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Vegetation controls on small-scale runoff and erosion dynamics in a degrading dryland environment

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Abstract:

This paper investigates the controls of vegetation on runoff and erosion dynamics in the dryland environment of Jornada, New Mexico, USA. As the American southwest has seen significant shifts in the dominant vegetation species in the past 150 years, an understanding of the vegetation effects on hydrological and erosional processes is vital for understanding and managing environmental change. Small-scale rainfall simulations were carried out to identify the hydrological and erosional processes resulting from the grassland and shrubland vegetation species. Results obtained using tree-regression analysis suggested that the primary vegetation control on runoff and erosion is the shrub type and canopy density, which directly affects the local microtopographic gradient of mounds beneath the shrubs. Significant interactions and feedbacks were found to occur among the local mound gradient, crust cover, soil aggregate stability and antecedent soil moisture between the different vegetation species for both the runoff and erosion responses. Although some of the shrub species were found to produce higher sediment yields than the grass species, the distinguishing feature of the grassland was the significantly higher enrichment in the fine sediment fraction compared to all other surface cover types. This enrichment in fines has important implications for nutrient movement in such environments. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS rainfall simulation; erosion; runoff; vegetation; tree regression; drylands

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INTRODUCTION

Land degradation in semi-arid environments is typically associated with significant changes in vegetation species (Abrahams *et al*., 1995; Ludwig and Tongway, 1995; Seixas, 2000; Parizek *et al*., 2002; Titus *et al*., 2002). Research suggests that these vegetation changes are often persistent and irreversible, and indicate a shift in the stable state(s) of the ecosystem. Existing hypotheses in the literature (Schlesinger *et al*., 1990) have related these vegetation changes to ongoing feedbacks on water and sediment transfers and the consequent nutrient dynamics associated with these fluxes. The last 150 years in the US southwest has seen a shift in dominant vegetation species from grass to shrubs, which has resulted in high erosion rates and potentially high nutrient losses associated with these high rates of sediment and water transfers (Buffington and Herbel, 1965; Fredrickson *et al*., 1998; Schlesinger *et al*., 1999; Neave and Abrahams, 2002; Parsons *et al*., 2003). Currently, degrading landscapes in the US southwest are a mosaic of vegetation patches comprising both grass and shrub species, and research is showing that these vegetation patterns affect redistribution of water, sediment and nutrients within the landscape leading to further changes in the reorganization of the ecosystem structure (Abrahams *et al*., 1995; Parsons *et al*., 1996; Wainwright *et al*., 2000 Scheffer and Carpenter, 2003; Peters *et al*., 2005; Turnbull *et al*., 2008).

Despite widespread recognition that important interactions and feedbacks occur between vegetation, runoff and erosion over a range of scales (Wainwright *et al*., 2002; Peters *et al*., 2005), currently there is only limited quantitative information on the control mechanisms that lead to differences in water and sediment fluxes from different vegetation types at the plant level. One mechanism that has been identified is the change in microtopography that accompanies a shift from grassland to shrubland in the US southwest (Parsons *et al*., 1996). In areas dominated by overland flow, as shrubs invade, runoff is concentrated between them and the shrubs come to sit atop small mounds as a result of a combination of differential splash rates (Parsons *et al*., 1992) and the removal of finer material by overland flow in the plant interspaces that come to form shallow swales. Shrubland is hydraulically more efficient than grassland leading to higher runoff and erosion rates. However, most work on investigating the grass to shrub transition has focussed on changes in landscapes dominated by creosotebush (see review in Wainwright *et al*., 2000). Differences in the structure of the vegetation and associated mounds, and the relative types and rates of formation process might be expected to generate significant differences in the ways in which mounds under different shrub types function. Similarly, the nature of formation of the intershrub areas is expected to produce surfaces with different levels of crusting, concentrations

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of coarse particles, microtopography and corresponding differences in runoff and erosion characteristics. These differences are in turn likely to be different from the characteristics of grassland surfaces.

It is hypothesized in this paper that vegetation exerts a first-order control on runoff and erosion dynamics through direct interactions with the soil surface characteristics. In particular, differences are expected to occur between the shrubs and the grass species due to differences in their canopy and root structures and in their surface coverage. Specifically, we expect erosional and hydrological differences between the shrub species, the grass and the intershrub areas that are a direct result of the vegetation structural differences. This study aims to quantify the differences in runoff and erosion behaviour among a range of shrub and grass vegetation types in a single area at the same time to minimize the effect of confounding variables on observed differences. Specifically, the objectives are (1) to investigate the relationships between the surface and soil characteristics that are directly and indirectly affected by vegetation type, and the runoff and erosion response from different vegetation communities and (2) to use tree-regression statistics to examine the effect of the interactions between variables on runoff and erosion.

STUDY AREA

The study focuses on quantifying the vegetation controls on runoff and erosion in the Jornada Basin. The Jornada Basin (32°31′N, 106°47′W) is situated *ca* 40 km NNE of Las Cruces, New Mexico, USA. The climate is semi-arid to arid with a mean annual precipitation of 245 mm and a mean annual potential evapotranspiration of 2204 mm. The precipitation regime is characterized by intense, short-duration, convective summer storms (Wainwright, 2006). Dominant shrubland species of the region are creosotebush (*Larrea tridentata*), honey mesquite (*Prosopis glandulosa*) and tarbush (*Flourensia cernua*). These shrub species have steadily increased since the 1850 s and have replaced large areas of black grama grass (*Bouteloua eriopoda*) and other grasses (Buffington and Herbel, 1965; Gibbens *et al*., 2005). Jornada has seen an increase in the dominance of the mesquite shrub from 11% in 1938 to more than 37% in 1998. In addition, areas of creosotebush increased from 40 to 46% over the same time period, while in contrast the areas of grassland decreased from 26% coverage to 7% (Gibbens *et al*., 2005). Reasons for such changes in vegetation have been cited as a combination of climate change, grazing by livestock and plant competition for available space, moisture and nutrients (Whitford, 2002), and because of interactions of factors at local levels (Yao *et al*., 2006).

The study sites were situated within communities of mesquite, black grama grassland and creosotebush, located on the bajada slopes of Summerford Mountain, a rocky inselberg at the northern tip of the Doña Ana Mountains mostly composed of quartz monzonite, with localized rhyolites. The bajada is made up mainly of igneous alluvial deposits derived from the igneous rocks of Summerford Mountain with a contribution of sandy deposits from the ancestral and present Rio Grande. The surface horizon texture of these soils consists of sandy loams or loamy sands and contains variable amounts of gravel on the surface as erosional lags. Soils are classified as Typic Haplargids and Torriorthentic Haplustolls with localized Typic Haplocalcids (Gile *et al*., 1981; Monger, 2006). Mesquite shrubs occur predominantly in the eastern and central part of the Jornada Basin, whereas the creosotebush shrubs are more predominant within the lower and upper piedmont slopes of the basin. Black grama grasslands occur typically on upland slopes and in the central plain of the basin and exhibit varying degrees of degradation. Figure 1 shows the location of the different vegetation types within the study area.

