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Microtopography and soil-surface materials on semi-arid piedmont hillslopes, southern Arizona

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Many semi-arid piedmont hillslopes are vegetated by a sparse shrub community. The shrubs are commonly located atop small mounds of fine material whereas the intervening inter-plant areas are swales with a desert pavement surface. In this paper we test the hypothesis that such microtopography and distribution of soil-surface materials of a hillslope in southern Arizona result from the effects of rainsplash erosion. We show that the protection afforded by shrubs to the ground surface beneath them results in differential rainsplash. More sediment is splashed into the areas beneath shrubs than is splashed outward. Furthermore, surface materials of small mounds have the same size distribution as sediment transported by rainsplash. The mounds, however, are not wholly accumulation features. Some of the difference in elevation between the mounds and the inter-plant swales is due to removal of sediment from the swales by overland flow. Desert pavement forms in the swales as a lag deposit that results from the water-sorting action of rainsplash erosion. Inasmuch as the microtopography and distribution of soil surface materials on the studied hillslope are a consequence of the present shrub vegetation, they must have formed in the century or so since this vegetation replaced the former grassland.

Introduction

Many semi-arid, piedmont hillslopes are vegetated by a sparse shrub community, associated with which are characteristic microtopography and soil-surface materials. Shrubs, or groups of shrubs, are commonly located atop small mounds between which are shallow swale-like areas. In the swales, a desert pavement often forms the topmost element in the soil profile, whereas the mounds are typically surfaced with finer material (Fig. 1). This small-scale patterning of the ground surface has been shown to have significant consequences for the infiltration characteristics of these hillslopes (Lyford & Qashu, 1969; Abrahams & Parsons, 1991) and for spatial variations in soil chemical properties (e.g. Lajtha & Schlesinger, 1986). Of fundamental importance is the origin of this patterning.

A variety of processes has been proposed to account for the mounds. The most widely held view is that they result from eolian deposition (e.g. Lyford & Qashu, 1969; Muller,

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Figure 1. Typical cross section of microtopography and soil-surface materials associated with sparse shrub vegetation of semi-arid hillslopes.

1953; Petrov, 1962, p. 147; West, 1983, p. 405). Supposed accumulations of this type are known as *nebkha* or shrub-coppice dunes (Cooke & Warren, 1973, p. 317). In some environments, however, it has been claimed that the wind deposition hypothesis is untenable. Rostagno & del Valle (1988) argued that in Patagonia the presence of coarse fragments in mounds was evidence against their having an eolian origin. These authors proposed that the mounds represent 'a relict land surface, removed in the intermound area mainly by wash erosion' (p. 347). Elsewhere, it has been asserted that mounds are accumulation features resulting from the effects of differential rainsplash (e.g. Carson & Kirkby, 1972, p. 189). Rainsplash transports material from the swales to the areas beneath the shrubs, but return sediment transport is inhibited because the shrub canopy protects the area beneath from rainsplash. Consequently, splashed sediment accumulates under the shrubs.

Studies of mounds have generally given little consideration to the intervening swale areas other than, in some cases, to note the presence in the swales of a desert pavement. No attempt appears to have been made to associate the formation of mounds with the presence of desert pavement in the intervening swales. Such an association is important because the formation of desert pavement has, itself, been the subject of much debate. Briefly, this debate centres around the four mechanisms that have been suggested to explain the surface concentration of rock fragments: namely deflation (e.g. Symmons & Hemming, 1968), water sorting (e.g. Sharon, 1962; Cooke, 1970), upward migration of coarse particles (e.g. Mabbutt, 1965), and the effect of the interplay of eolian deposition, colluviation and rock fracturing (McFadden *et al.*, 1987). Although this debate has generally been conducted in the context of smooth, often extensive pavements largely free of vegetation, the widespread occurrence, within the swales of the hillslopes under discussion, of patchy, discontinuous pavements implies that the roles of the proposed mechanisms need to be examined in the context of these pavements also.

