were collected during each rainfall simulation experiment. These samples were analyzed gravimetrically to determine their water and sediment content, and from them hydrographs and sedigraphs were prepared for each experiment.

3.4. Surface properties

Prior to the rainfall simulation experiments, the surface properties of each plot were measured. This was done by placing a 10-cm grid above the plot and inspecting the ground surface beneath each intersection point in the grid. For each plot, the percent gravel (%G) (particle diameter > 2 mm), percent fines (%F) (particle diameter ≤ 2 mm), percent vegetation (%V) and percent litter (%L) were determined. In addition, whether or not the surface was disturbed by animals was noted and the diameter (D_A) and height or depth of the disturbance were measured. Plots located beneath shrubs also had the percent canopy (%C) recorded.

The average surface properties of the rainfall simulation plots are presented in Table 2. The original data used to compile this and other tables in this publication are available at http://jornada.nmsu.edu.

Surface property data were also collected at the community level using 10-m transects. The same surface property and disturbance variables recorded in the small plots were measured at 0.33-m intervals along the transects (Table 3).

Table 3
Average surface properties of the vegetation communities based on transects

Community	Fines (%)	Gravel (%)	Vegetation (%)	Litter (%)	Canopy (%)	Proportion of surface disturbed (%)	Average diameter of animal disturbance (mm)
Grassland	17	30	40	13	1	3	385
Degraded grassland	33	33	14	20	5	12	479
Shrubland	28	30	34	8	27	16	478

4. Results and discussion

Regression equations relating (1) S_Y to W_Y and S_C and (2) W_Y and S_C to surface properties are presented in Table 4.

4.1. Controls of water yield

The regression analyses indicate that animal activities do not affect W_Y in any of the four environments. In the grassland, the only surface property that is significantly related to W_Y is %V (Table 4). The relation is inverse with $r^2 = 0.563$. This result indicates the important influence of vegetation on soil infiltration rates. Plants protect soils from the direct impact of raindrops, thus reducing surface seal development, plant roots increase soil porosities and organic material improves soil structure. Thus, soils beneath plants typically have higher infiltration rates than exposed soils (Wood et al., 1987).

Water yields from the degraded grassland plots are typically much greater than those from the grassland plots. The former plots generate an average water yield of 2.34 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$ compared to 1.32 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$ for the latter. Stepwise regression analyses of the degraded grassland data suggest that W_Y is controlled by %L. The relation between W_Y and %L is negative with $r^2 = 0.534$ (Table 4).

The control of runoff by litter cover may be due to loose organic material damming overland flow. Such dams increase surface ponding and promote infiltration. In addition, and probably more importantly, litter may reduce water yield by inhibiting surface sealing. Soils covered by litter are protected from the direct impact of raindrops and therefore are likely to exhibit less surface sealing than exposed soils.

The shrub plots have an average water yield of 1.02 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$ and behave like the grassland plots. Regression analyses disclose a strong positive relation between %F on each plot and W_Y with $r^2 = 0.615$ (Table 4). Points within the shrub plots which have fines on the ground surface represent points devoid of vegetation and litter.

Table 4
Regression analyses for the small plot experiments

Environment	Regression equation	R^2 or r^2	P_1^*	P_2^{**}	N or n
Grassland	$\log S_Y = \log W_Y + \log S_C$	1.000	0.001	0.626	8
	$\log W_Y = 0.542 - 1.830 \times 10^{-2}\%\text{V}$	0.563	0.032		8
Degraded	$\log S_Y = \log W_Y + \log S_C$	1.000	0.004	0.010	10
	$\log W_Y = 0.863 - 4.620 \times 10^{-2}\%\text{L}$	0.534	0.016		10
	$\log S_C = 3.349 + 1.277 \times 10^{-3} D_A$	0.707	0.002		10
Shrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.300	14
	$\log W_Y = -0.874 + 2.623 \times 10^{-2}\%\text{F}$	0.615	0.001		14
Intershrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.040	0.000	13
	$\log W_Y = 0.457 - 1.278 \times 10^{-2}\%\text{L}$	0.230	0.097		13
	$\log S_C = 3.274 + 1.285 \times 10^{-3} D_A$	0.627	0.001		13

* P_1 represents the probability that the coefficient associated with the first variable in the equation is 0.
** P_2 represents the probability that the coefficient associated with the second variable in the equation is 0.