Vegetation characteristics

The creosotebush, mesquite and black grama have different root and canopy structures, which we hypothesize have a first-order control on the local soil characteristics, and hence on the hydrology. The strongest differences in root and canopy structures are between the two shrubs and the grass, and arise principally due to differing water-adaptation strategies in the environment (Wainwright, 2009). Table I summarizes the main differences between the three vegetation types and the implications for soil and water characteristics. The adaptation of different shrub species to the dryland landscape may lead to their preferential location within parts of Jornada in place of the grassland but equally, once established, the shrubs may alter the soil and surface characteristics around them. A distinguishing feature of the two shrubs is the development of fine sediment mounds under the shrubs due to the entrapment of aeolian- and rainsplash-derived sediment within the large canopies (Reynolds *et al*., 1999). The relative rates of aeolian- *versus* raindrop-related accumulation vary according to source area (e.g. the relative location of the creosotebush and grass sites in the lee of Summerford Mountain compared to the dominant wind direction in periods of high wind velocity: Okin and Gillette, 2001; Wainwright, 2005; Okin *et al*., 2006). By contrast, grass-covered areas do not exhibit such sediment mound features and the microtopography is typically less pronounced. The presence of large canopies in the shrub species also affects the hydrological characteristics through interception of the rainfall and a reduction in the kinetic energy of the raindrops. The two shrubs have different canopy densities with typical values of leaf area index (canopy cover/total leaf area) reported in the range of 1·0–1·6 for mesquite (e.g. Kustas *et al*., 2000) and in the range of 0·5–0·8 for creosotebush (e.g. Ritchie *et al*., 2001). These differences in canopy density affect the kinetic energy of rainfall reaching the soil beneath the shrubs (e.g. Wainwright *et al*., 1999), with the dense mesquite shrub intercepting higher amounts of rainfall

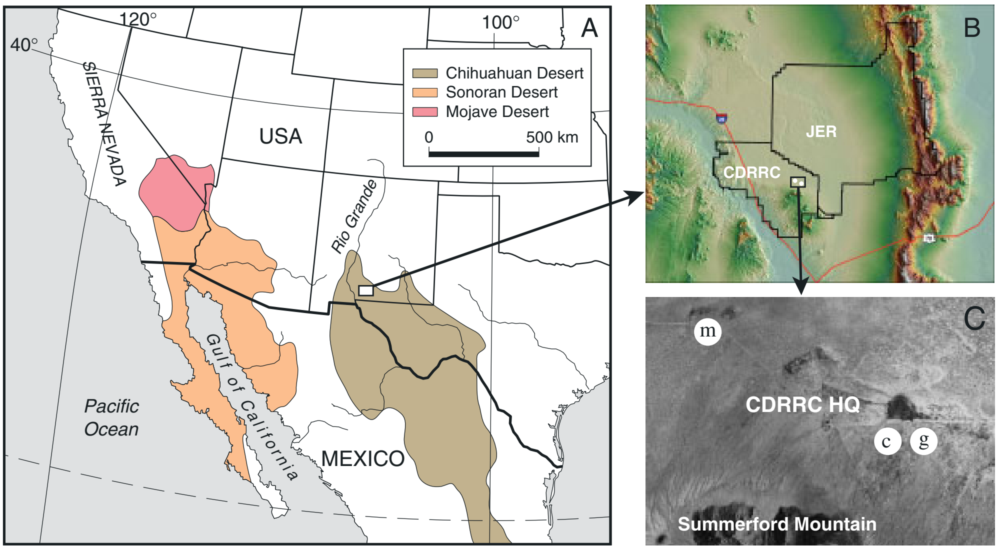


Figure 1. A. Location of Jornada Long-Term Ecological Research (LTER) site within the Chihuahuan desert, New Mexico, USA. B. The LTER includes the 78 000 ha Jornada Experimental Range (JER) and the 22 000 ha Chihuahuan Desert Rangeland Research Centre (CDRRC). C. Location of (m) the area of *Prosopis glandulosa* (honey mesquite), (c) the area of *Larrea tridentata* (creosotebush) and (g) *Bouteloua eriopoda* (black grama grassland) within the CDRRC in Jornada

than the creosotebush and providing better protection of the underlying soil from rain splash processes. In contrast to both the shrubs and the grass, the intershrub areas are dominated by bare soil not protected by any vegetation canopy, except during particularly wet years, when there may be a cover of annuals. This cover was not present at the time of the experiments discussed here. Rain falls with maximum kinetic energy on unprotected soil, causing more material to be lost to the shrub area than from it, accentuating the topography around the shrub (Abrahams and Parsons, 1991). In addition, runoff is concentrated downslope in the intershrub areas, increasing the velocity of the flow and exceeding the critical threshold for sediment transport. Previous studies have shown that the horizon of the soil within these intershrub areas is selectively eroded, lowering the surface of the intershrub areas and further reinforcing the raised topography of the shrub mounds adjacent to them (Abrahams *et al*., 1992; Bromley *et al*., 1997; Wainwright *et al*., 2000).

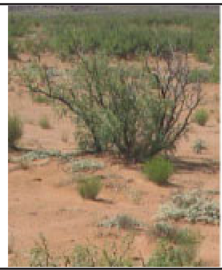
METHODS

Description of the field experiments

A series of 54 rainfall-simulation experiments were undertaken during August and September 2004 in the Jornada Basin. The experiments were carried out on small-scale plots (1 m × 1·5 m) on three vegetation types. At least 10 experiments were undertaken within the black grama grassland, and in both shrub and intershrub areas of creosotebush and mesquite, in order to encompass the microtopographical variations of the shrubland and to capture the variability in the plant characteristics within each vegetation type. Experiments were not carried out on tarbush areas due to practical difficulties associated with establishing plots on the low gradient slopes on which the tarbush is situated. Plots were selected based on having representative shrubs, lacking disturbance by animals and having proximity to an access route for the water tanker used in the rainfall simulations. Each runoff plot was bounded on three sides by 15-cm-high metal plates, approximately 5 cm of which was pushed into the soil, with a collection gutter dug into the fourth downslope end of the plot (Bolton *et al*., 1991; Parsons *et al*., 2003). Rainfall simulation was used because it overcame both the temporal and spatial variability in precipitation; it allowed a controlled comparison between vegetation types under a similar rainfall regime (Wainwright *et al*., 2000; Rickson, 2002); it allowed a series of experiments to be undertaken within a short time period and a reduction in the likelihood of variability in external factors; and it facilitated the repetition of experiments on plots of each vegetation type in order to describe the variability associated with the vegetation and soils. Small-scale plots were used to enable multiple plots to be established relatively rapidly within each vegetation type, to allow isolation of individual shrub species and because small plots are more cost-effective, practical and water conservative than large rainfall-simulation plots.

