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Rainfall energy under creosotebush

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Simulated rainstorms of 15 min duration and average intensity 148 mm h^{-1} were applied to seven creosotebushes. Intensity of the sub-canopy rainfall was reduced to 90% of the rain falling out with the canopy, whereas the kinetic energy was reduced to 70%. Although leafdrip makes up 28·9% of the sub-canopy rainfall, it contributes only 10% of the sub-canopy kinetic energy. Comparison of the effective kinetic energy (that possessed by raindrops with sufficient energy to detach sediment) beneath the canopy with that outside the canopy shows that the former is 55% of the latter. These results quantify the process of differential splash that contributes to the build-up of mounds beneath desert shrubs, and improves the understanding of the development of islands of fertility in desert ecosystems.

Keywords: *Larrea tridentata*; rainfall energy; raindrop-size distribution; throughfall; leafdrip; raindrop erosion; islands of fertility

Introduction

Vegetation plays an important role in controlling the energy of rainfall that reaches the ground surface. This role derives from two effects of vegetation upon rainfall. First, energy is dissipated as a result of the interception of rainfall. Some of the intercepted rainfall is diverted to stemflow or lost to evaporation. The remainder reaches the soil surface as leafdrip and has a lower velocity, and hence kinetic energy, than the non-intercepted rainfall, which is falling at terminal velocity. Second, leafdrip falling from vegetation to the ground surface may have a different drop-size distribution from that of the original rainfall. This difference in size distribution may result in leafdrip having higher or lower energy than rainfall because of the direct relationship between drop size, and therefore mass, and kinetic energy. The combined effect of interception losses (stemflow and evaporation), leafdrip and raindrops reaching the ground at terminal velocity through gaps in the canopy (throughfall) leads to a complex relationship between vegetation and rainfall energy at the ground surface. Brandt (1986)

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demonstrated that under 40-m-tall rainforest canopies energy reaching the ground surface was significantly greater than outside the canopy, whereas under 10-m-tall oak canopies an increase was found in some, but not all, cases. Beneath very low vegetation, the energy reaching the ground surface is thought to be reduced. Parsons *et al.* (1992) attributed the growth of mounds beneath shrubs in the Sonoran Desert in part to the difference between rainfall energy beneath and between shrubs and the consequent difference in sediment transport by splash. Such differential splash leads to the build up of mounds because there is insufficient energy to transport as much sediment away from the shrubs as is deposited beneath them. This mechanism was further demonstrated in modelling the formation of desert pavement by Wainwright *et al.* (1995). However, in neither study were quantitative data on the effects of desert shrubs on sub-canopy rainfall energy used and, indeed, no such data are presently available. The aim of this paper is to provide such data for creosotebush (*Larrea tridentata* DC.).

Creosotebush is the dominant shrub species of the hot deserts of North America (Shreve, 1942; Mabry *et al.*, 1977) and covers many areas of former grassland in the Chihuahuan and Sonoran Deserts (Buffington & Herbel, 1965; Hastings & Turner, 1965). A consequence of this vegetation change is the development of so-called 'islands of fertility' in which resources are concentrated beneath shrubs (Schlesinger *et al.*, 1990). The extent to which this concentration develops is determined in part by the effects of creosotebush on rainfall energy because nutrients are adsorbed onto the sediments (Schlesinger *et al.*, 1999) which accumulate as mounds beneath shrubs as a result of the process of differential splash. A quantitative estimation of the effects of creosotebush on rainfall energy will help to provide a better understanding of the formation of islands of fertility.

Field area and methods

The study was undertaken within the Jornada Long-Term Ecological Research Site (32° 31′N, 106° 47′W), 40 km NNE of Las Cruces, New Mexico, on the bajada surface fringing Mount Summerford. The location experiences a semi-arid climate with a mean annual temperature of 14·7°C and a mean annual precipitation of 245 mm. The majority (68·6%) of this precipitation falls as intense, short-duration, convective summer storms (Wainwright, 1999).