Performing a multiple regression analysis with %V and %L as the two independent variables lends support to this interpretation. The derived equation model is:

$$\log W_Y = 0.63 - 1.52 \times 10^{-2}\%V - 1.33 \times 10^{-2}\%L$$

with R^2 of 0.537. This equation shows that W_Y is negatively related to both %V ($P = 0.004$) and %L ($P = 0.030$). Thus, in the shrub plots the positive relation between W_Y and %F merely reflects a negative relation between W_Y and the independent variables of %V and %L.

The intershrub plots have an average water yield of 2.37 $cm^3\ s^{-1}\ cm^{-2}$, a value which is similar to that for the degraded grassland. Stepwise regression analyses indicate that W_Y from the intershrub environment has the same controls as the degraded grassland. The only surface property significantly related to W_Y is %L. The relationship is negative with $r^2 = 0.230$ (Table 4).

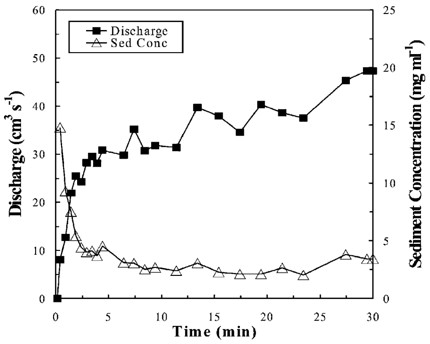
These findings indicate that water yields from the different environments on the Summerford bajada are controlled by the character of the ground surface and, more particularly, by the amount of vegetation, both live and dead, covering the surface. Environments with relatively dense vegetation covers have smaller water yields than those with relatively sparse covers. In environments that are comparatively devoid of live vegetation, water yield is controlled by the availability of litter. Where large amounts of litter are present, water yield tends to be reduced as ponding behind litter dams increases and surface sealing decreases.

4.2. Controls of sediment concentration

Regression analyses between sediment concentration and surface properties indicate that within the degraded grassland and intershrub environments the only surface property that is significantly correlated with sediment concentration is the mean diameter of animal disturbance, D_A ($r^2 = 0.707$ and 0.627, respectively) (Table 4). In these environments, the exposed soils commonly form surface seals. When small mammals dig in search of food they disrupt the surface seals and scatter sediment. This lose sediment is easily entrained by overland flow. Thus, the activities of small mammals considerably increase both the detachment and removal of sediment, and D_A becomes an important control on S_C and S_Y because it represents the proportion of a plot surface that is disturbed.

The significance of small mammal activities can be seen through a comparison of sedigraphs for plots with large and small D_A values. In the degraded grassland, plot D20 has the lowest D_A value. The sedigraph for this plot displays a monotonically decreasing form (Fig. 4) which signifies a progressive exhaustion of detached sediment. In the initial runoff, sediment concentration is high because there is relatively little water and abundant loose sediment, which has both accumulated on the ground surface since the last rain event and is being produced by raindrops falling on a thin film of water. As discharge increases, the availability of loose sediment declines and the sedigraph displays a rapid downward trend.

In comparison, D17 has the highest D_A value of the degraded grassland plots. The sedigraph for this plot displays oscillations superimposed on a rising trend (Fig. 5). The

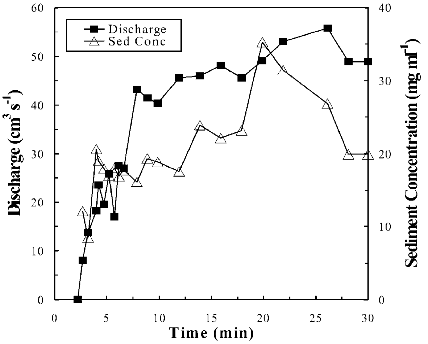


a.

		-220							
	100								
					-200				

b.

Fig. 4. Hydrograph and sedigraph for D20 (a) accompanied by a graphical representation of disturbance for that plot (b). Numbers in cells (b) indicate diameter of each recorded disturbance in mm. Positive for a mound, negative for a hole. Each block unit represents 10 cm^2.



a.

