Catena xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Small-scale effects of annual and woody vegetation on sediment displacement under field conditions

Oren Hoffman [a,*], Hezi Yizhaq [b], Bertrand R. Boeken [a]

[a] The Wyler Dept. of Dryland Agriculture, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Israel
[b] The Department of Solar Energy and Environmental Physics, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Israel

ARTICLE INFO

Article history:
Received 3 May 2012
Received in revised form 4 April 2013
Accepted 4 April 2013
Available online xxxx

Keywords:
Erosion protection
Herbaceous vegetation
Rain splash
Runoff flow
Semi-arid shrubland
Wind speed

ABSTRACT

Interactions between desert vegetation and erosive forces are prominent and are part of landscape evolution in deserts. The role of annual herbaceous plants in these processes is usually overlooked. Likewise, the interactions and relative contributions of the different erosive forces are rarely studied.

We examined the effects of mound-forming shrubs and annual plants on sediment dispersal at small spatial scales in the semi-arid shrubland of the northern Negev Desert of Israel. We conducted a field experiment to test the displacement of dyed sediment by wind, runoff and rain splash in 5×5 cm areas on shrub-mounds, placed under the canopy and on mound margins, and on the biological soil crust-covered intershrub space. As experimental treatments, we used artificial rain covers and removal of annuals and their litter.

We found that 1) most sediment displacement was caused by rain splash, which was effectively reduced by shrub canopy and less so by annual plant cover, and 2) runoff effects were limited to a fraction of rain events, took place only in the intershrub space, and were significantly reduced by annual plants and their litter. The combined effect of shrubs, annuals, and litter on sediment movement was significantly stronger than the effect of any single element.

Accordingly, we conclude that, in addition to shrubs, herbaceous annual plants play a significant role in shrub-mound growth and maintenance, and thus also, in erosion control and vegetation pattern formation in dryland landscapes. Since herbaceous plants enhance mound formation, which in turn enhances shrub growth, our findings are further evidence of the crucial feedback interactions that are central to understanding ecosystem functioning, dynamics and pattern formation in water-limited ecosystems.

1. Introduction

1.1. Vegetation and geomorphology

Many ecosystems in semi-arid regions have been under processes involving the loss of vegetation cover, productivity, and species diversity (Okin et al., 2009), coupled with geomorphic processes, mainly soil degradation and erosion (Reinhardt et al., 2010; Ries, 2010). Semi-arid ecosystems, especially, experience increased risks from such processes, due to the combined effect of sparse vegetation cover and concentrated erosive episodes (Ludwig et al., 2005; Marston, 2010), along with an increase in anthropogenic pressure (Cantón et al., 2011; Schönbach et al., 2011). Since soil degradation implicitly includes the loss of substrate and resources necessary for plant establishment and growth, feedback mechanisms are likely to operate between geomorphic processes and vegetation dynamics (Ravi et al., 2010; Reinhardt et al., 2010; Wainwright et al., 2000). These mechanisms play an important role in desertification processes in semi-arid regions worldwide (Okin et al., 2009; Schlesinger et al., 1990).

Ecohydrology in arid and semi-arid landscapes is characterized by runoff source-sink relations, dictated by surface conditions that determine infiltration and ponding at small scales, and connectivity at larger scales (Kirkby, 2002; Okin et al., 2009). Since runoff is a dominant erosive force, sedimentation and erosion are affected by the same surface conditions. Other erosive forces influencing sediment transport are splash from raindrop impact and wind. Vegetation is one of the most important factors in erosion mitigation, acting on the erosive forces as well as on soil-surface conditions (Marston, 2010). Our aim is to examine the effects of semi-arid vegetation on the erosive effects of these three forces (runoff, splash and wind) under natural conditions, and to compare the relative importance of these forces in the sediment budget.

1.2. Erosion control

Vegetation cover affects rain-driven sediment transport through three main mechanisms: 1) reduction of direct raindrop impact, thereby protecting the aggregate structure from mechanical break-down

* Corresponding author. Tel.: +972 58207841.
E-mail addresses: orenhof@post.bgu.ac.il (O. Hoffman), yiyeh@exchange.bgu.ac.il (H. Yizhaq), bboeken@bgu.ac.il (B.R. Boeken).

0341-8162/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.catena.2013.04.003

(Cantón et al., 2009); 2) reduction of the splash dispersal of accumulated sediment, thus controlling the erosion-accumulation balance (Wainwright et al., 1999); and 3) increasing surface roughness by the herbaceous vegetation, therefore reducing runoff velocity (Vásquez-Méndez et al., 2010). Plant litter also reduces runoff, as Boeken and Orenstein's (2001) experiments in the same research site showed. In addition, vegetation can mitigate wind-driven erosion through a reduction of air velocity and entrapment of wind-blown sediment (Hupy, 2004; Leenders et al., 2007). So far, studies have been limited to addressing the effects of either rain or wind, despite the likelihood of interactions among hydrologic and aeolian effects in semi-arid regions (Ravi et al., 2010).

The material input into the semi-arid area of the northern Negev is aeolian, bringing dust and fine sand from the west into the region (Offer and Goosens, 2001; Offer et al., 1998). Once deposited, the dust and sand can be further mobilized by local aeolian and hydrological processes (Shachak and Lovett, 1998; Zaady and Offer, 2010) and, in many cases, are transported downslope by run-off and rain splash (Eldrige et al., 2002; Field et al., 2009). Surface structure controls the redistribution of sediment by controlling its movement velocity across the surface (Kirkby, 2002; Marston, 2010). Vegetation has a large impact on surface roughness and structure in natural landscapes, and thus plays an important role in sediment transport and retention, leading to less erosion and increased sedimentation with denser vegetation (Cantón et al., 2011; Michaelides et al., 2009).