Nine initial surface properties were measured at each plot to characterize the soil and vegetation associated with each vegetation type. These properties, which are a function of vegetation type, are hypothesized to exert a significant control on the runoff and erosion dynamics. Antecedent moisture content of the soil was measured prior to rainfall onset by use of a Theta probe (Sharpley and Kleinman, 2003). Soil aggregate stability was measured by use of an aggregate stability kit for field soils, as outlined by Herrick *et al*. (2001) to provide an indication of soil quality and strength. Four or five ordinal rankings of aggregate stability were made for each plot at both the soil surface (0–2 mm) and the soil sub-surface (20–30 mm). While this method may not be as accurate as laboratory-based measurements of

Table I. Properties of the three main vegetation types found in Jornada, LTER, New Mexico

Structural Feature	Vegetation type		
	Prosopis glandulosa	*Larrea tridentata*	*Bouteloua eriopoda*
Common name	Honey Mesquite	Creosotebush	Black Grama Grassland
Life Cycle	Perennial	Perennial	Perennial
Picture			
Roots	Extensive underground root systems that can proliferate quickly and spread over long distances and maximise use of of soil water (e.g. Drewa and Havstad, 2001)		Dense but shallow root system below the basal area of the plant - the grass is not very effective at responding to small rainfall events. Nonetheless grassland productivity remains closely linked with rainfall (Stephens and Whitford, 1993).
	Roots have low turnover rates and are thus relatively long-lived within the environment.		
	The deep roots of the shrubs are able to tap the deeper soil reserves during prolonged periods of drought (Reynolds *et al.*, 1999) allowing the shrubs to outcompete grasses for moisture in excessively dry conditions.		
	Deep and anchoring roots reduce the likelihood of breakage or removal of shrubs from the environment. Mesquite able to withstand aeolian-driven sand abrasion more effectively than creosotebush (e.g. Peters and Havstad, 2006).		Shallow roots increase likelihood of removal from environment.
Leaves	Deciduous with principal leaf growth in late spring. Growth independent of drought conditions (Reynolds *et al.*, 1999).	Evergreen with principal leaf growth in spring; a combination of soil temperature and rainfall determines amount of growth.	Small proportion of biomass as leaves and small leaf area to cope with water-stress (Fernandez *et al.*, 2002).
Canopy	The large and dense canopy of the mesquite (typically 4 times greater than creosotebush) allows it to capture aeolian and eroded sediments and litter (e.g. Titus *et al.*,2002). Typical LAI ranges reported for the mesquite are 1.0 - 1.6 (e.g. Kustas *et al.*, 2000)	The canopy of the creosteobush allows interception of aeolian and eroded sediments but is less dense than the mesquite (e.g. Perkins *et al.*, 2006). Typical LAI ranges reported for the creosote bush are 0.5 - 0.8 (e.g. Ritchie *et al.*, 2001)	N/A
	Stemflow accounts for between 16 and 25 % of intercepted rainfall, entering the soil at the root crown and contributing to the tight cycling of nutrients (Whitford *et al* ., 1995).		

aggregate stability, it does have the advantage of minimizing soil damage on transport and allows for quick, inexpensive analysis of large number of samples. A comparison between this field-based technique and laboratory methods yielded a good correlation (Herrick *et al.*, 2001). Description of the percentage of crusting, stone, litter and vegetation cover, vegetation height and slope gradient was also determined for each plot. This description was established by a simple grid method (Schlesinger *et al.*, 1999; Neave and Abrahams, 2001) over the plot area (1·5 m^2) every 10 cm. Ten centimetres deep surface soil samples were extracted adjacent to the plots to enable a comparison between the initial soil and the eroded-sediment particle size composition and for determining organic matter composition. Where there was a soil mound present beneath a shrub, the local gradient was measured, using a clinometer, in the overall predominant downslope direction of the plot. Table II gives a summary of the initial plot characteristics according to vegetation type.

The rainfall simulations were conducted at a rainfall intensity of 125 mm h^{-1} ±13% for between 16 and 30 min. The coefficient of spatial variation in intensity was between 15 and 20%, based on four gauges surrounding the plots. Such a high intensity was used in order to accentuate the differences between the plot erosion responses (Schlesinger *et al.*, 1999) and because high intensity, low frequency events have been found to generate a disproportionate amount of the total runoff and erosion from areas within dryland environments (e.g. Wainwright, 1996; Martínez-Mena *et al.*, 2001; Howes and Abrahams, 2003). In addition, such high intensities were used in previous studies in the same environments (e.g. Schlesinger *et al.*, 1999; Parsons *et al.*, 2003) and hence were used again in this study to enable comparison with previous results. Runoff and eroded sediment were collected in sterile polyethylene bottles via the gutter at the downslope edge of the plot. The sampling protocol followed that of Schlesinger *et al.* (1999) whereby collection of the first sample commenced at the point of runoff

Table II. Summary statistics for each vegetation type based on data collected from the 54 plots. SAS is the surface aggregate stability and SSAS is the sub-surface aggregate stability

Vegetation type	Vegetation cover (%)		Litter cover (%)		Crust cover (%)	
	Mean	s.d	**Mean**	s.d	**Mean**	s.d
Creosotebush	**64·5**	11·9	**12·9**	9·1	**40·5**	28·6
Creosotebush intershrub	**1·0**	2·1	**4·0**	3·5	**49·0**	22·9
Grassland	**57·5**	7·2	**4·4**	3·6	**36·0**	7·7
Mesquite	**68·5**	9·4	**12·3**	6·0	**36·5**	30·9
Mesquite intershrub	**1·1**	1·7	**3·3**	1·9	**90·5**	6·4

Vegetation type	Stone cover (%)		Slope angle (°)		Soil organic matter (%)	
	Mean	s.d	**Mean**	s.d	**Mean**	s.d
Creosotebush	**8·4**	6·6	**6·9**	1·4	**0·33**	0·16
Creosotebush intershrub	**7·1**	4·5	**3·2**	1·5	**0·42**	0·13
Grassland	**0·0**	0·0	**1·9**	0·9	**0·56**	0·13
Mesquite	**0·8**	1·9	**10·0**	3·8	**0·31**	0·09
Mesquite intershrub	**5·2**	4·5	**3·7**	2·3	**0·26**	0·08

Vegetation type	Antecedent soil moisture (%)		SAS		SSAS	
	Mean	s.d	**Median**	Mode	**Median**	Mode
Creosotebush	**7·4**	3·6	**3**	3	**1**	1
Creosotebush intershrub	**7·6**	3·1	**2**	1	**1**	0
Grassland	**12·2**	11·2	**3**	3	**1**	1
Mesquite	**3·5**	1·7	**1**	1	**1**	0
Mesquite intershrub	**8·8**	6·2	**1**	1	**1**	0