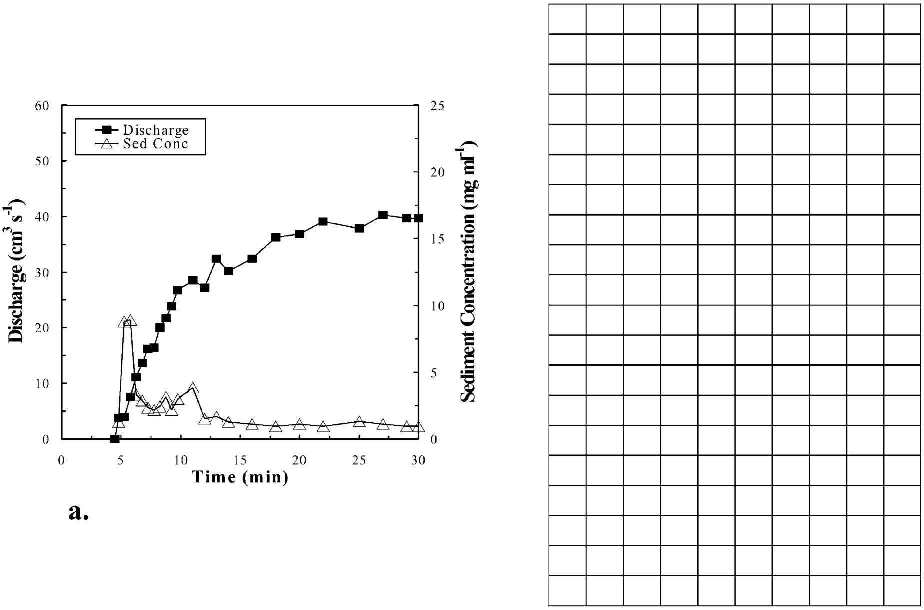
					-800				
					-800	-800	-800		
		-220	-260			640	640		
						640			
								640	640
1040	1040								640
-720	-720	620	-300			-520	1040	1040	120
540	540	-360				620	620	-720	-720
	-440	380	380		-380	400	400		
			300	240	-240	-200	-2160	-2160	-2160
						-160	440	-2160	-2160
									-2160
					560				
320					-160				540
			-740						540
			-740						
-460									
					120				

b.

Fig. 5. Hydrograph and sedigraph for D17 (a) accompanied by a graphical representation of disturbance for that plot (b). Numbers in cells (b) indicate diameter of each recorded disturbance in mm. Positive for a mound, negative for a hole. Each block unit represents 10 cm^2.

most likely explanation for the observed fluctuations in sediment concentration is that they reflect spatial variability in the availability of loose sediment. If there were discrete patches of loose sediment located different distances from the plot outlet, sediment originating at such patches would reach the outlet at different times. Multiple discrete sediment sources might therefore be expected to give rise to sedigraphs with multiple peaks. Figs. 4 and 5 show the amount and location of animal disturbance in plots D20 and D17, respectively. Where there is a large amount of disturbance, the sedigraph continues to rise throughout the discharge event. Concurrent rises in concentration and discharge may or may not reflect a condition of transport capacity. Six of the 10 sedigraphs from the degraded grassland show sediment concentration increasing and decreasing at least once as discharge increases.

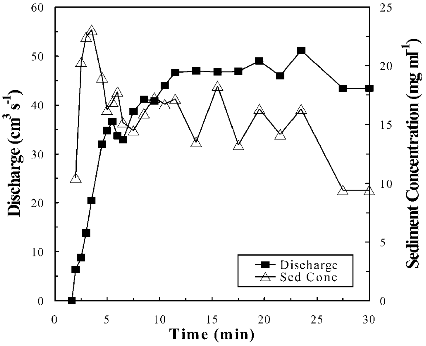
A comparison of the sedigraphs for the intershrub plots CI30 and CI23 reveals a similar pattern. CI30 has the lowest D_A value for the intershrub plots. The sedigraph for this plot shows an initial early peak and then a rapid decline (Fig. 6). Plot CI23, however, has the highest D_A value for the intershrub plots, and the sedigraph for this plot shows a much less rapid decline in response to increasing discharge (Fig. 7). Six of the 13 sedigraphs from the intershrub environment show sediment concentration increasing and decreasing at least once as discharge increases. These findings once again suggest that surface disruptions increase the availability of sediment for transport by overland flow.



a.

b.

Fig. 6. Hydrograph and sedigraph for CI30 (a) accompanied by a graphical representation of disturbance for that plot (b). Numbers in cells (b) indicate diameter of each recorded disturbance in mm. Positive for a mound, negative for a hole. Each block unit represents 10 cm^2.



a.