Seven creosotebush shrubs were selected for study. The heights of these shrubs ranged from 1·29 to 1·9 m, and their diameters (average of the long and short axes) from 1·37 to 2·50 m (Table 1). These shrubs were sawn off at ground level and secured in a clamp 30 cm above the ground beneath a rainfall simulator of the type described by Luk *et al.* (1986). Simulated rainfall of 15 minutes duration and an average intensity of 148 mm h^{-1} was applied to these shrubs. This rainfall had a median drop size of 1·76 mm and a mean kinetic energy of 0·97 J m^{-2} s^{-1}. No comparison is made here between the simulated drop-size characteristics and local, natural drop-size characteristics because of the inherent variability in the latter, as well as a lack of good data for any region (Parsons, 1999). For each experiment, rain falling outwith the canopy was recorded using four rain gauges. Because of the large spatial variability in canopy cover, and hence proportions of leafdrip and throughfall, it is difficult to obtain a representative sample, using rain gauges, of the sub-canopy rainfall (throughfall and leafdrip combined). Accordingly, we estimated sub-canopy rainfall using the equation:

$$r_{sc} = r - s_f - e - c_s \qquad (1)$$

Table 1. *Shrub characteristics and experimental results*

	Length m	Width m	Height m	Canopy cover %	Exterior stem angle °	Rainfall intensity $mm\,h^{-1}$	Sub-canopy rainfall intensity $mm\,h^{-1}$	Throughfall intensity $mm\,h^{-1}$	Leafdrip intensity $mm\,h^{-1}$	Rain KE $J\,m^{-2}\,s^{-1}$	Sub-canopy KE $J\,m^{-2}\,s^{-1}$	Throughfall KE $J\,m^{-2}\,s^{-1}$	Leafdrip KE $J\,m^{-2}\,s^{-1}$
Shrub 1	1·60	1·50	1·30	43·2	31·1	138·0	125·6	78·4	47·2	1·05	0·65	0·60	0·05
Shrub 2	2·85	2·15	1·72	58·6	29·4	118·0	102·0	48·8	53·2	0·75	0·40	0·31	0·08
Shrub 3	1·61	1·60	1·29	30·6	55·1	179·0	162·1	124·3	37·8	1·35	1·00	0·94	0·06
Shrub 4	2·01	1·68	1·40	21·7	38·0	153·0	141·5	119·9	21·6	1·06	0·86	0·83	0·03
Shrub 5	2·00	1·90	1·50	17·4	52·6	148·5	139·6	122·6	17·0	0·82	0·70	0·68	0·02
Shrub 6	1·50	1·25	1·90	48·8	63·0	159·0	137·9	81·4	56·5	0·99	0·63	0·51	0·12
Shrub 7	2·50	2·30	1·60	34·9	30·1	138·5	117·4	90·1	27·3	0·75	0·53	0·49	0·04
Average	2·01	1·77	1·53	36·5	42·8	147·7	132·3	89·5	37·2	0·97	0·68	0·62	0·06
S.D.	0·51	0·37	0·23	14·8	13·8	19·1	19·3	21·8	15·7	0·22	0·20	0·21	0·03

where r_{sc} is the sub-canopy rainfall (mm h^{-1}), r is the measured rainfall intensity outwith the canopy (mm h^{-1}), s_f is the rate of stemflow (mm h^{-1}), e is the evaporation during the experiment (mm h^{-1}) and c_s is the rate of increase of canopy storage (mm h^{-1}). Stemflow volumes were measured by directing all of the flow into a calibrated bucket and reading the water level in the bucket every 30 s (Abrahams *et al.*, in preparation). To convert these volumes into stemflow rates, the volumes were divided by the area of the circumscribing ellipse (a measure of the canopy area) and the sample duration. Free-water-surface evaporation reaches a maximum of 11·6 mm day^{-1} in July, when these experiments were undertaken (average 8·7 mm day^{-1}: Wainwright, 1999). Thus, for 15 min experiments carried out shortly after sunrise, the evaporation rate is sufficiently small to be taken as zero. Analysis of the stemflow hydrographs (Abrahams *et al.*, 1999) suggests that canopy storage is satisfied within the first two to three minutes of the experiments. After this time, the rate of increase of canopy storage can also be taken to equal zero so that equation 1 reduces to:

$$r_{sc} = r - s_f. \tag{2}$$

During the experiments, drop-size distributions for rainfall beneath and outwith the canopy were obtained using the flour-pellet technique (Bentley, 1904). The technique involves exposing a tray with a shallow covering of flour to the rain, so that drops are caught in the flour. Care was taken to place the flour tray at the equivalent of ground level for the shrub. To avoid problems with the estimation of increases in canopy storage, these samples were taken 10 min into the experiments. The flour trays were then taken back to the laboratory and oven-dried at 105°C for 24 h to form hardened pellets. After the experiments, the shrubs were photographed against a white background both in plan and in profile.