1.3. Shrub mounds

Shrubs affect the landscape structure in Park Shaked (PSK), in the north-western Negev Desert of Israel (Shachak et al., 2008), through the development of mounds of loose soil and organic matter underneath and around their canopies (Eldrige et al., 2002). The mounds contrast strongly with the surrounding surface as they lack biogenic soil crust (BSC). BSC forms on the surface of undisturbed bare soil, reducing water infiltration and seed retention (Boeken and Shachak, 1994; Eldrige et al., 2000). The shrub-associated mounds usually have a higher content of nutrients and more loose soil particles than the surrounding crust-covered matrix (Zaady et al., 1998). Consequently, the mounds act as sinks for water and sediment, transported by runoff across the BSC-covered surface. This makes shrub mounds favorable habitats for annual plants, and therefore greatly enhances primary production and biodiversity (Boeken and Orenstein, 2001; Boeken and Shachak, 1998; Shachak et al., 2008).

1.4. Annual mound vegetation

Long-lived woody plants, such as desert shrubs, have been the focus of theoretical and applied research into the process of landscape modification and ecohydrological feedbacks (Gilad et al., 2004; Meron, 2012; Shachak et al., 2008). However, annual plants are mostly overlooked in this context, even though their contribution to biomass and cover can exceed that of shrubs in dry regions (Fernández et al., 1991; Knapp et al., 2008). Here, we focus on annuals that may be especially important for the process of the maintenance of shrub-associated soil mounds (Zaady et al., 2004), although most of the current models so far ignore this possibility (Meron, 2011). We believe that consideration of the interactive or mutual effects of annual and woody plants will allow for more realistic landscape evolution models, which are key tools in theoretical and applied ecosystem study and management.

1.5. Objectives

In this study, we investigate the effects of different cover types on overland sediment transport, focusing on these specific questions: 1) What is the effect of annual plant and litter cover on sediment transport? 2) Is this effect altered by the presence of shrub canopy cover? 3) What are the relative contributions of different erosion forces (wind, run-off and splash) to sediment transport?

Previous studies in this field have measured the rates and amounts of runoff and sediment yield at scales ranging from one to several hundred m^2 (e.g., Eldrige et al., 2002; Oren, 2001; Wainwright et al., 2000). These scales are relevant for ecosystem functions and management; however, they are under the influence of a non-linear scale dependence that can mask the mechanisms acting at small scales (Cantón et al., 2011; Leys et al., 2010). We focus on the micro-scale (0.05 m^2) with the intent to test the effect of rainfall on sediment displacement in the presence of different combinations of cover elements. The effects of the different cover elements can be contingent on their location and the relative strength of the different erosion forces, as depicted in the slope cross-section in Fig. 1. Our small spatial scale allows for testing the importance of location for vegetation control over sediment transport.

Rainfall simulation experiments have produced a large quantity of data (e.g., Eldrige et al., 2002; Podwojewski et al., 2011; Segoli, 2009), yet the unrealistic rainfall intensities, spatial distribution, and duration used in most experiments may have disguised crucial, but subtle, effects (Jomaa et al., 2012). Therefore, our focus on natural rainfall events is likely to produce more realistic results.

2. Methods

2.1. The study site

Park Shaked LTER station (31°17′N, 34°37′E) is located in the semi-arid region of the north-western Negev Desert, Israel (Fig. 2). Mean annual precipitation is 150–200 mm, occurring between November and March, with dry years receiving less than 100 mm of rainfall. The natural landscape is a sparse shrubland, dominated by dwarf shrubs (0.1–0.6 m height), mainly *Noaea mucronata*. Shrub cover can reach 25% of the area in some locations but has decreased considerably in the last decade (Boeken, 2008; Shachak, 2011) to less than 10% on most slopes, due to prolonged droughts.

2.2. Experimental approach

A field experiment was conducted during the winter and spring of 2010/11 to test sediment movement on mounds under the canopy of the sub-shrub *Noaea mucronata* (Chenopodiaceae) in the study site under natural climatic conditions. We chose to simulate a scenario of a fine layer of aeolian dust, deposited following a dust storm (personal observation on 22/10/2010), and to track its dispersal. We used sediment collected in the field, from similar mounds, with a vacuum cleaner and sieved in the lab down to particles less than 350 μm in diameter. A particle size distribution analysis with high-resolution laser diffraction revealed that the material consisted mostly of particles with diameters of 180-190 μm or 60-70 μm (Appendix A), signifying mostly fine sand (and silt). This size group tends to be more easily transported than the smaller clays or the larger coarse sand (Bagnold, 1941; Legout et al., 2005). The material was marked, using a water-resistant spray color, in order to allow tracking of its movement along the surface following rainfall.