Vegetation type	Clay (%)		Silt (%)		Sand (%)	
	Mean	s.d	**Mean**	s.d	**Mean**	s.d
Creosotebush	**3·0**	1·7	**19·8**	9·5	**77·2**	11·2
Creosotebush intershrub	**5·0**	0·6	**25·1**	6·8	**70·0**	6·2
Grassland	**5·7**	1·9	**31·5**	9·4	**62·8**	11·3
Mesquite	**3·0**	0·9	**15·8**	5·6	**81·2**	6·4
Mesquite intershrub	**3·7**	0·2	**20·5**	5·8	**75·8**	6·1

initiation and ceased once sufficient sample was available for analysis. The remaining samples were collected for 15 s every 1 to 4 min. The sampling intervals became longer during the latter half of the simulations as runoff reached equilibrium (Schlesinger *et al.*, 1999). Following collection, the samples were filtered within 4 h to 0·45 μm using a polypropylene membrane filter to obtain a filtrate and a sediment fraction. Out of the 54 plots, 3 plots for each of the five vegetation types were randomly selected for particle-size analysis. For each of these 15 plots, the surface soil and eroded-sediment samples were air dried and particle size analysis was undertaken according to the Wentworth classification scheme. The samples were then wet sieved with a dispersal agent and a subsample of the <0·063 mm fraction was analysed for the percentage of clay using a Malvern Mastersizer.

Description of statistical approach

Establishing the controls on runoff production using field experimental data is difficult because complex relationships and feedback mechanisms exist between the vegetation, soils and climate (e.g. Schlesinger *et al.*, 1990). A commonly used statistical approach for the analysis of a dependent variable according to a set of independent variables involves a linear model such as multiple regression using continuous data or the general linear model (GLM), which allows a combination of continuous and categorical data. Both types of model assume a linear relationship between the dependent and independent variables and normality of the residuals (Erickson and Nosanchuk, 1992). If a sufficient number of independent variables is used, these linear models usually produce some significant results because the model will start to capitalize on chance and to model the noise in the dataset (Littell *et al.*, 1992). Previous studies have indeed typically applied such a linear analysis approach of vegetation parameters on runoff and erosion (e.g. Schlesinger *et al.*, 2000a, 2000b), providing a limited insight into the controls and inter-relationships between the various aspects of the soil-vegetation-hydrology system. In this study, the field experiments generated 54 measurements of runoff coefficient and eight variables that could be used to analyse these data. Applying the linear model of regression, only five independent variables at most could have been used in the model to predict the runoff coefficient before the model started to overfit the data. Using the linear model approach, the determination of the most important variables would have been difficult and subjective, and importantly, the interactions between the variables on the resultant runoff produced would have been difficult to ascertain (Littell *et al.*, 1992). Therefore, in this paper we use a tree-regression approach to examine how the soil-related characteristics of differing vegetation types interact to affect the runoff and sediment production. Tree regression determines a set of 'if-then' logical conditions between the independent variables and the dependent variable and splits the dataset according to the largest deviance produced (Rejwan *et al.*, 1999). This statistical method has several key advantages over the linear models, not least because it is a non-linear and non-parametric approach, i.e. no implicit assumptions are made about the underlying relationships between the independent and dependent variables; the independent variables can consist of a combination of continuous and categorical data; the tree regression automatically identifies interactions among variables and displays these interactions as a simple tree diagram (Rejwan *et al.*, 1999); and finally, by cross-validating the dataset, the number of branches that can be produced by the tree regression before the model begins to fit the noise in the data can be identified, and the tree can be 'pruned' or 'shrunk' to avoid this overfit. Pruning involves removing those branches that are least important and simplifying the model. Shrinking halts the generation of branches when new splits result in very little overall improvement in the model prediction (Clark and Pregibon, 1992). The data must be cross-validated in both cases to ascertain the number of branches that can be used before overfit occurs. Cross-validation involves splitting the dataset into a number of roughly equal-sized parts, and using all but one of those parts to grow the tree and test the outcome on the remaining part. Cross-validation via both the pruning and shrinking of the data was undertaken to investigate which method produced the clearest outcomes. The trees were eventually pruned, because this produced the simplest models, and the overfits were easily identified.

RESULTS

Runoff production

For most of the experiments, runoff produced a typical pattern involving a rapid rising limb resulting from an increase in the contributing area of the plot tending towards an equilibrium discharge. Peak discharge was highly variable both within and between vegetation types. The mean peak discharge ranged from 15·1 $cm^3 s^{-1}$ on the mesquite plots to >30 $cm^3 s^{-1}$ on the other two vegetation types and the two intershrub areas (Table III), and varied between 21 and 46% within the vegetation types. The mean runoff coefficients and yields produced according to vegetation type are given in Table IV. Analysis of variance (ANOVA) indicated a significant difference in the runoff coefficients produced during the first 16 min of each simulation according to vegetation type ($p < 0·001$).

The results of the tree-regression analysis for runoff are given in Figure 2. Each box of the tree shows the variable and the split of that variable that is important in determining the runoff coefficient produced. Out of the original nine variables, the four that were found to be most significant in splitting the data were the slope gradient, crust cover, antecedent moisture and the surface aggregate stability. The small number of observations of the runoff coefficient produced an overfit when any more 'nodes' were added to the model.

Table III. Summary statistics of peak discharge (cm^3 s^{-1}), runoff yield (l) and coefficient (%) over each simulation according to vegetation type

Vegetation type	Peak Q (cm^3 s^{-1})			Runoff yield (l)			Runoff coefcient (%)		
	Mean	s.d	c.v	Mean	s.d	c.v	Mean	s.d	c.v
Creosotebush	40.7	11.5	28.4	26.4	7.7	29.2	54.7	14.9	27.2
Creosotebush intershrub	38.3	11.8	30.7	24.9	11.9	47.8	49.2	23.2	47.1
Grassland	44.1	9.3	21.1	23.3	4.1	17.7	48.5	7.5	15.5
Mesquite	15.1	6.9	45.9	8.6	4.7	53.8	17.0	8.7	51.2
Mesquite intershrub	33.3	10.0	30.2	24.5	9.1	37.3	50.7	16.6	32.8

Table IV. Range of sediment concentrations (g l^{-1}), erosion rates (g s^{-1}) and sediment yields (g) measured according to vegetation type. Note that the sediment yields are those calculated for the first 16 min of each simulation

Vegetation type	Sediment concentration (g l^{-1})			Min erosion rate (g s^{-1})	Max erosion rate (g s^{-1})	Peak erosion rate (g s^{-1})			Sediment yield (g)		
	Min	Max	Mean			Mean	s.d	c.v	Mean	s.d	c.v
Creosotebush	0.03	23.00	5.05	<0.01	0.90	0.33	0.28	83.8	145.4	119.4	82.1
Creosotebush intershrub	0.54	42.82	7.96	0.01	0.63	0.35	0.19	54.2	182.9	128.7	70.4
Grassland	1.21	16.63	6.37	0.03	0.43	0.25	0.11	43.4	134.0	54.1	40.4
Mesquite	0.16	181.90	34.35	<0.01	2.67	0.81	0.84	102.8	330.9	371.9	112.4
Mesquite intershrub	0.28	7.94	2.81	0.01	0.27	0.13	0.09	67.9	68.1	54.6	80.2