In this paper we address the question of the formation of both the mounds and the desert pavement. Specifically, we test the hypothesis that the microtopography, desert pavement and particle size difference between swales and mounds of shrub-covered, semi-arid hillslopes result from the effects of rainsplash erosion.

Study area

The study was conducted on a hillslope within the Walnut Gulch Experimental Watershed, Tombstone, Arizona (31° 43′N, 110° 41′W). The hillslope has a maximum gradient of about 5° and is typical of the shrub-covered, dissected piedmont in the watershed. Open shrub communities have replaced grassland over much of the northern Sonoran Desert during the last century (Glendening, 1952; Hastings & Turner, 1965) and exposed the friable soils to erosion, particularly by high-intensity rainfall (Glendening, 1952, p. 319). Such rainfall is characteristic of summer thunderstorms which account for two-thirds of the annual precipitation at Walnut Gulch (Osborn, 1983). On the particular hillslope under study, the dominant shrub species are *Larrea tridentata* (creosote bush),

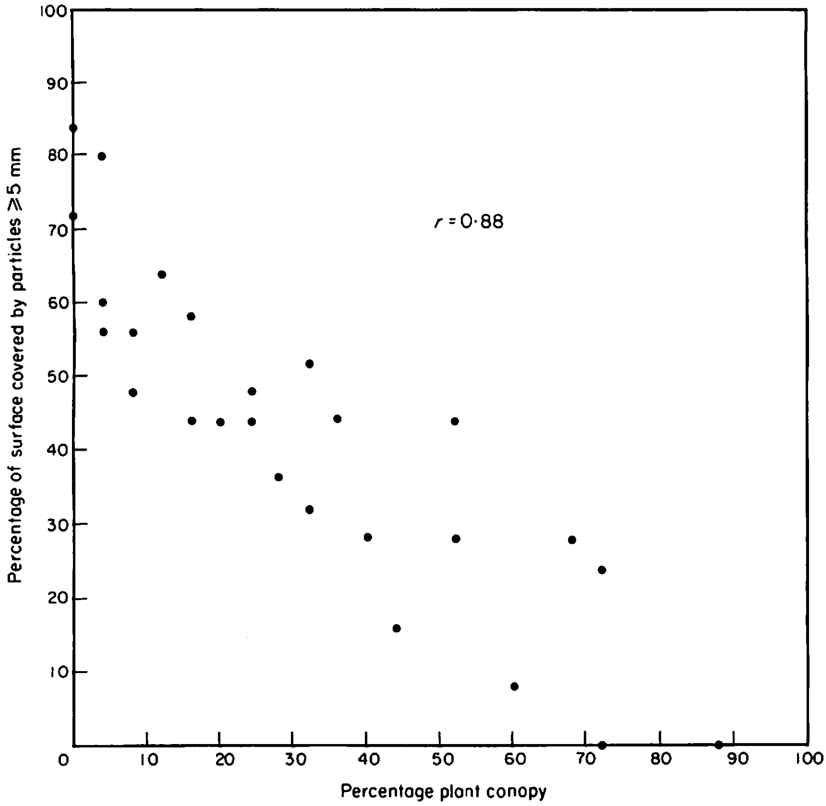

Figure 2. Relationship between plant canopy cover and surface particles ≥5 mm in the study area.

Dasyliron wheeleri (sotol), *Acacia constricta* (white thorn), *Rhus microphylla* and *Yucca elata* (palmilla) with a ground layer principally of *Zinnia pumila* (desert zinnea) and *Dyssodia acerosa*. In addition, scattered among, and of a similar size to, the shrubs are clumps of *Nolina microcarpa* (beargrass). Elsewhere, other shrub species, for example *Haplopappus tenuisectus* (burroweed), dominate but the structure of the community remains similar.