				160					-200
	-260								
							-80		
							180	-180	
						240			
				-340	-180	-180	-1560	-1560	-1560
						-1560	-1560	-1560	-1560
						-1560	-1560	-1560	-1560
							-1560	-1560	
			-260					-200	
			-140	-180	-440				
					-260				
				120					
	680			-380			-400		

b.

Fig. 7. Hydrograph and sedigraph for CI23 (a) accompanied by a graphical representation of disturbance for that plot (b). Numbers in cells (b) indicate diameter of each recorded disturbance in mm. Positive for a mound, negative for a hole. Each block unit represents 10 cm^2.

Sediment concentration is not correlated with any surface property in either the grassland or shrub environments. This is consistent with the explanation that animal activities contribute the major source of hillslope sediment by disrupting surface seals. In the grassland and shrub environments, only limited animal digging occurs. Consequently, the sediment concentration of runoff from these environments is typically low and there is little variation in sediment concentration to explain.

These results have significant implications for the prediction of sediment movement within the Jornada Basin, for they show that estimates of rates of sediment transport are unlikely to be accurate unless the effect of animal activities is taken into account. This is especially true in a community such as the shrubland because the small mammals preferentially dig in the intershrub environments where overland flow is concentrated.

4.3. Sediment yield

Fig. 8 summarizes the above findings. This figure shows that sediment yield is controlled by water yield and sediment concentration. The strengths of these controls are indicated by the associated beta coefficients (Clark and Hosking, 1986). Ground surface properties influence sediment yield through water yield and/or sediment concentration. Thus, in the well vegetated grassland and shrub environments sediment yield is controlled by water yield which, in turn, is controlled by vegetation cover. Sediment concentration does not have a significant effect on sediment yield in these environments.

In contrast, in the sparsely vegetated degraded grassland and intershrub environments sediment yield is controlled both by water yield and sediment concentration. Water

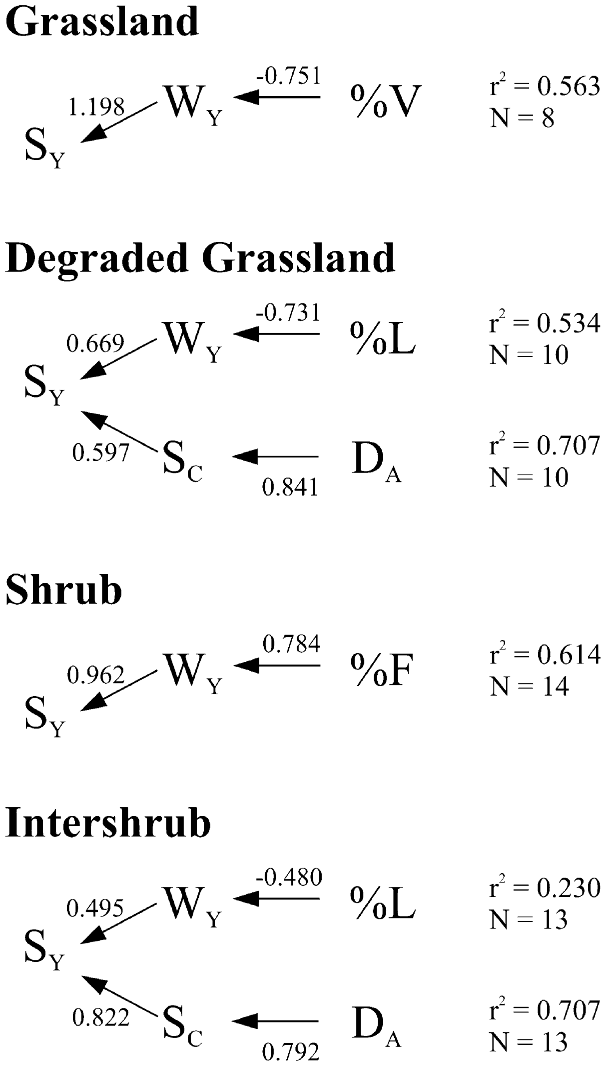


Fig. 8. Causal diagrams representing results of the regression equations derived following a 30-min rainfall event.

yield, in turn, is controlled by litter cover, while sediment concentration is controlled by animal disturbance.