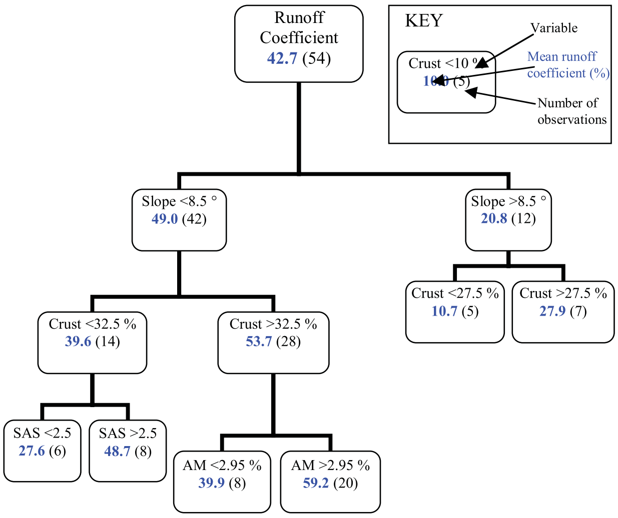


Figure 2. Tree-regression results of the runoff coefficient produced during each rainfall experiment according to the interactive effect of the plot gradient (°), crust cover (%), SAS or surface aggregate stability and AM or antecedent soil moisture (%)

The largest split in the dataset was determined by the local gradient of the plots. Of the 42 plots with a slope <8·5°, the lowest runoff coefficient (27·6%) was produced by the 6 plots with a crust cover <32·5% and a median surface aggregate stability <2·5. A similarly low runoff coefficient was produced when the low gradient interacted with antecedent soil moisture <2·95%. However, if a low gradient was combined with a surface aggregate stability >2·5, the mean runoff coefficient was double at 48·7%, and combined with a crust cover >32·5%, the runoff coefficient was 53·7%, almost double that produced by those plots with a low crust cover. The 12 plots with a gradient >8·5°, plots with a crust cover >27·5% produced runoff coefficients similar to plots with a lower slope gradient, low crust and low surface aggregate stability (27·6%) while plots with a steep gradient and low crust cover produced the lowest overall mean runoff coefficient of 10·7%.

Sediment production

Sediment discharge typically followed a pattern of an increase up to a peak rate, followed by a decline towards the end of the simulation. This pattern of erosion was produced on approximately one third of the 54 simulation experiments. On a further 15% of the plots, the erosion rate followed the typical discharge pattern, increasing over time then equilibrating towards the end of the simulation. In both cases, the initial rise in erosion rate was associated with the rise in discharge from these plots and suggests that, at the beginning of these simulations, the erosion rate was transport-limited and not detachment-limited. However, the eventual decline in erosion rate observed in one third of the experiments indicates that for some plots, the sediment supply diminished towards the end of the simulation. Erosion rates are summarised according to vegetation type in Table IV. Rates were highly variable within each vegetation type, but the mesquite shrubs produced the highest overall maximum erosion rate of 2·67 g s^{-1}. The mean sediment yields produced were found to be significantly different according to vegetation type (ANOVA, $p = 0{\cdot}037$). The mesquite produced the highest (331 g) and the mesquite intershrub plots the lowest (68 g) mean sediment yields of the five vegetation types (Table IV). The grassland, creosotebush shrubs and creosotebush intershrub areas all produced similar mean yields of 134, 145 and 183 g, respectively.

The tree-regression outcomes between sediment yield and the plot characteristics are shown in Figure 3. Three additional hydrological variables were considered in the sediment yield analysis: the number of natural rainfall events in the season prior to each experiment, the rainfall rate and the runoff yield in the first 16 min of the experiment. The gradient, surface-soil aggregate stability, runoff yield and crust cover were found to be significant determinants of sediment yield. As with the runoff coefficient, the largest split in the data was determined by the local gradient of the plot. The 12 plots with gradients steeper than 8·5° produced a mean sediment yield that was three times greater than the sediment yield produced on plots with gradients <8·5°. The surface aggregate stability also had a strong influence on the sediment yield produced from the steeper slopes. The five plots with a steep slope and a surface aggregate stability of <1·5 produced a mean sediment yield of 588·3 g. Sediment yield was reduced to a mean of 217·2 g when the surface aggregate stability was >1·5. On plots with a gradient <8·5°, the next most significant variable was the runoff yield. Plots that produced a runoff yield >24·9 l over the first 16 min of the simulation generated a sediment yield three times that generated on plots with a runoff yield <24·9 l. The combined effect of a shallow slope and lower runoff yield produced the lowest mean sediment yield of 65·0 g. On the 20 plots with low slopes but a higher runoff yield, crust cover was also found to have a significant influence on the sediment yield. In fact, the combination of a slope <8·5° with a runoff yield >24·9 l and a crust cover <75% generated a higher mean sediment yield than that produced by the plots with steep slopes and high surface aggregate stability. This sediment yield was increased further when the final split in these data was taken into consideration; the five plots with a runoff yield >29·8l produced a mean sediment yield of 315·5 g compared to a mean of 186·8 g when the runoff yield was <29·8l.

Particle-size distribution of sediment

Particle-size analysis analysis was undertaken on eroded sediment samples from 15 randomly selected experiments out of the total 54 simulations. To obtain a sufficient sample size for analysis, the samples collected during the course of each simulation were grouped into three intervals, each containing an equal number of samples: the first four samples were grouped to form the 'beginning' sample, the second four samples were grouped to represent the 'middle' 5 min and the final four samples were grouped to represent the 'end' 12 min of the simulations.

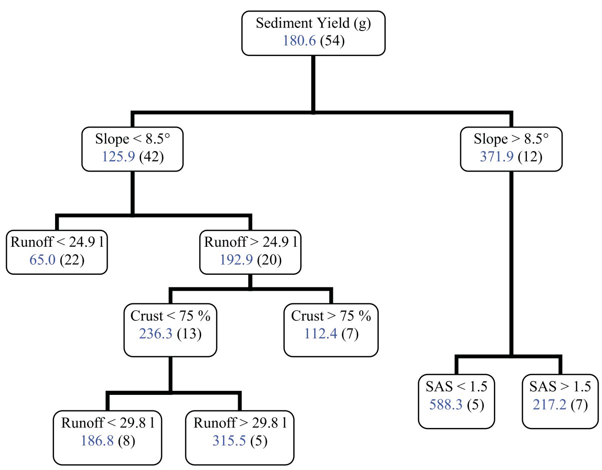


Figure 3. Tree-regression output of the sediment yield produced during each rainfall experiment according to the interactive effect of the gradient (°), runoff yield (l), crust cover (%) and SAS (median surface aggregate stability)

The particle size compositions over time for the different vegetation types are shown in Figure 4. Over the course of the simulations, there was typically a decrease in the percentage contribution of the <0·063 mm fraction. This pattern was observed in 10 of the 15 plots, particularly in the creosotebush, the creosotebush intershrubs and the mesquite intershrub plots. Of the five plots that did not produce this pattern, two plots (one grass and one mesquite) produced an increase in the percentage of eroded sediment found in the finest size fraction over the course of the simulation. On two other plots (one grass and one mesquite), the lowest percentage contribution of the <0·063 mm fraction to the total eroded losses was in the middle section of the simulations; in contrast, the highest contribution of this fraction to overall sediment losses was in the middle part of the simulation on one grassland plot. The contribution of the <0·063 mm fraction in the eroded sediment was particularly high (41–91%) from the grassland plots; however, all other vegetation plots produced eroded sediment enriched in the <0·063 mm size fraction compared to their initial surface soils. The enrichment of eroded sediment in the fine fraction has important implications for the transfer and loss of most surface soil nutrients as these tend to be preferentially adsorbed onto the finest soil particles (Haygarth *et al*., 2006).