2.3. Experimental layout

Each experimental unit consisted of a frame of 5 cm × 5 cm made of thin wire (1 mm diameter), placed flush on the surface and pinned down on all corners with 2 cm pins of the same material (Fig. 3). The soil surface within each frame was covered with a layer of ca. 2 mm of the dyed sand (total volume 5 mL), spread as evenly as possible across the entire frame surface. Cover treatments were done prior to placing the frame and sand, administered across an entire shrub

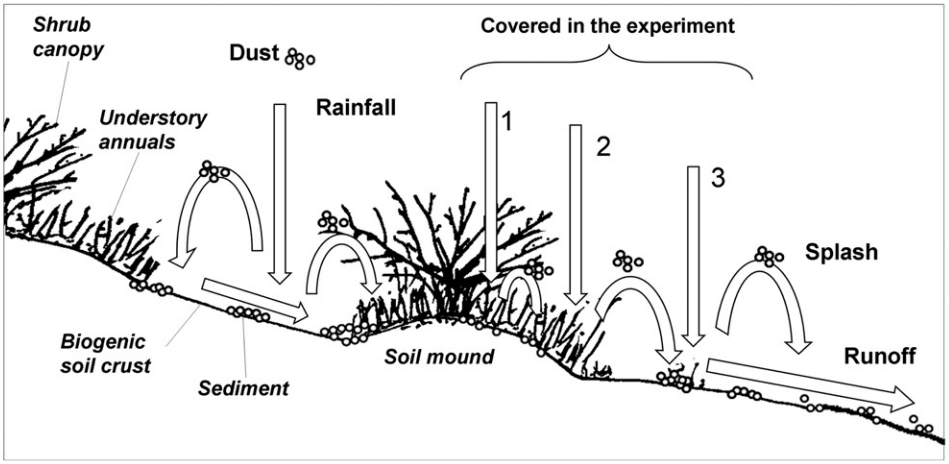

Fig. 1. A schematic drawing of a slope with cover elements (shrub canopy, annual understory, litter and BSC) and vectors of sediment transport (raindrop splash, runoff and wind, denoted by arrows). Numbers represent the three locations in our experiment: 1 — mound center (underneath shrub canopy), 2 — mound margin (outside canopy), and 3 — inter-mound matrix.

mound and its surrounding intershrub area within a 10 cm radius of the mound edge. The treatments were: 1) clipped — clipping of all the annual vegetation near the ground, and removal of the clipped biomass, 2) brushed — clipping the annual vegetation and removal of the layer of litter and loose aggregates from the surface using a brush, and 3) control — no manipulation of the surface. Within each patch, the frames were placed around a *N. mucronata* shrub (with at least a 20 cm diameter canopy) with one frame under the canopy, and two frames outside of the canopy's cover, one on the upslope and one on the downslope mound margins (Fig. 3). In several patches, an additional frame was placed on the matrix outside of the mound.

The spatial layout of the experiment was designed so as to represent some of the variability of topographic conditions at the study site, such as aspect and location on the slope. Accordingly, the patches were distributed in blocks spread around the main watershed. Two experimental blocks were located on east-facing slopes and one experimental block on a west-facing slope. The treatments were randomly assigned to one of three shrub patches in a small area (inter-patch distance <3 m), forming a cluster of three patches, each one treated differently (i.e., one set), with three sets in a block. This design reduced the variability of weather patterns (wind, rainfall) within each set, although the stochastic nature of these factors could still have produced random and uncontrolled variability.

The erosive forces in the ecosystem can be roughly separated into three processes: wind erosion, runoff erosion, and rain splash erosion. A full separation of these effects cannot be completely achieved experimentally, and the interactions between them may also play a role in landscape evolution (Ravi et al., 2010). However, breaking apart the two components of rain-driven erosion (runoff and drop impact) could help us understand the importance of vegetation structure in erosion control. For this, artificial rain covers were placed over the shrub patch on one third of the patches. These structures were built to eliminate raindrop impacts, while allowing for wind and runoff to pass through the patches. This had the dual purpose of estimating the protection given by the shrub canopy compared with artificial cover, and decoupling between raindrop impact and runoff.

The experiment was run twice during the wet season (from 28 November 2010 until 10 January 2011, and again from 28 January

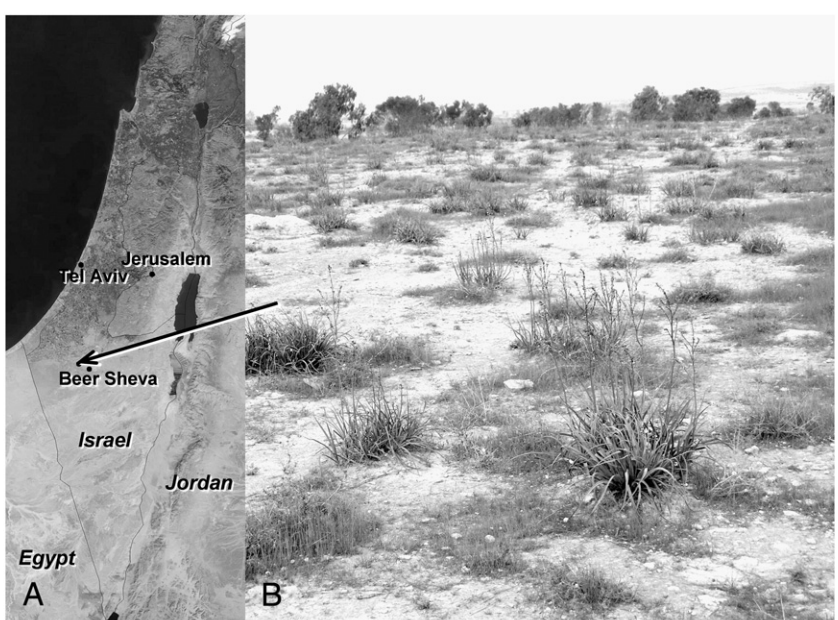

Fig. 2. A. Satellite image of Israel with the location of Park Shaked LTER (arrow). B. A photograph of the landscape in the study site during the growing season, with dense annual understory of shrub patches.