In these shrub communities, the vegetation usually covers less than half the ground surface. For the hillslope under study, transects show an average of 44% vegetation cover and almost all plants or groups of plants stand atop mounds, the areas of which are roughly proportional to the canopy areas of the plants. The heights of the mounds range upward from a few centimetres to about 20 cm but show no simple relationship to their areas. Consequently, the mounds exhibit a variety of side-slope gradients ranging from a few degrees up to more than 30°. In the swales between plants a discontinuous gravel pavement forms the surface of the Hathaway gravelly loam soil (Gelderman, 1970), developed on the underlying, weakly consolidated, coarse Quaternary alluvium. The close inverse relationship between vegetation cover and the development of a pavement surface on the hillslope under study is demonstrated by a graph of proportion of the surface covered by stones ≥5 mm against percentage plant canopy cover for 26 1-m^2 areas on the hillslope (Fig. 2).

Analyses

The efficacy of differential rainsplash

If differential rainsplash is responsible for the mounds of finer material beneath the plants, then sediment traps located beneath plant canopies and designed to differentiate between

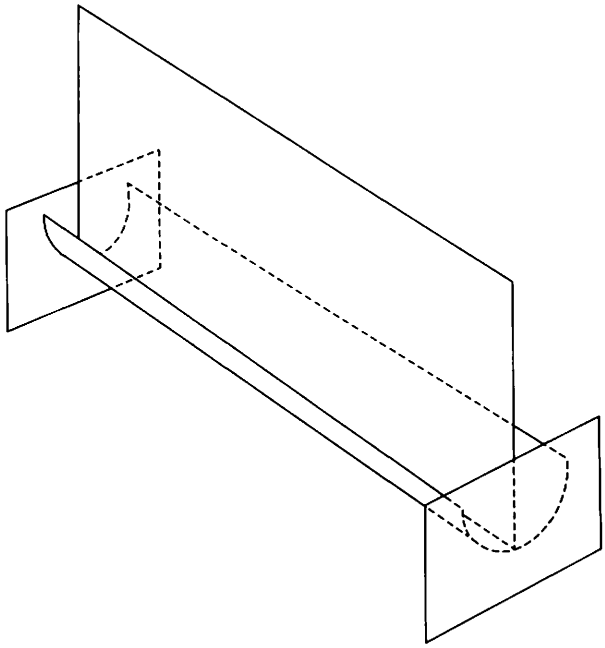

Figure 3. Splash trap used in this study.

inward and outward splash should catch more of the former than the latter. Furthermore, the material caught in the sediment traps should have the same size distribution as that forming the mounds. We sought to test these predictions in the following way.

We designed a splash trap consisting of a semi-circular trough divided in half lengthways by a vertical splash-board (Fig. 3). Four such traps, each oriented at 90° to its two neighbours, were installed around several selected plants. The troughs were partially buried in the ground and located just within the areas of the plant canopies (Fig. 4). Artificial rainfall at an intensity of 145 mm h^{-1} was then applied for 15 min. over areas about 5 m in diameter centred on the plants, using two portable rainfall simulators, each of which delivered near-uniform rainfall from two nozzles (Luk *et al.*, 1986). For this locality, a rainstorm of such intensity and duration has a return period of a little less than 50 years (Osborn & Renard, 1988, Figs 1, 2). During the rainfall simulations troughs that threatened to overflow were emptied by pipetting the water into sample bottles. Once the rain had ceased the water remaining in the troughs was also pipetted into the sample bottles, and the traps and sample bottles were removed to the laboratory. The traps were left to dry and the sample bottles were placed in drying ovens. Once dry, sediment was brushed off the splash-boards into the troughs and then collected together with the sediment from the sample bottles. The sediment samples were treated to remove organic matter and then weighed.

Data were collected from two examples of each of the following species: *Nolina microcarpa*, *Rhus microphylla*, *Dyssodia acerosa* and *Zinnia pumila*. The first of these species was taken to be typical of shrubs with a dense permanent canopy, the second of shrubs with a more sparse and/or seasonal canopy, and the last two of the smaller ground plants. For the larger plants we used splash traps 41 cm long with splash-boards 18 cm high; for the smaller plants the traps were 17 cm long with splash-boards 6 cm high. Unfortunately, data from one of the *R. microphylla* were corrupted and could not be used in this analysis.