DISCUSSION

A summary of the vegetation controls on runoff and erosion dynamics is presented in Figure 5 based on the outcomes of the tree-regression analyses presented in the previous sections. The statistical analysis indicates that the largest divergence in the data is due to differences between the mesquite and all the other vegetation types and point to shrub type and density being the primary vegetation control on the hydrological processes through the direct influence on the local mound gradient. The canopy also has an effect on crust development by intercepting rainfall and reducing raindrop impact on soil immediately below the canopy. Steep soil mounds and low crust covers are a particular feature of the dense mesquite shrubs, which characteristically are associated with aeolian sediment accumulations. The creosotebush, grass and the intershub areas have low local gradients and medium to high crust covers due to less dense canopies and reduced rainfall interception. Erosion rates on the steep, mesquite-covered areas increase when combined with a low surface aggregate stability, which increases the

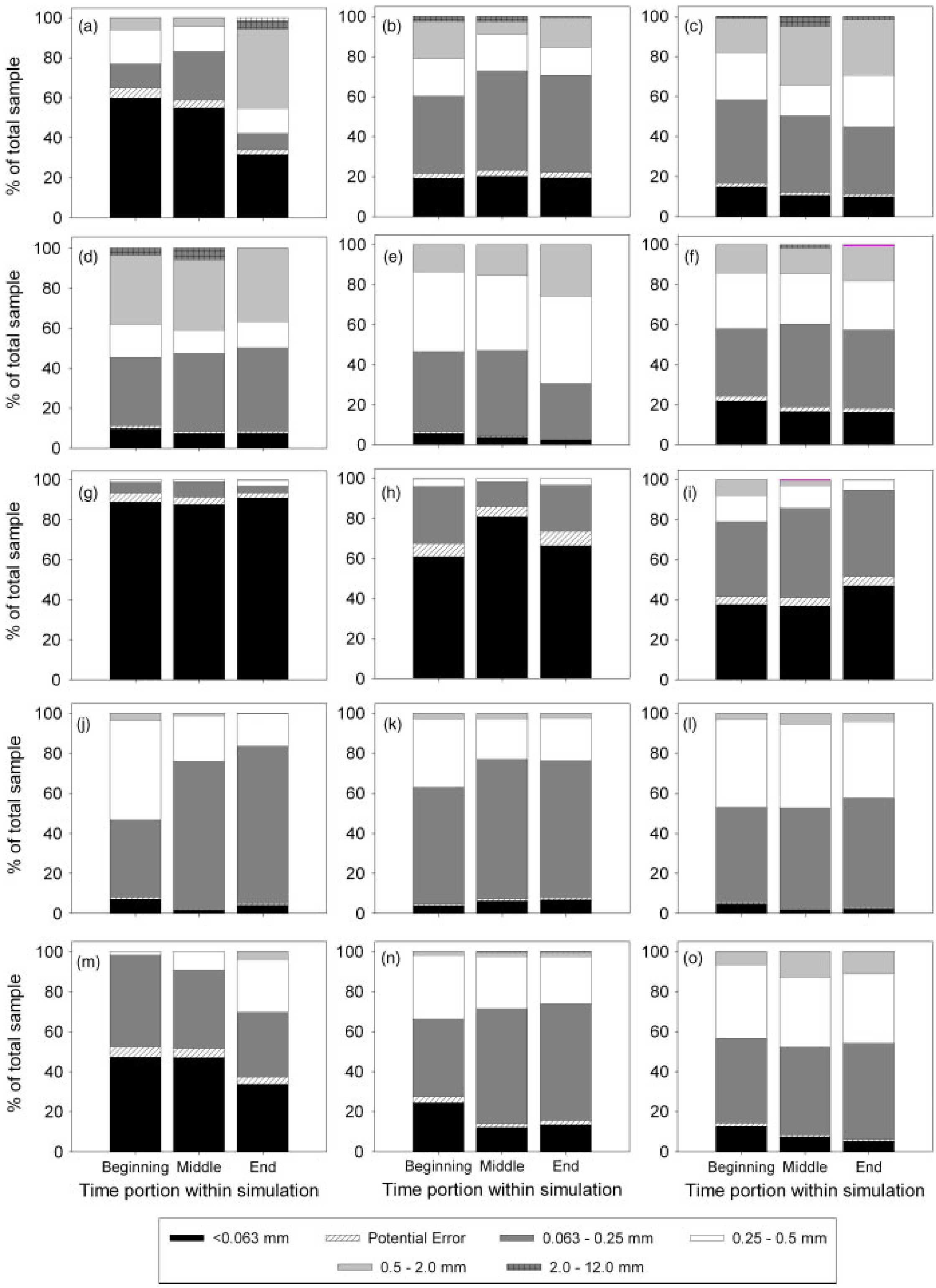


Figure 4. Particle size composition of the sediment eroded over the course of each rainfall simulation event for creosotebush plots (a, b and c) creosotebush intershrub plots (d, e and f), grassland plots (g, h and i), mesquite plots (j, k and l) and mesquite intershrub plots (m, n and o)

erodibility of the soil. However, despite high erosion rates on the mesquite, only a small proportion of the eroded sediment is composed of fines ($<0{\cdot}063$ mm). In contrast, on the grassland, the low local gradient and medium crust cover lead to low erosion rates. However, the eroded sediment from the grassland is the most enriched in the fine fraction, and this has implications for nutrient relocation as nutrients tend to be preferentially adsorbed onto the finer fractions of the soil. The creosotebush areas that have low gradients and variable crust cover produced variable runoff and erosion rates depending on the surface aggregate stability. Similarly, the enrichment in fines was variable depending on the erosion dynamics and varied from low to medium.