Please cite this article as: Hoffman, O., et al., Small-scale effects of annual and woody vegetation on sediment displacement under field conditions, Catena (2013), http://dx.doi.org/10.1016/j.catena.2013.04.003

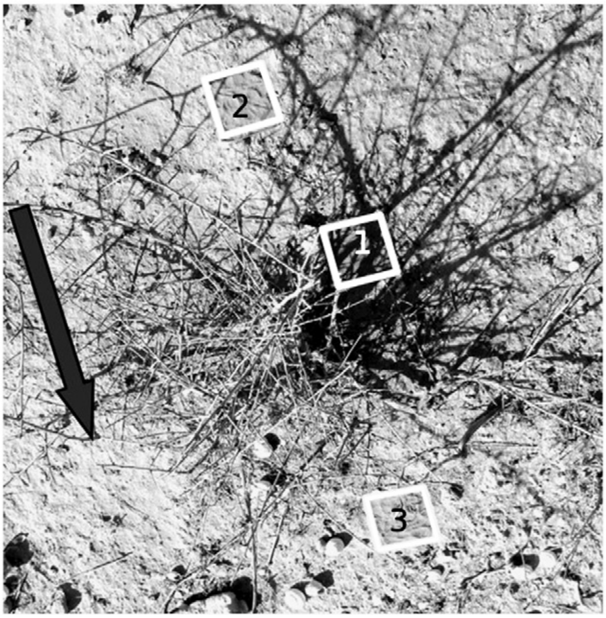

Fig. 3. A photograph of a single shrub-patch with three frames with dyed sediment (white squares) following removal of annuals and litter (brushed treatment). The arrow signifies slope direction.

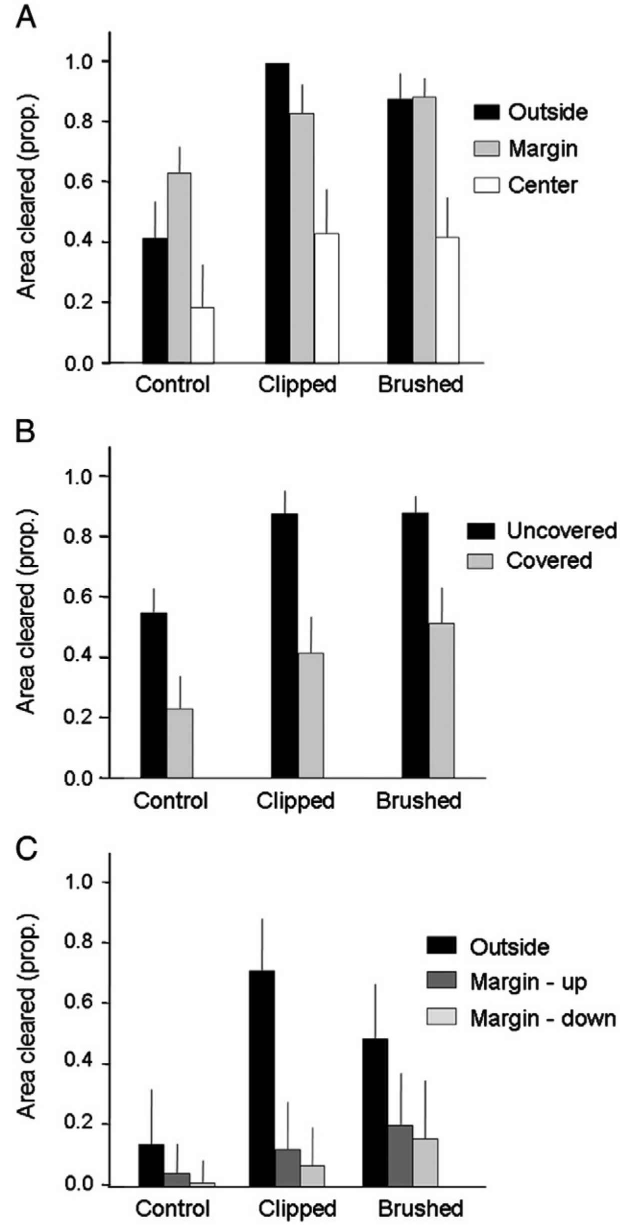

Fig. 4. Means and standard errors of proportional area cleared from frames vs. treatments, A — for three locations in patches without rain cover, B — for pooled marginal and outer locations in patches with and without rain cover, C — for marginal and outer locations in covered patches.

2011 until the end of the rainy season on 10 April 2011) and once during the dry season (from 4 May 2011 to 23 June 2011). Analysis of Variance (ANOVA) was used to compare the overall differences in means of sediment movement between runs.

2.4. Data analysis and environmental measurements

The response data collected in the field were proportions of area cleared of dyed sand from within the frames, and were arcsine transformed to meet ANOVA assumptions of variable normal distribution. We used a factorial two-way ANOVA design with 'vegetation treatment', 'rain-cover' and their interaction as independent variables (Zar, 1999). This distinguished between effects of raindrop impact, which was eliminated by rain-cover, and runoff reduction by the different cover elements (shrub, annuals, and litter). Further analyses on subsets of the data were performed using one-way or two-way ANOVA where appropriate. Meteorological data, collected at a meteorological station located at the research site, were compared between the relevant periods; rainfall, wind speed, and wind direction at a 10 m height were measured in 15 min intervals and summed for the relevant temporal scales.