4.4. Storm durations

Although storm intensities of greater than 100 mm h^{-1} are not uncommon within the Jornada Basin, only an extreme precipitation event would maintain such an intensity for 30 min. Consequently, there is a need to determine whether the preceding findings apply to more frequent, shorter duration storms of the same intensity. The caliber of the data collected for this study permit such an analysis.

Accordingly, sediment yields, water yields, and sediment concentrations were computed for each plot after 5, 10, 15, and 20 min of rainfall. Regression equations between these variables and the surface properties were calculated for each duration (Table 5). The results of these analyses are summarized as follows.

(1) Water yield always has a positive significant effect on sediment yield, irrespective of the rainfall duration.

(2) Sediment concentration has a significant effect on sediment yield after 10 min of rain on the degraded grassland plots and after 15 min of rain on the intershrub plots. Sediment concentration does not have a significant effect on sediment yield on the grassland and shrub plots irrespective of rainfall duration.

Table 5
Regression equations for 5-, 10-, 15-, and 20-min storm durations

Duration	Environment	Regression equation	R^2 or r^2	P_1^*	P_2^{**}	N or n
5 min	Grassland	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.728	8
	Degraded	$\log S_Y = \log W_Y + \log S_C$	1.000	0.005	0.394	10
	Shrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.075	14
		$\log W_Y = -1.710 + 1.999 \times 10^{-2}\%F$	0.452	0.008		14
	Intershrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.001	0.202	9
10 min	Grassland	$\log S_Y = \log W_Y + \log S_C$	1.000	0.002	0.791	8
	Degraded	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.868	10
	Shrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.376	14
		$\log W_Y = -1.271 + 2.207 \times 10^{-2}\%F$	0.562	0.002		14
	Intershrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.001	0.111	12
		$\log S_C = 3.541 + 1.012 \times 10^{-3} D_A$	0.528	0.007		12
15 min	Grassland	$\log S_Y = \log W_Y + \log S_C$	1.000	0.001	0.592	8
		$\log W_Y = 3.289 \times 10^{-2} - 1.490 \times 10^{-2}\%V$	0.422	0.081		8
	Degraded	$\log S_Y = \log W_Y + \log S_C$	1.000	0.004	0.129	10
		$\log W_Y = 0.277 - 4.390 \times 10^{-2}\%L$	0.378	0.059		10
		$\log S_C = 3.567 + 1.040 \times 10^{-3} D_A$	0.628	0.006		10
	Shrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.447	14
		$\log W_Y = -1.111 + 2.413 \times 10^{-2}\%F$	0.603	0.001		14
	Intershrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.001	0.007	13
		$\log W_Y = 1.306 \times 10^{-2} - 2.560 \times 10^{-2}\%L$	0.291	0.057		13
		$\log S_C = 3.436 + 1.020 \times 10^{-3} D_A$	0.494	0.007		13
20 min	Grassland	$\log S_Y = \log W_Y + \log S_C$	1.000	0.001	0.577	8
		$\log W_Y = 0.253 - 1.620 \times 10^{-2}\%V$	0.479	0.057		8
	Degraded	$\log S_Y = \log W_Y + \log S_C$	1.000	0.005	0.039	10
		$\log W_Y = 0.544 - 4.500 \times 10^{-2}\%L$	0.446	0.035		10
		$\log S_C = 3.451 + 1.197 \times 10^{-3} D_A$	0.691	0.003		10
	Shrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.000	0.494	14
		$\log W_Y = -1.011 + 2.503 \times 10^{-2}\%F$	0.614	0.001		14
	Intershrub	$\log S_Y = \log W_Y + \log S_C$	1.000	0.009	0.001	13
		$\log W_Y = 0.208 - 1.900 \times 10^{-2}\%L$	0.284	0.061		13
		$\log S_C = 3.350 + 1.191 \times 10^{-3} D_A$	0.615	0.002		13

[*] P_1 represents the probability that the coefficient associated with the first variable in the equation is 0.

[**] P_2 represents the probability that the coefficient associated with the second variable in the equation is 0.

(3) After 30 min of rain, water yield on the grassland is controlled by vegetation cover. This negative relation becomes established within 15 min of the start of rain.

(4) After 30 min of rain, water yield from the shrub plots is positively correlated with the percentage of the ground covered by fines. This relation exists within 5 min of the start of rain.