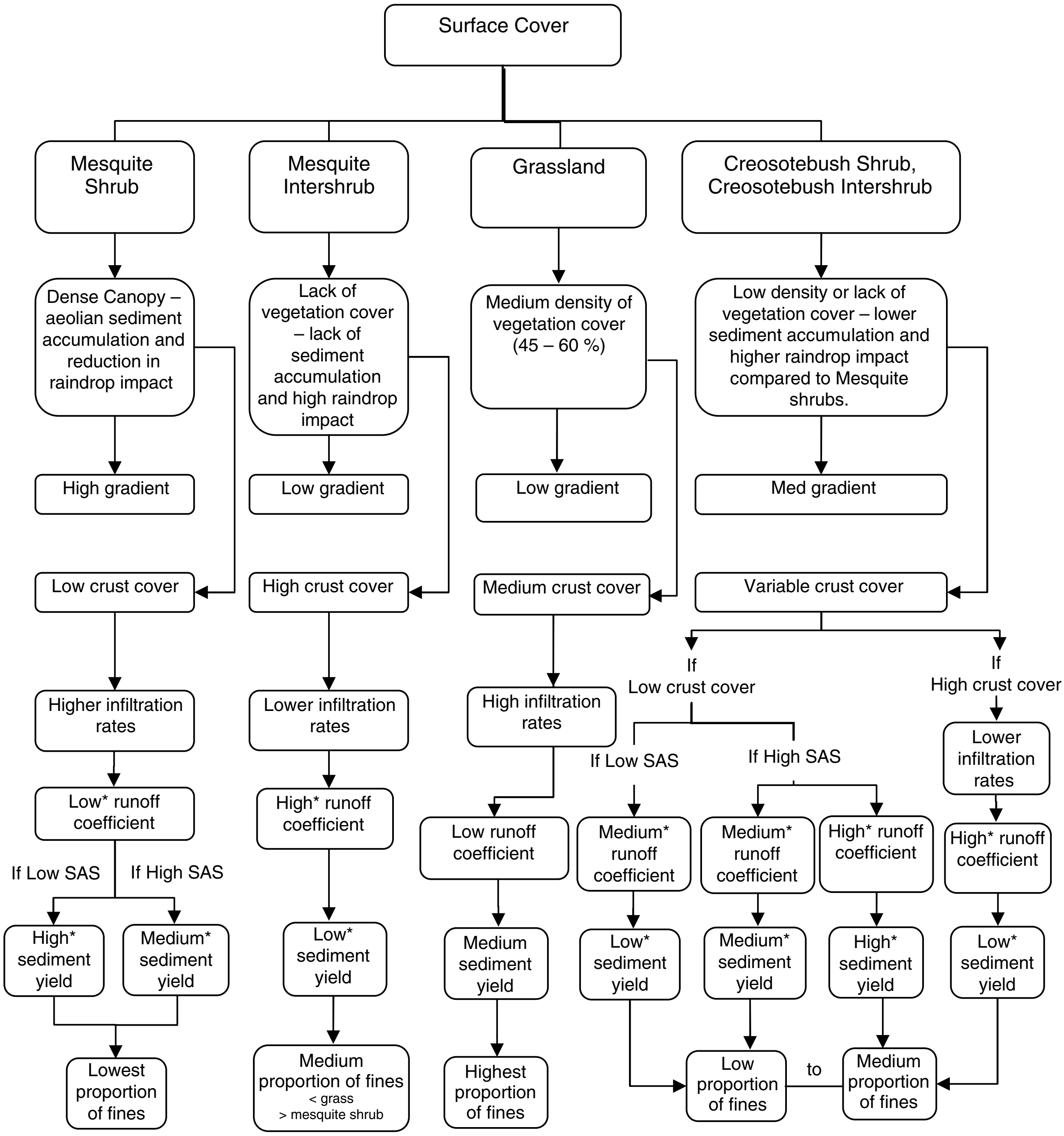


Figure 5. Summary chart of the vegetation controls on runoff and erosion

Runoff characteristics

The main hypothesis in this paper is that vegetation type exerts a first-order control on runoff and erosion by directly affecting the soil and surface characteristics. Statistical analyses using tree regression found the local slope gradient to be the primary control on both runoff coefficient and sediment yield. The local soil surface gradient is a direct manifestation of the vegetation type, particularly due to the characteristics of the canopy as discussed earlier. Shrubs with dense canopies are more able to capture aeolian sediments, which increases the size of the soil mound beneath the canopy leading to a steep local slope gradient (Whitford *et al.*, 1995; Aguiar and Sala, 1999; Reynolds *et al.*, 1999). Large shrub soil mounds and associated high local slope gradients are typical of the mesquite shrub that has a canopy typically four times as dense as that of the creosotebush (Reynolds *et al.*, 1999). Eleven out of the 12 plots that had slopes steeper than 8·5° were indeed mesquite plots. The only non-mesquite plot that was steeper than 8·5° was a creosotebush plot containing the tallest (120 cm) of all the shrubs measured on the 54 plots, which may have encouraged greater sediment accumulation and steeper slope gradients on this plot.

The mesquite plots with the steepest slopes (>8·5°) produced the lowest runoff coefficients due to the low surface crust cover which enhanced infiltration rates (Abrahams *et al.*, 1988; Baird, 1997). The dense canopies

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of the mesquite shrubs intercept more rainfall which reduces the raindrop impact and the formation of a crust as water moves directly into the soil profile via stems and roots (Dunne *et al.*, 1991; Martínez-Mena *et al.*, 1999; Wainwright *et al.*, 1999; Abrahams *et al.*, 2003). The significantly larger sediment yields produced by the mesquite compared to the other vegetation types give support to the positive feedback mechanism associated with the low crust cover, high local gradient and erosion process. In addition, the tree regression highlighted that plots with a low surface aggregate stability were more likely to produce lower runoff coefficients. The low stability of the aggregates found in the soils of the mesquite, which are indicative of the lower cohesiveness of the soil, may have contributed to the increased erosion on the mesquite plots (Kidron, 2001). The combined effect of high vegetation cover, high gradients and low crust cover on the mesquite shrubs thus generated a significantly lower runoff coefficient and higher sediment yield from the mesquite shrubs compared to the mesquite intershrubs (Tables III and IV).

On plots with shallower gradients ($<8{\cdot}5°$), the presence of a lower crust cover ($<32{\cdot}5\%$) resulted in an increase in infiltration, thus halving the mean runoff coefficient produced. In addition, the plots with low crust cover and low surface soil aggregate stability produced the lowest runoff coefficients of the shallow plots. Low soil aggregate stability appears to have encouraged greater erosion from these plots, leading to an enhanced infiltration and reduced runoff production (Kidron, 2001). Finally, plots with higher crust cover and high antecedent soil moisture produced the highest overall mean runoff coefficient, a value six times greater than that produced by plots with steep slopes and low crust cover. Greater similarity in the mean and ranges of crust cover and gradients of the creosotebush shrub and intershrubs and the grassland resulted in their varied and comparable mean runoff coefficients (Table III).