3. Results

3.1. Patches without rain cover

A factorial ANOVA of the proportion of the area where the deposited colored dust disappeared vs. treatment (control, clipping, and brushing) and the position of the frame on the mound (center, margin and outside) for mounds without rain cover showed a significant effect of surface treatment ($F[2, 44] = 7.977$ $p = 0.001$) and location ($F[2, 44] = 11.597$, $p < 0.0001$), but no significant interaction effect ($F[4, 44] = 0.823$, $p = 0.5171$). The low values of sediment displacement in the control patches (48%, Fig. 4A), compared with the significantly higher values in the clipped and brushed patches (72%), support our hypothesis that herbaceous understory vegetation reduces the erosion of shrub mounds. However, the close similarity of the clipping and brushing treatments implies that litter and loose sediment (present in the clipping treatment and removed in the brushing treatment) have little effect. Rain splash may mask the effect of the litter layer on runoff-driven sediment loss, even on the crusted intershrub matrix, as reflected by the lack of differences between the mound margin and outside the mound (with ~70% lost). The dramatic reduction in sediment loss that we observed only underneath the shrub canopy (center, with 35% lost; Fig. 4A) also reflects the importance of rain splash for mound erosion, and of the shrub canopy in blocking its impact.

3.2. Effect of artificial rain cover

Artificial rain covers reduced sediment loss by ca. 50% over all treatments (Fig. 4B), similar to the effect of shrub canopy in the uncovered patches (center vs. margin, Fig 4A). Moreover, the rain covers reduced the effects of both treatments, compared to uncovered patches, evident from the weaker treatment effect in covered patches ($F[2,19] = 2.82$, $p = 0.086$). In patches with an artificial rain cover,

Please cite this article as: Hoffman, O., et al., Small-scale effects of annual and woody vegetation on sediment displacement under field conditions, Catena (2013), http://dx.doi.org/10.1016/j.catena.2013.04.003

raindrop impact was minimal, and the large differences between surface treatments are most likely attributable to runoff movement. Accordingly, we conclude that rain splash was the main cause of sediment displacement in our experiment, and that it was significantly blocked by both shrub canopy and artificial rain cover, and reduced by herbaceous vegetation cover, but only slightly reduced by a layer of loose material.

Artificial rain covers revealed that runoff erosion did occur on the crusted area surrounding the shrub patches. While the treatment effects in the covered patches were similar to the effects in the uncovered patches, as shown by the non-significant interaction effect (treatment × rain cover: $F[2, 59] = 0.284$, $p = 0.753$), the location x rain cover interaction was marginally significant ($F[2,60]=$, $P = 0.0843$). In contrast to the uncovered patches, in patches with a rain cover, significantly more sediment was lost from the frames outside the mounds than on the margins (Fig. 4C). This large difference signifies the importance of runoff in the crusted intershrub matrix and its near absence on the mounds themselves, including the margins. This is consistent with our own field observations of runoff events during the experimental period (O. Hoffman, 20/01/2012, pers. comm.). Accordingly, we conclude that runoff movement is primarily controlled by topography, with surface roughness by annuals and litter exerting a strong effect in the intermound, as is evident from the differences between treatments in the outer frames (Fig. 4C).

3.3. Seasonal variation in erosion processes

The experiment was run twice in the rainy season. The overall mean proportional area displaced was similar in both periods with a mean of ca. 50%. Rainfall simulations and observations have shown that runoff generation requires a minimum rainfall amount, which may vary considerably according to surface conditions (Podwojewski et al., 2011; Ruiz Sinoga et al., 2010). Examination of the frequency distribution of rainfall intensity throughout two winter months (November–December 2010) revealed a high frequency (15 out of the 20 rainy days) of extremely low-intensity events with less than 5 mm of rain/day, below the threshold for runoff generation (ca. 5 mm/hour, Eldrige et al., 2002; Segoli et al., 2008). Moreover, another four days registered less than 15 mm/day, which would only create runoff if the entire daily amount were concentrated in less than three hours. Thus, runoff only occurs in a small fraction of rain events, whereas all events create raindrop impact. Accordingly, raindrop impact may be responsible for more sediment loss, and consequent erosion and deposition, simply due to its higher frequency (Jomaa et al., 2012; Wainwright et al., 2000).

After the rainy season, we removed all the remaining dyed sand and replaced it. The experiment was then run again during the dry season to examine the effects of treatments on wind-related erosion. On average, the proportion that was cleared of the frame area in the dry season (10% ± 2%) was only a fraction of that in the rainy season (mean 50% ± 4%). Due to the low values and high variability resulting from the dry season experiment, we could not discern the effects of treatment and position. These results reflect the relatively weak effects of wind-driven erosion processes in the study site, compared to the rainfall-driven processes.

Wind measurements (Appendix B in supplemental material) showed that the threshold velocity for sand entrainment (ca. 6 m/s at 10 m height; Fryberger et al., 1979) was reached many times throughout the dry season, ca. 10% of the time (averaged for 15 min intervals) between April and August. Nevertheless, wind erosion in the experiment was very low during this period, even following *in situ* annual vegetation removal. Apparently, this is due to surface wind speed reduction by the shrub canopy and the remaining vegetation at the larger scale (Leenders et al., 2007; Wolfe and Nickling, 1993) (See Appendix C for small-scale wind measurements).