Kinetic energy of the rainfall was obtained from the flour pellets which were dried for 24 h at 105°C, sieved through -2, -1, 0, 0·5, 1 and 2-φ meshes and then weighed. The total mass for each size class was converted to the equivalent number of pellets from which the equivalent raindrop diameters were obtained. The number of drops calculated varied between 2276 and 28,879. Kinetic energy was calculated for each size class using the terminal velocity for drops of a given diameter, and total kinetic energy was then determined as the sum these values, which gives a better estimate of kinetic energy than using the median drop size (Simmons, pers. comm.). The fall height of the rainfall simulator, together with the exit velocity from the nozzles, means that almost all the raindrops hit the ground at or within 10% of their terminal velocity. Accordingly, the kinetic energy for the rainfall has been calculated on the basis of the terminal velocity of water drops in stagnant air given by Laws (1941) and Gunn & Kinzer (1949). To determine the kinetic energy of the sub-canopy rainfall it was necessary, first, to calculate the proportions of leafdrip and throughfall. These proportions were identified from the canopy cover, which was estimated by projecting the plan-view photograph onto a grid and counting the grid-intersection points overlain by the canopy, and dividing by the canopy area. The amount of sub-canopy rainfall coming from throughfall was assumed to equal the proportion of open space within the ellipse multiplied by the rainfall measured outside the canopy. The amount coming from leafdrip was then calculated as the sub-canopy rainfall minus the throughfall rate. Second, to determine the heights of leafdrip, the profile photographs were projected onto the same grid. The number of grid-intersection points overlain by the canopy on transects at different levels through the shrub were counted to obtain an estimate of the proportion of the canopy at different heights. For throughfall, kinetic energy was calculated as for rainfall, using terminal velocities. The kinetic energy of leafdrip was determined as the mean velocity of drops of a given diameter falling from a given height weighted by the proportion of canopy at that height. The relationship between drop size, fall height and drop velocity was derived from Laws (1941).

Results

The results of the experiments (Table 1) show that there is a significant difference in both intensity ($p = 1{\cdot}36 \times 10^{-4}$) and kinetic energy ($p = 3{\cdot}53 \times 10^{-4}$) between rainfall and sub-canopy rainfall. The mean sub-canopy intensity is reduced to 90% of the rainfall intensity, whereas the mean kinetic energy is reduced to 70%. That the latter reduction is greater than the former is dominantly due to the reduced fall height of the leafdrip, but is in part also a function of the fining in the drop-size distribution (Fig. 1). Estimated median drop sizes are 1·76 mm, 1·61 mm and 1·31 mm for the rainfall, sub-canopy rainfall and leafdrip, respectively. As might be expected, there is a strong relationship between rainfall intensity and rainfall kinetic energy both within ($r^2 = 0{\cdot}90$, $p = 0{\cdot}001$) and outwith ($r^2 = 0{\cdot}67$, $p = 0{\cdot}02$) the canopy. Although, on average, leafdrip makes up 28·1% of the sub-canopy rainfall, it contributes only 9·9% of the sub-canopy kinetic energy. Indeed, this value is probably a slight overestimate, as some drops will fall from leaves and re-impact on lower parts of the shrub before reaching the ground, in which case their fall velocity and kinetic energy will be reduced. In other words, the dominant control on rainfall energy under creosotebush is the amount of throughfall, which, in turn, is controlled by canopy cover.