(5) Water yield from the degraded grassland and intershrub plots is controlled by litter cover. Both relations are established within 15 min of rain.

(6) After 30 min of rain sediment concentrations on the degraded grassland and intershrub plots are related to animal disturbance. These positive relations are in place after 10 min of rain on the intershrub and after 15 min of rain on the degraded grassland plots.

(7) No surface property is significantly correlated with sediment concentration on either the grassland or the shrub plots for any rainfall duration.

These results indicate that the relations observed at the end of 30 min of rain are all established within 15 min of the start of rain, and some relations are established even earlier. The relations are weakest for the short rain durations because runoff begins at different times on different plots. Within the intershrub plots, for example, times to runoff range from 1.62 to 10.27 min. It follows that during a rainfall event of 5 min, some plots generate a significant amount of runoff while others produce none. Consequently, there is a great deal of ‘noise’ in the data for the short rainfall durations stemming from the variations in time to runoff. This noise reduces the likelihood of detecting significant relations based on rainfall simulations over short durations. Performing rainfall simulations for 30 min diminishes the influence of this noise and allows the surface properties controlling sediment yield to be more readily identified.

5. Conclusion

The average sediment yields recorded during 30-min simulated rainfall experiments on grassland, degraded grassland, shrub, and intershrub plots in the Jornada Basin were 0.006372, 0.033063, 0.004716, and 0.013646 g s^{-1} cm^{-2}, respectively. The higher sediment yields in the degraded grassland and intershrub environments are attributed to the higher rates of surface runoff and the greater availability of loose sediment due to animal digging.

In the grassland and shrub environments, which have relatively good vegetation covers, water yield is negatively correlated with the proportion of the ground surface covered by vegetation. This negative correlation reflects the beneficial effect of vegetation on infiltration. Plants increase soil permeability directly by producing root macropores and soil organic material and indirectly by protecting the soil surface from raindrop impact. Therefore, as vegetation cover declines, soil infiltration rates decline and surface runoff increases.

In the degraded grassland and intershrub environments, which have relatively sparse vegetation covers, water yield is negatively correlated with the proportion of the ground surface covered by litter. This negative correlation is attributed to litter promoting soil sealing and surface ponding. Litter protects the soil from raindrop impact, thus impeding surface sealing and enhancing soil infiltration. In addition, litter tends to dam surface runoff, leading to an increase in the volume of water held in ponds. Increased ponding, in turn, favors infiltration.

The sedigraphs from the four environments display either monotonically declining, oscillating, or rising forms. Those plots with oscillating or rising sedigraphs contain numerous discrete sources of sediment associated with animal digging, whereas those with monotonically declining sedigraphs do not.

The only surface property that is significantly correlated with sediment concentration is the average diameter of animal disturbance, D_A. Sediment concentration is positively correlated with animal disturbance in the degraded grassland and intershrub environments where animal digging is extensive. In the grassland and shrub environments where there is considerably less animal digging, no significant correlation was found between sediment concentration and any surface property.

Comparisons of sedigraphs and D_A values indicate that plots with monotonically decreasing sedigraphs have low D_A values. Such plots experienced a progressive exhaustion of detached sediment as runoff flushes loose material off the plots early in the flow event. In contrast, those sedigraphs displaying oscillating or rising forms are typically generated on plots with high D_A values. Animal activities within these plots increase sediment yields and produce discrete sources of sediment that cause the sedigraphs to either oscillate or increase as discharge decreases.

These results have important implications for the prediction of sediment movement within the Jornada Basin or, indeed, in any dry land environment that is subject to animal disturbance. If estimates of rates of sediment transport within such environments are to be accurate, they must take into account the role played by animals in generating sediment.

Although these findings probably apply over much of the American Southwest, they are especially relevant to the Jornada Basin because over the past 100 years the vegetation has been transformed from grassland to shrubland (Buffington and Herbel, 1965). Shrubland communities, with a larger percentage of exposed ground surface, generate larger volumes of runoff which are capable of transporting higher sediment loads than do grassland communities. Furthermore, animal activities within the exposed intershrub environments of the shrubland communities break protecting surface seals and make loose sediment available for transport. These activities increase the erodibility of flows in the shrubland, especially in intershrub areas, removing soil and nutrients from these areas (Schlesinger et al., 1999, 2000) and possibly inhibiting the re-establishment of the grasses.

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