4. Discussion

4.1. Usefulness of the experimental approach

The use of natural rainfall within an experimental framework has several limitations and benefits. The main limitation is the natural variation in the spatial distribution of the rain, leaving some unexplained variation in the results and limiting repeatability to some extent. However, we argue that the benefits of using the naturally occurring rainfall outweigh these limitations, since simulated rain differs from natural events in its high intensity and its even spatial and temporal distribution (Abudi et al., 2012). Regarding the effects of intensity, the minimum used in simulated rain experiments in the northern Negev region, 30 mm/h (Abudi et al., 2012; Eldrige et al., 2002), is more than ten times the average (1.74 mm/h) and more than twice the maximum (13.3 mm/h) compared to values recorded throughout 2011. Using extremely high rain intensities can lead to overestimation of runoff and sediment yield potential under current climatic conditions. Moreover, due to the non-linear nature of runoff onset and erosion processes (Ghahramani et al., 2012), results obtained in such experiments are hard to relate to the naturally occurring processes.

4.2. Combined effects of herbaceous and woody vegetation

The results show that both the shrubs and the annuals on the mounds reduce sediment loss from shrub mounds. The effect of raindrop protection by shrub canopy is clearly evident (see Fig. 4A), with herbaceous cover affecting rain splash impact to a lesser degree, while litter and other loose material do not contribute. In contrast, annuals and litter have an effect on runoff, but only in the crusted intershrub matrix, since runoff does not occur on mounds. Even in the matrix, runoff erosion appears to be secondary in importance to raindrop splash since strong runoff occurs only in some rain events (Furbish et al., 2009). Results were similar for locations with only one element of vegetation (shrub or annuals), but sediment loss was lowest when all three cover layers (i.e., shrub, annuals, and litter) were present. Our conclusions are further supported by the experimental work of Zaady et al. (2004) on the effects of herbicide usage, which demonstrated the significance of biological activity for both runoff generation and soil resource retention. Due to herbicide application, the reduced activity of crust-forming micro-organisms has led to soil loss following rainfall, and the reduced growth of annual plants in the shrub patches has hampered the sink function of the shrub patches. In that case, as in our current study, the results clearly demonstrate that the geomorphic process of rain-induced soil erosion is affected by a combination of the different functional groups of organisms as landscape modulators (see also Li et al., 2008).

4.3. Effects on mound formation

In addition to our results on erosion control, annual plant cover also increases the deposition of sediment on the mound by trapping material dispersed via rain splash or wind and runoff, thereby enhancing the growth of shrub-mounds and the formation of landscape patterns (Boeken and Orenstein, 2001). The formation and growth rate of the mounds have so far been attributed to the effect of shrubs on patterns of splash and runoff (Buis et al., 2010; Shachak and Lovett, 1998). However, the dense stands of annual plants on mound margins may be particularly important in shaping the mound (Hoffman, 2011, unpublished). The shapes and sizes of mounds on a particular slope, and their density, determine the hydraulic connectivity and flow patterns, as they are the elements of pervasive roughness (Kirkby, 2002). Consequently, since the combination of the different cover elements is important for mound growth and maintenance, pattern formation is an emergent property of the

Please cite this article as: Hoffman, O., et al., Small-scale effects of annual and woody vegetation on sediment displacement under field conditions, Catena (2013), http://dx.doi.org/10.1016/j.catena.2013.04.003

entire plant community (shrubs, annuals and BSC), which cannot be fully predicted when considering each element alone (e.g. Chaudhary et al., 2009).

The additive effect of annual plants on shrub-mound formation and maintenance is drastically reduced by intense livestock grazing, except directly under the shrub canopy where they are protected (Facelli and Temby, 2002). Consequently, mound growth is slower due to erosion by raindrops and trampling by livestock (Golodets and Boeken, 2006). This geomorphic effect of grazing may take years to be visually apparent, but could have strong long-term consequences on productivity due to a reduction of resource retention on slopes.

5. Conclusions

Current mathematical models of pattern formation in drylands typically consider only an infiltration-vegetation feedback and root augmentation growth as driving mechanisms (e.g. Gilad et al., 2007; Meron, 2012), yet patterns of sedimentation and erosion on the soil surface have a strong effect on hydrological processes, stressing the need to introduce a soil-vegetation and an annual-shrub feedback (Meron, 2011). Furthermore, separate and interactive effects of different water- and wind-driven processes have rarely been studied in natural landscapes, although they are prominent, especially in semi-arid regions (Field et al., 2009; Ravi et al., 2010, 2011). The complexity of interactions between the different cover types and physical processes needs to be considered when trying to predict future scenarios under climate or land-use change. For the semi-arid northern Negev shrubland specifically, the recent large reduction in shrub cover due to recurrent droughts may have further consequences on ecosystem structure and function (Shachak, 2011). Any attempt to predict these consequences should take into account the interactive and combined effects between functional plant groups and hydrological and aeolian processes.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catena.2013.04.003.

Acknowledgments

The research was financed by grant No. 09R-09 of the International Arid Lands Consortium. We thank Dr. Itzhak Katra from the Ben-Gurion University Department of Geography for his help with particle size and wind speed measurements. We thank the anonymous reviewers for their helpful comments. This is publication no. 799 of the Mitrani Department of Desert Ecology.