Discussion

The shrubs selected for this study encompass almost all of the range of shapes of creosotebush identified by Whitford *et al.* (1996), with average exterior stem angles varying from 29·4° to 63·0°. Exterior stem angles were measured from the profile slides using the method of Whitford *et al.* by taking the tangent of the ratio of the vertical height of the topmost, exterior edge of the bush to the horizontal distance from the stem to the vertical line projected from the ground to this top edge. The measurement used here is based on the average of the two edges visible in the photograph. The extreme values of the exterior stem angles are found in shrubs two and six (Fig. 2). In consequence, the measurements of sub-canopy rainfall energy should be typical. However, the technique employed in the calculation of sub-canopy rainfall energy is time-consuming. Therefore,

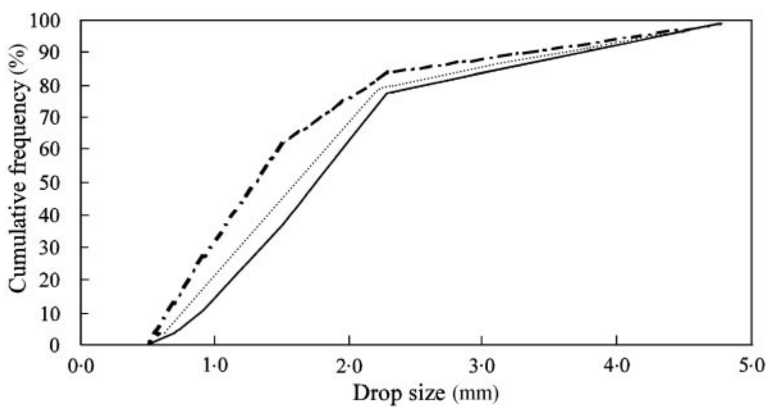

Figure 1. Comparison of mean drop-size distributions for rainfall, sub-canopy rainfall and leafdrip under creosotebush. The drop-size distributions were measured directly for rainfall and sub-canopy rainfall, and estimated for leafdrip, based on the relative proportions of the sub-canopy rainfall coming from throughfall (with the same drop-size distribution as rainfall) and from leafdrip: ——, rainfall; ·······, sub-canopy rainfall; -·-·-, leafdrip.

Figure 2. (a) Shrub 2, an example of a bush with a small exterior stem angle; and (b) shrub 6, an example of a bush with a large exterior stem angle.

we have explored alternative methods to calculate proportions of throughfall and leafdrip, and the effective height of leafdrip based upon simple measurements of shrub dimensions.

Unfortunately, neither canopy area, nor shrub height, nor exterior stem angle proves to be a significant predictor of canopy cover ($p = 0{\cdot}66$, $p = 0{\cdot}19$ and $p = 0{\cdot}60$, respectively). Thus, there appears to be no alternative but to obtain some measure of canopy cover. Simplified calculations using effective height of leafdrip were carried out

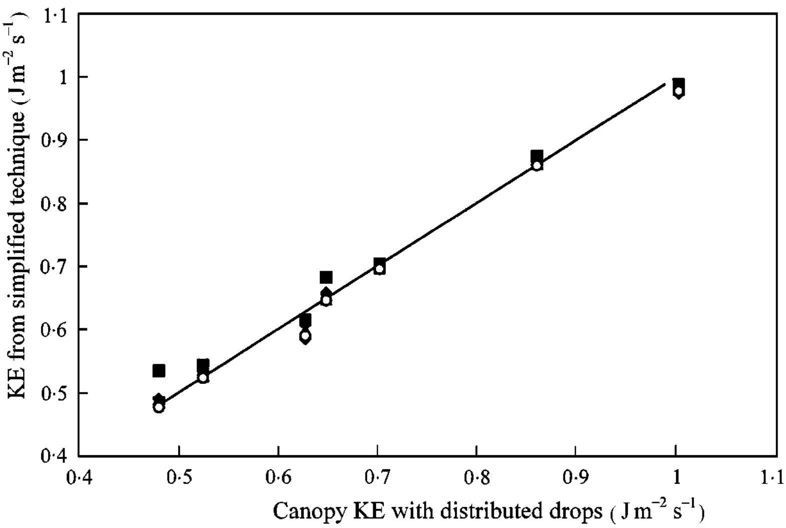

Figure 3. Comparison of the effects of using different simplified methods for calculating drop velocities of leafdrip on the predicted sub-canopy kinetic energy: ◆, half height; ■, bush centroid; ▲, canopy weighted mean; ×, canopy median; ○, weighted mean velocity; ▬ , 1:1 line.

assuming the effective height to be half the shrub height, the shrub centroid (three-quarters of the shrub height, assuming the canopy to be an inverted cone), the weighted mean height of the canopy and the canopy median height. The two latter