The results of the experiments on the remaining seven plants are given in Table 1. For only one of these seven plants was a greater amount of sediment splashed away from it than towards it. Under a null hypothesis of no differential splash there is only a 5% probability

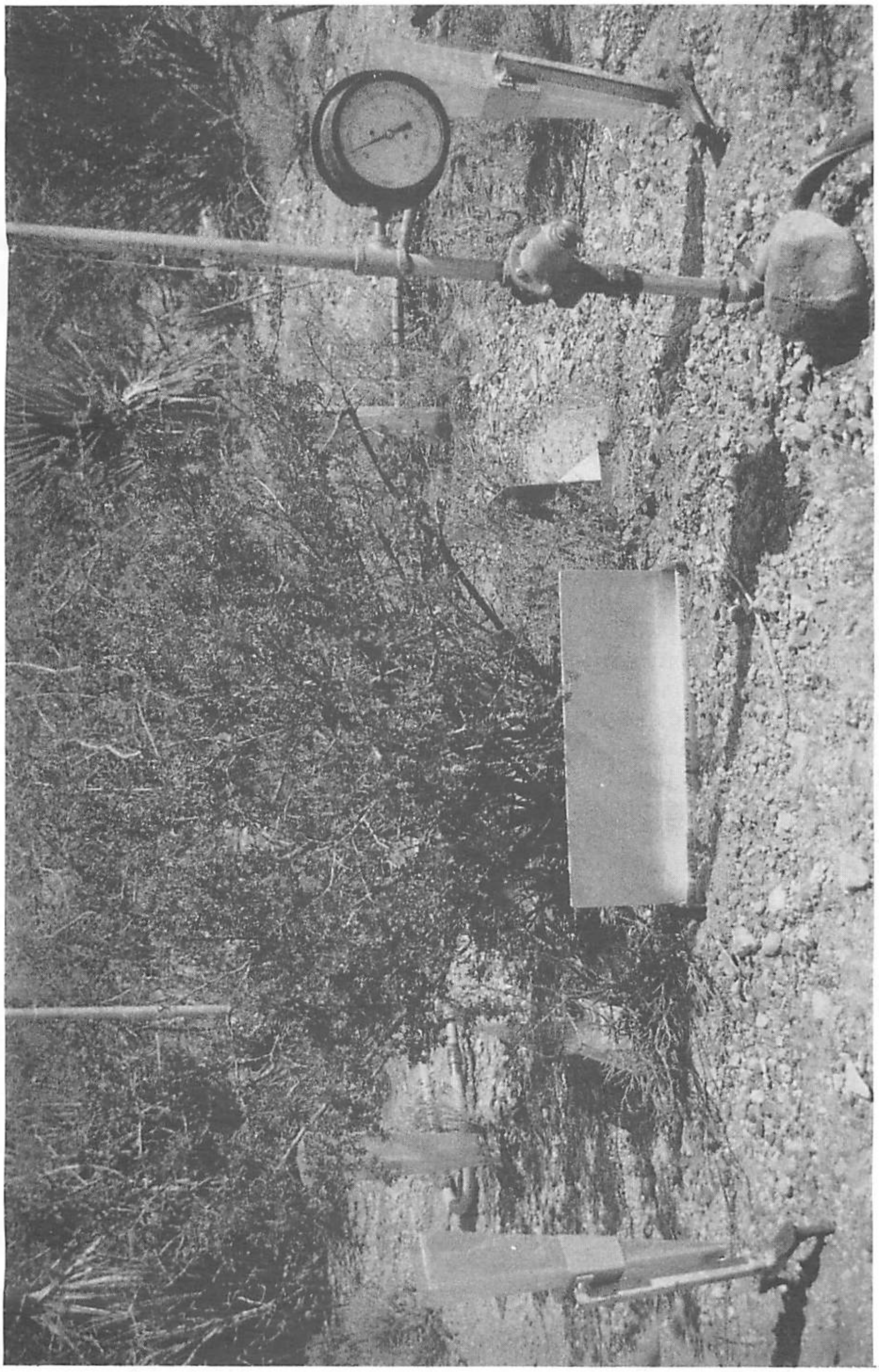

Figure 4. Splash traps installed around a *Rhus microphylla*.