References

Abudi, I., Carmi, G., Berliner, P., 2012. Rainfall simulator for field runoff studies. Journal of Hydrology 454–455, 76–81.
Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London.
Boeken, B., 2008. Park Shaked LTER-Ma'arag station: research and education activities 1991–2008. Israel LTER, Network (Ma'arag).
Boeken, B., Orenstein, D., 2001. The effect of plant litter on ecosystem properties in a Mediterranean semi-arid shrubland. Journal of Vegetation Science 12, 825–832.
Boeken, B., Shachak, M., 1994. Desert plant communities in human-made patches: implications for management. Ecological Applications 4, 702–716.
Boeken, B., Shachak, M., 1998. Colonization by annual plants of an experimentally altered desert landscape: implications for management. Journal of Ecology 86, 804–814.
Buis, E., Temme, A.J.A.M., Veldkamp, A., Boeken, B., Jongmans, A.G., van Breemen, N., Schoorl, J.M., 2010. Shrub mound formation and stability on semi-arid slopes in the Northern Negev Desert of Israel: A field and simulation study. Geoderma 156, 363–371.
Cantón, Y., Solé-Benet, A., Asensio, C., Chamizo, S., Puidefabregas, J., 2009. Aggregate stability in range sandy loam soils: relationship with runoff and erosion. Catena 77, 192–199.
Cantón, Y., Solé-Benet, A., de Vente, J., Boix-Fayos, C., Calvo-Cases, A., Asensio, C., Puigdefábregas, J., 2011. A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. Journal of Arid Environments 75, 1254–1261.
Chaudhary, V.B., Bowker, M.A., O'Dell, T.E., Grace, J.B., Redman, A.E., Rillig, M.C., Johnson, N.C., 2009. Untangling the biological contributions to soil stability in semiarid shrublands. Ecological Applications 19, 110–122.
Eldrige, D.J., Zaady, E., Shachak, M., 2000. Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. Catena 40, 323–336.
Eldrige, D.J., Zaady, E., Shachak, M., 2002. Microphytic crusts, shrub patches and water harvesting in the Negev Desert: the Shikim system. Landscape Ecology 17, 587–597.
Facelli, J.M., Temby, A.M., 2002. Multiple effects of shrubs on annual plant communities in arid lands of South Australia. Austral Ecology 27, 422–432.
Fernández, A.R.J., Sala, O.E., Golluscio, R.A., 1991. Woody and herbaceous aboveground production of a Patagonian steppe. Journal of Range Management 44, 234–237.
Field, J.P., Breshears, D.D., Whicker, J.J., 2009. Toward a more holistic perspective of soil erosion: Why aeolian research needs to explicitly consider fluvial processes and interactions. Aeolian Research 1, 9–17.
Fryberger, S., Ahlbrandt, T., Andrews, S., 1979. Origin, sedimentary features, and significance of low-angle aeolian sand sheet deposits, Great Sand Dunes National Monument and vicinity, Colorado. Journal of Sedimentary Petrology 49, 733–746.
Furbish, D.J., Childs, E.M., Haff, P.K., Schmeeckle, M.W., 2009. Rain splash of soil grains as a stochastic advection dispersion process, with implications for desert plant–soil interactions and land-surface evolution. Journal of Geophysical Research 114, F00A03.
Ghahramani, A., Yoshiharu, I., Mudd, S.M., 2012. Field experiments constraining the probability distribution of particle travel distances during natural rainstorms on different slope gradients. Earth Surface Processes and Landforms 37, 473–485.
Gilad, E., von Hardenberg, J., Provenzale, A., Shachak, M., Meron, E., 2004. Ecosystem engineers: from pattern formation to habitat creation. Physical Review Letters 93, 105-1–105-4.
Gilad, E., Shachak, M., Meron, E., 2007. Dynamics and spatial organization of plant communities in water-limited systems. Theoretical Population Biology 72, 214–230.
Golodets, C., Boeken, B., 2006. Moderate sheep grazing in semi-arid shrubland alters small-scale soil surface structure and patch properties. Catena 65, 285–291.
Hupy, J.P., 2004. Influence of vegetation cover and crust type on wind-blown sediment in a semi-arid climate. Journal of Arid Environments 58, 167–179.
Jomaa, S., Barry, D.A., Brovell, A., Heng, B.C.P., Sander, G.C., Parlange, J.-Y., Rose, C.W., 2012. Rain splash soil erosion estimation in the presence of rock fragments. Catena 92, 38–48.
Kirkby, M., 2002. Modeling the interactions between soil surface properties and water. Catena 46, 89–102.
Knapp, A.K., Briggs, J.M., Collins, S.L., Archer, S.R., Bret-Harte, M.S., Ewers, B.E., Peters, D.P., Young, D.R., Shaver, G.R., Pendall, E., Cleary, M.B., 2008. Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. Global Change Biology 14, 615–623.
Leenders, J.K., v. Boxel, J.H., Sterk, G., 2007. The effect of single vegetation elements on wind speed and sediment transport in the Sahelian zone of Burkina Faso. Earth Surface Processes and Landforms 32, 1454–1474.
Legout, C., Leguédois, S., Le Bissonnais, Y., Malam Issa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124, 279–292.
Leys, A., Govers, G., Gillijns, K., Berckmoes, E., Takken, I., 2010. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: the role of residue cover. Journal of Hydrology 390, 143–154.
Li, X.J., Li, X.R., Song, W.M., Gao, Y.P., Zheng, J.G., Jia, R.L., 2008. Effects of crust and shrub patches on runoff, sedimentation, and related nutrient (C, N) redistribution in the desertified steppe zone of the Tengger Desert, Northern China. Geomorphology 96, 221–232.
Ludwig, J.A., Wilcox, B.P., Breshears, D.D., Tongway, D.J., Imeson, C., 2005. Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. Ecology 86, 288–297.
Marston, R.A., 2010. Geomorphology and vegetation on hillslopes: interactions, dependencies, and feedback loops. Geomorphology 116, 206–217.
Meron, E., 2011. Modeling dryland landscapes. Mathematical Modeling of Natural Phenomena 6, 163–187.
Meron, E., 2012. Pattern-formation approach to modelling spatially extended ecosystems. Ecological Modeling 234, 70–82.
Michaelides, K., Lister, D., Wainwright, J., Parsons, A.J., 2009. Vegetation controls on small-scale runoff and erosion dynamics in a degrading dryland environment. Hydrological Processes 23, 1617–1630.
Offer, Z.Y., Zaady, E., Shachak, M., 1998. Aeolian particle input to the soil surface at the Northern limit of the Negev desert. Arid Soil Research and Rehabilitation 12, 55–62.
Offer, Z.Y., Goosens, D., 2001. Ten years of aeolian dust dynamics in a desert region (Negev desert, Israel): analysis of airborne dust concentration, dust accumulation and the high-magnitude dust events. Journal of Arid Environments 47, 211–249.
Okin, G.S., Parsons, A.J., Wainwright, J., Herrick, J.E., Bestelmayer, B.T., Peters, D.C., Fredrickson, E.L., 2009. Do changes in connectivity explain desertification? Bioscience 59, 237–245.
Oren, Y., 2001. Patchiness, disturbance, and the flows of matter and organisms in an arid landscape: a multiscale experimental approach. Ben- Gurion University of the Negev (PhD dissertation).
Podwojewski, P., Janeau, J.L., Grellier, S., Valentin, C., Lorentz, S., Chaplot, V., 2011. Influence of grass soil cover on water runoff and soil detachment under rainfall simulation in a sub-humid South African degraded rangeland. Earth Surface Processes and Landforms 36, 911–922.
Ravi, S., Breshears, D.D., Huxman, T.E., D'Odorico, P., 2010. Land degradation in drylands: Interactions among hydrologic–aeolian erosion and vegetation dynamics. Geomorphology 116, 236–245.
Ravi, S., D'Odorico, P., Breshears, D.D., Field, J.P., Goudie, A.S., 2011. Aeolain processes and the biosphere. Reviews of Geophysics RG3001.
Reinhardt, L., Jerolmack, D., Cardinale, B.J., Vanacker, V., Wright, J.P., 2010. Dynamic interactions of life and its landscape: feedbacks at the interface of geomorphology and ecology. Earth Surface Processes and Landforms 35, 78–101.