Plots with a higher crust cover produced a more rapid discharge response and typically greater runoff coefficients as well. The crust cover acted as a barrier to infiltrating water, decreasing the time to runoff and increasing the magnitude of the runoff response (Le Bissonnais, 1990; Rostagno *et al.*, 1999; Parsons *et al.*, 2003). The mesquite intershrubs all had crust covers $>80\%$, along with low slope gradients and a lack of vegetation cover (Table II). The interaction of these factors generated a significantly higher runoff coefficient from the mesquite intershrubs compared to the mesquite shrubs. In contrast, the creosotebush shrubs had comparable crust cover to the creosotebush intershrubs at the start of the simulations and produced similar runoff responses. Antecedent soil moisture was the final factor identified as generating an important split in the runoff coefficients. The lower soil antecedent moisture increases the infiltration rate of the soil, prolonging runoff initiation and equilibrium from those areas of each plot not covered by a crust and thus reducing the runoff coefficient (Abrahams *et al.*, 1995).

Erosion characteristics

One of the fundamental reasons behind the higher sediment yield produced by 11 mesquite plots and 1 creosotebush plot was the steep slope gradient of the plots as a result of the soil mounds generated beneath the shrubs. The steeper slopes generate higher velocities of runoff with higher erosivity and, on five plots, the additional combination with low surface aggregate stability led to enhanced soil erodibility that generated higher sediment yields. The denser canopy of the mesquite was hypothesized to reduce the kinetic energy of the raindrops impacting the surface leading to a reduction in the sediment yield produced by the mesquite compared to the other vegetated plots, and particularly compared to the intershrub plots. However, the results indicate that the local steep slopes can generate highly erosive runoff that in combination with the soil surface properties produce the higher sediment yields from the mesquite.

On plots with shallower slopes, the tree-regression analysis indicates a close relationship between the sediment yield and the runoff characteristics. The higher runoff yields provided a higher transport capacity for the eroded sediment, and in many cases, this transport capacity, rather than the sediment supply, dictated the overall sediment dynamics. The crust cover also had a significant control on sediment yields. Plots with a greater crust cover had a resistant top soil layer and a lower ready supply of sediment that could be eroded from the plots. The lower sediment production from the mesquite intershrubs was due to the combination of a low gradient and high crust cover; at low slopes, the crust covers are stable enough to withstand breakdown from the runoff. However, when the crust cover was $<75\%$ on low slopes, a runoff yield $>29{\cdot}8$ l led to a higher sediment yield than from those plots with steep slopes ($>8{\cdot}5°$) and a higher surface aggregate stability.

Particle-size characteristics

The common decrease in the finest fraction over the course of the simulation was attributed by Farenhorst and Bryan (1995) to the changing energy of the discharge produced during the course of the simulations. Initially, the discharge from the simulations was too low to provide sufficient energy to transport any particle sizes other than fines over a measurable distance. However, as the discharge increased and equilibrated Farenhorst and Bryan (1995) noted that the fines became trapped in the surface microtopography, and the available energy increased to a sufficient level to transport the coarser particles. This explanation is supported by the data presented in Figure 4. For example, creosotebush plot (A) in Figure 4 produced a decrease in the percentage of fines over the course of the simulation and an increase in particles $>2{\cdot}0$ mm by the end of the simulation.

The preferential erosion of fines found to be dominant in this study supports previous studies where the sediment eroded from plots was finer than the matrix soil. Parsons *et al.* (1994) found that fines enrichment on their larger-scale (18 m wide by 35 m long) rainfall-simulation plots was due primarily to selective transport by runoff, rather than selective detachment by raindrops. The sediment detached via rainsplash was found to be coarser than the surface soil, but finer material was preferentially eroded from the plot, suggesting that the flow was not competent to transport coarser sediments, particularly in the upper part of the plot. Similar findings were also obtained in the field study by Malam Issa *et al.* (2006) on a 10 m by 4 m experimental plot in Senegal. Particle-size detachment according to rainsplash was not measured in this study. However, the close relationship between the sediment yield and runoff and the high percentage of preferential erosion in the <0·063 mm fraction suggests that the erosion patterns found in this study are probably the result of selective transport by runoff in the majority of cases, rather than selective detachment by raindrops.

Despite the results presented in this paper, it should be recognized that any study using a plot-based approach is inherently limited and care should be taken not to overinterpret the results (e.g. Wainwright *et al.*, 2000). In particular, it must be recognized that the runoff and erosion rates measured here do not scale in a linear way (Parsons *et al.*, 2004, 2006; Wainwright *et al.*, 2008), and consequently neither do dissolved or sediment-bound nutrients (Brazier *et al.*, 2007). While the controls demonstrated in this paper are important at the plant interspace scale, they are unable to capture the controls on runoff and erosion dynamics at larger spatial and temporal scales. For example, Müller *et al.* (2007) used a modelling approach to show that runoff, erosion and nutrient fluxes at ecotones produce feedback to influence the temporal stability of different vegetation types and thus the location of the ecotone, and that these influences can extend in some cases for distances of more than 100 m upslope or downslope into a vegetation type. Therefore, a full understanding of vegetation controls on runoff and erosion dynamics requires integration of the results of this paper with studies from other scales.

CONCLUSIONS

This paper has identified the vegetation controls on runoff and erosion dynamics in Jornada at the small scale and, through a series of rainfall-simulation experiments, has provided significant insights into the interactions between vegetation, hydrology and soil erosion. Vegetation type provides a first-order control on runoff and sediment production in Jornada, primarily through the effect of shrub type on the local mound gradient of the plot, the crust cover and the surface soil aggregate stability. Analysis carried out using tree regression points to the importance of the interaction between vegetation characteristics and the resultant local gradient and soil surface properties in the runoff and erosion response. In particular, the interactions between local gradient, crust cover and surface aggregate stability were shown to be significant determinants of the runoff and sediment yield from plots covered with different vegetation types. In contrast to our hypothesis that the plots within the two shrubs (mesquite and creosotebush) would produce the most similar runoff and erosion dynamics, the largest difference in response was between the mesquite and the other surface cover types. This difference has been attributed to the denser mesquite canopy that is effective in reducing the rainfall impact on the soil. A distinguishing feature of the grassland plots was the higher enrichment of the eroded sediment in the finer fraction (<0·063 mm), despite similar erosion rates to other plots. The high enrichment from the grassland plots has significant implications for the sediment-bound transport of nutrients around Jornada, as higher concentrations of nutrients are typically associated with the finest particle sizes. Therefore, based on these small-scale data alone, the main consequences of changes in vegetation cover from grass to shrub are as follows: (1) Runoff does not appear to change significantly with vegetation type. (2) Despite the similarity in runoff, there is a potential for an increase in erosion rates under some shrubs due to locally steep gradients in the shrub areas and the surface properties associated with those areas and soil types. (3) There is a change in topography, from a relatively flat to a more accentuated shrub–intershrub surface where the shrubs accumulate sediment and form a mound beneath them while the intershrub areas remain relatively flat. (4) These changes in topography seem to lead to feedbacks in hydrological and erosional processes that would further enhance this topography.

In an area that has seen significant shifts in the dominant vegetation species over the past 150 years, this understanding of processes and feedbacks is fundamental both for understanding and managing landscape change.

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