Table 1. *Data from splash experiments*

Plant genus	Mound gradient (degrees)	Total sediment splashed toward plant (g)	Total sediment splashed away from plant (g)	Balance*
Nolina	16	32·05 (58·5)†	22·70 (41·5)†	9·35
Nolina	13	4·61 (74·0)	1·62 (26·0)	2·99
Rhus	7	33·97 (62·1)	20·75 (37·9)	13·22
Dyssodia	13	3·08 (57·9)	2·24 (42·1)	0·84
Dyssodia	11	4·34 (77·5)	1·26 (22·5)	3·08
Zinnea	20	1·63 (58·4)	1·16 (41·6)	0·47
Zinnea	26	5·95 (45·4)	7·15 (54·5)	−1·20

* A negative value indicates that more sediment was splashed away from the plant than towards it.

†Figures in parentheses denote percentages of sediment splashed toward and away from each plant.

that only one of seven experiments would show more splash away from the plant than towards it. The true statistical significance of the results in Table 1 are, in all likelihood, greater than that given under the stated null hypothesis because the splash traps were installed on mounds sloping outward. Hence, there is an inherent bias in the experiment in favour of outward-splashing sediment. That the anomalous result is due to this bias is suggested by the fact that the plant for which outward-splashed exceeds inward-splashed sediment has the mound with the steepest side-slopes.

The rainfall simulation experiments reveal that differential splash may occur and that the net transport of sediment towards plants may create mounds. If such a mechanism has operated on the hillslope under study, then the size distribution of the sediment forming the mounds should match that collected in the splash traps. Furthermore, if this distribution is different from that of the vegetation-free areas, it would argue strongly in favour of the mounds' having been formed by the differential rainsplash mechanism.

Analyses of the size distribution of the sediment caught in the splash traps and the surface material beneath the plants are presented in Table 2. In all cases, the sediment can be seen to be dominantly sand-sized. This agrees with other descriptions of the size distribution of splashed sediment (e.g. Ellison, 1944; Poesen & Savat, 1981). Results of t-tests on the percentages of sand in these two sets of data indicate that they cannot be regarded as samples from different populations (t = 1·39, p = 0·20). By contrast, two samples of surface material <2 mm obtained from the inter-plant areas had a mean of 71% sand, 19% silt and 10% clay. The probabilities that such a percentage of sand would be

Table 2. *Size distribution of material finer than 2 mm obtained from splash experiments and surface samples of mounds beneath plants*

Plant genus	Splash troughs			Mounds		
	%Sand	%Silt	%Clay	%Sand	%Silt	%Clay
Nolina	88	9	3	87	8	5
Nolina	77	23	0	81	12	7
Rhus	83	13	4	78	13	9
Dyssodia	95	5	<1	81	11	8
Dyssodia	93	6	1	88	7	5
Zinnea	85	15	0	88	8	4
Zinnea	93	7	<1	83	11	6

Table 3. *Changes with depth in size distribution of material beneath three plants*

Plant genus	Depth (cm)	Material <2 mm			Material ≥2 mm	
		%Sand	%Silt	%Clay	%2–5 mm	%≥5 mm
Nolina	0–5	84	8	5	3	0
	5–10	68	12	7	11	2
Haplopappus	0–5	76	10	4	6	4
	5–10	61	15	8	7	9
	10–15	43	14	9	16	18
Rhus	0–5	76	11	8	3	2
	5–10	63	11	7	7	12
	10–15	60	12	9	11	8

obtained from populations with means and standard deviations as those of the two sets of samples in Table 2 are 0·005 (for the splash troughs) and 0·0007 (for the mounds). Thus the size of the sediment on the surface beneath the mounds does match that of the sediment caught in the splash traps, and this material does have a size distribution different from that of the material finer than 2 mm contained within the surface soil in the inter-plant areas. Consequently, there is strong evidence that the surface of the mounds beneath the plants results from differential splash.