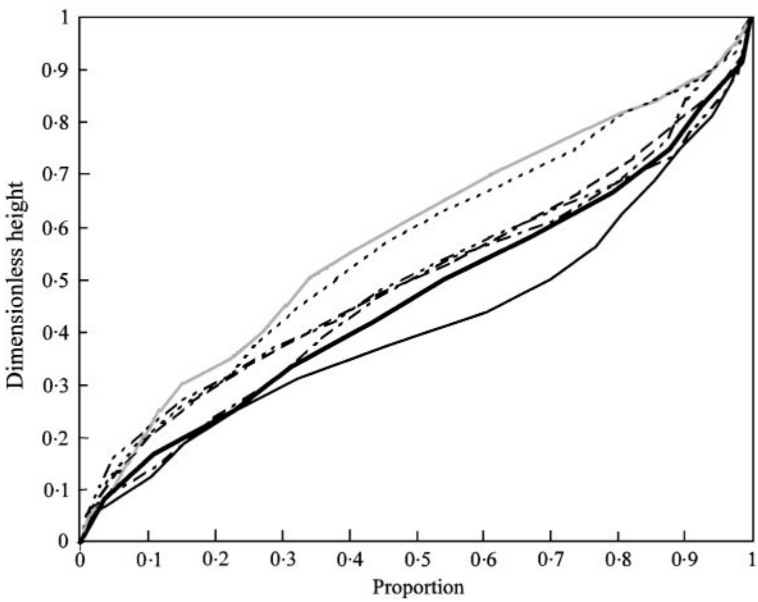

Figure 4. Shapes of shrubs used in the experiments shown as cumulative proportion of canopy against dimensionless height: ——, shrub 1; – – –, shrub 2; ······, shrub 3; –·–·, shrub 4; –··–, shrub 5; ——, shrub 6; ▬▬, shrub 7.

Table 2. *Predicted values of kinetic energy effective in the transport of sediment*

	Effective rainfall KE $J m^{-2} s^{-1}$	Effective sub-canopy rainfall KE $J m^{-2} s^{-1}$	Effective leafdrip KE $J m^{-2} s^{-1}$	Effective throughfall KE $J m^{-2} s^{-1}$	Effective sub-canopy rainfall KE/effective rainfall KE $J m^{-2} s^{-1}$
Shrub 1	0·94	0·31	0·009	0·30	0·33
Shrub 2	0·59	0·12	0·023	0·10	0·21
Shrub 3	1·23	0·65	0·053	0·60	0·53
Shrub 4	0·86	0·53	0·004	0·53	0·62
Shrub 5	0·56	0·39	0·011	0·38	0·70
Shrub 6	0·73	0·27	0·079	0·19	0·37
Shrub 7	0·48	0·20	0·0002	0·20	0·42
average	0·79	0·36	0·026	0·33	0·45
S.D.	0·25	0·18	0·029	0·18	0·17

measurements are based on the sampled transects down the shrub. All of the measurements give values which are very similar to those provided by the mean velocity of drops of a given diameter falling from a given height weighted by the proportion of canopy at that height (Fig. 3). This result is perhaps not surprising given that leafdrip contributes such a small amount to total sub-canopy kinetic energy (Table 1) and because the median canopy volume occurs at around half the height (Fig. 4). Therefore, the error involved in using any of these simpler methods can be considered to be inconsequential in the case of creosotebush.

For calculating sediment detachment by raindrops, it is important to recognize that not all drops that contribute to total rainfall kinetic energy have sufficient energy individually to detach sediment. Morgan *et al.* (1988) put the threshold at which individual raindrops do possess enough such energy at $8{\cdot}45 \times 10^{-5}$ J. As Brandt (1989) points out, this is the energy possessed by a drop of 2 mm diameter falling at terminal velocity. To compare the effectiveness of sub-canopy rainfall to rainfall outwith the canopy, the kinetic energy of those drops which are capable of detaching sediment was calculated. For rainfall and throughfall, this is the energy of drops in the two largest size classes (equivalent raindrop diameters of 2·295 and 4·975 mm). In the case of leafdrip, it includes drops in the 2·295 mm class falling from heights greater than 1·88 m, and drops in the 4·975 mm class falling from higher than 0·09 m. The results (Table 2) demonstrate that, whereas kinetic energy is reduced by 30% by the creosotebush canopies, the *effective* kinetic energy is reduced by 55%. It is the difference in effective kinetic energy that is responsible for the development of mounds beneath desert shrubs by the process of differential splash (Parsons *et al.*, 1992; Wainwright *et al.*, 1995).