Ries, J.B., 2010. Methodologies for soil erosion and land degradation assessment in mediterranean-type ecosystems. Land Degradation and Development 21, 171–187.
Ruiz Sinoga, J.D., Romero, Diaz A., Ferre, Bueno E., Martínez Murillo, J.F., 2010. The role of soil surface conditions in regulating runoff and erosion processes on a metamorphic hillslope (Southern Spain) Soil surface conditions, runoff and erosion in Southern Spain. Catena 80, 131–139.
Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrel, L.M., Virginia, R.A., Whitford, W.G., 1990. Biological feedbacks in global desertification. Science 247, 1043–1047.
Schönbach, P., Hongwei, W., Gierus, M., Bai, Y., Müller, K., Lin, L., Susenbeth, A., Taube, F., 2011. Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. Plant and Soil 340, 103–114.
Segoli, M., 2009. Woody vegetation as Landscape Modulators: Sarcopoterium spinosum as a tangible model. PhD Thesis, Ben-Gurion University of the Negev, Beer-Sheva, Israel.
Segoli, M., Ungar, E.D., Shachak, M., 2008. Shrubs enhance resilience of a semi-arid ecosystem by engineering and regrowth. Ecohydrology 1, 330–339.
Shachak, M., 2011. Ecological textures: ecosystems in the northern Negev as a model. Ecology and Environment 2011, 18–29 (in Hebrew).
Shachak, M., Lovett, G.M., 1998. Atmospheric deposition to a desert ecosystem and its implications for management. Ecological Applications 8, 455–463.
Shachak, M., Boeken, B., Groener, E., Kadmon, R., Lubin, Y., Meron, E., Neeman, G., Perevolotsky, A., Shkedy, Y., Ungar, E.D., 2008. Woody species as landscape modulators and their effect on biodiversity patterns. BioScience 58, 209–221.
Vásquez-Méndez, R., Ventura-Ramos, E., Oleschko, K., Hernández-Sandoval, L., Parrot, J.F., Nearing, M.A., 2010. Soil erosion and runoff in different vegetation patches from semi-arid Central Mexico. Catena 80, 162–169.
Wainwright, J., Parsons, A.J., Abraham, A.D., 1999. Rainfall energy under creosotebush. Journal of Arid Environments 43, 111–120.
Wainwright, J., Parsons, A.J., Abraham, A.D., 2000. Plot-scale studies of vegetation, overland flow and erosion interactions: case studies from Arizona and New Mexico. Hydrological Processes 14, 2921–2943.
Wolfe, S.A., Nickling, W.G., 1993. The protective role of sparse vegetation in wind erosion. Progress in Physical Geography 17, 50–68.
Zaady, E., Offer, Z., 2010. Biogenic soil crusts and soil depth: a long-term case study from the Central Negev desert highland. Sedimentology 57, 351–358.
Zaady, E., Groffman, P., Shachak, M., 1998. Nitrogen fixation in macro- and microphytic patches in the Negev desert. Soil Biology and Biochemistry 30, 449–454.
Zaady, E., Levakov, R., Shachak, M., 2004. Application of the herbicide, simazine, and its effect on soil surface parameters and vegetation in a patchy desert landscape. Arid Lands Research and Management 18, 397–410.
Zar, J.H., 1999. Biostatistical Analysis. Prentice-Hall, New Jersey.

Please cite this article as: Hoffman, O., et al., Small-scale effects of annual and woody vegetation on sediment displacement under field conditions, Catena (2013), http://dx.doi.org/10.1016/j.catena.2013.04.003