The role of plant canopies in protecting the ground from erosion

Differential rainsplash is capable of accumulating material beneath plants and appears to have done so on the hillslope under study. The question arises as to whether this process alone is responsible for the microrelief on the hillslope; that is, are the mounds formed wholly by accumulation? This question was investigated by examining profiles through three of the taller vegetation mounds on the hillslope. One of these was that beneath the first *N. microcarpa* of Table 1, the other two lay beneath *H. tenuisectus* and *R. microphylla* plants. Table 3 shows changes in particle size with depth through the three mounds. It is evident that in all three mounds a marked change occurs below the first 5 cm. In each case, the topmost sample is both richer in sand and poorer in material ≥2 mm than samples from further down the profile, and it has a similar size distribution to that of splashed material (Tables 2 and 3). The examination of these three tall mounds indicates that the present microrelief is only partly due to accumulation, and that the swales have been lowered at the same time as the mounds have been accumulating.

Lowering of the swales and the formation of desert pavement

Simply by virtue of accumulating material beneath plants, the differential splash mechanism must result in some lowering of the inter-plant swales. However, the fact that the mounds appear to be only partly accumulation features requires that there has been some additional removal of material from the swales.

These hillslopes are subject to sporadic, high-intensity summer rainfall (Osborn, 1983; Osborn & Renard, 1988). Under these conditions, detachment of soil particles by raindrop impact is accompanied by infiltration–excess overland flow. Consequently, although some of the detached soil particles accumulate under the plants as a result of the differential splash mechanism, others are carried off the hillslope in threads of overland flow. Inasmuch as the detachment of soil particles by raindrops is concentrated in the inter-plant areas, these areas become lowered and depleted of their finer (principally sand-sized) particles to a greater extent than the areas beneath the plants become elevated through deposition of these particles. As fine material is removed from the swales, so progressively more of the swale surfaces become covered by a desert pavement made of the coarser fragments in the Quaternary alluvium. Thus the desert pavement of the swales is a lag deposit and its mode of formation is essentially a variation on the water-sorting mechanism discussed by Sharon (1962) and Cooke (1970).

Conclusion

The characteristic microtopography and soil-surface materials associated with the sparse shrub community of the study area appear to have been formed by rainsplash erosion—that is, a combination of rainsplash, raindrop detachment and overland flow. Some of the particles eroded from the inter-plant areas have, as a result of differential splash, accumulated beneath plants to create mounds. Removal of other raindrop-detached particles in overland flow has further contributed to the lowering of the inter-plant areas to form swales. Thus the mounds on these hillslopes do not simply represent accumulation features nor are they a relict surface as claimed by Rostagno & del Valle (1988) for similar features in Patagonia. Inasmuch as the microtopography and distribution of soil surface materials are a consequence of the present cover of shrub vegetation, they must have formed in the century, or so, since this vegetation replaced the former grassland.

The results of this study imply that detachment of particles by raindrop impact is an effective water-sorting mechanism for the creation of desert pavement provided the detached particles can be removed from the nascent pavement. In semi-arid areas some of these particles may collect beneath the sparse vegetation whereas others may be removed in threads of overland flow that locate in the swales. Thus mounds form beneath the plants while a discontinuous pavement surface develops between them. In vegetation-free areas, however, such a mechanism can only be effective in creating a pavement where there is an adequate gradient for the removal of the raindrop-detached particles in overland flow. In contrast, the presence of pavement in swales at Walnut Gulch on hillslopes with gradients very close to 0° suggests that on these hillslopes gradient is not a limiting factor.

An assessment of the wider significance of the processes reported in this paper, both in creating microtopography on semi-arid hillslopes and in forming desert pavement, requires studies from a range of desert environments. Of particular importance is an evaluation of the interplay of these and other processes that have been identified as contributing to the formation of these features of arid and semi-arid landscapes.

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