The impact of these results on the development of islands of fertility in desert ecosystems may be considered in two ways. First, the distribution of nutrients in the form of plant litter is likely to be affected in proportion to the difference in total kinetic energy beneath and outwith the canopy, because of the relatively high erodibility of litter fragments. The net accumulation of litter and its consequent decay should lead to an increase in the fertility beneath shrubs. Second, the distribution of nutrients adsorbed onto sediment particles will be affected in proportion to the difference in effective kinetic energy. The build up of mounds beneath shrubs as discussed above also leads to a net accumulation of nutrients adsorbed onto sediment, which may become available to the shrub and any plants in its understorey.

Conclusions

This study has provided the first quantitative estimates of the effect of desert shrubs in reducing rainfall energy that reaches the ground surface. The results show that creosotebush significantly reduces the rainfall energy and that this reduction is principally a function of canopy interception, as most of the sub-canopy rainfall energy derives from throughfall. Furthermore, the results provide insight into the process of sediment movement by differential splash, and support earlier empirical findings of its importance in the development of mounds beneath desert shrubs. The estimates herein are useful for modelling water and sediment movements in desert-shrub ecosystems.

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References

Abrahams, A.D., Parsons, A.J. & Wainwright, J. (in preparation). Disposition of stemflow under creosotebush.

Bentley, W.A. (1904). Studies of raindrops and raindrop phenomena. *Monthly Weather Review*, **32**: 450–456.

Brandt, C.J. (1986). Transformation of the kinetic energy of rainfall by variable tree canopies. Unpublished PhD thesis, University of London, 466 pp.

Brandt, C.J. (1989). The size distribution of throughfall drops under vegetation canopies. *Catena*, **16**: 507–524.

Buffington, L.C. & Herbel, C.H. (1965). Vegetation changes in a semi-desert grassland range from 1858 to 1963. *Ecological Monographs*, **35**: 139–164.

Gunn, R. & Kinzer, G.D. (1949). The terminal velocity of fall for water droplets in stagnant air. *Journal of Meteorology*, **6**: 243–248.

Hastings, J.R. & Turner, R.M. (1965). *The Changing Mile*. Tucson: University of Arizona Press. 317 pp.

Laws, J.O. (1941). Measurements of the fall velocity of water-drops and raindrops. *Transactions of the American Geophysical Union*, **22**: 709–721.

Luk, S.-H., Abrahams, A.D. & Parsons, A.J. (1986). A simple rainfall simulator and trickle system for hydro-geomorphological experiments. *Physical Geography*, **7**: 344–356.

Mabry, T.J., Hunziker, J.H. & Difeo, D.R. Jr. (Eds) (1977). *Creosotebush: Biology and Chemistry of Larrea in New World Deserts*. US/IBP Synthesis Series 6, Stroudsburg, PA: Dowden, Hutchinson & Ross. 284 pp.

Morgan, R.P.C., Brandt, C.J. & Stuttard, M.J. (1988). The Role of Plant Covers in Controlling Soil Detachment by Rainfall. Final Report to the Agriculture and Food Council, Research Grant Number AG63/189, June 1988, 27pp.

Parsons, A.J. (1999). Accuracy levels for modelling soil erosion. Paper Presented at BGRG Rainfall Simulation Group/COST 623 Soil Erosion and Global Change Meeting, Leicester, 18–21 April 1999.

Parsons, A.J., Abrahams, A.D. & Simanton, J.R. (1992). Microtopography and soil-surface materials on semi-arid piedmont hillslopes, southern Arizona. *Journal of Arid Environments*, **22**: 107–115.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A. & Whitford, W.G. (1990). Biological feedbacks in global desertification. *Science*, **247**: 1043–1048.

Schlesinger, W.H., Abrahams, A.D., Parsons, A.J. & Wainwright, J. (1999). Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: I. Rainfall simulation experiments. *Biogeochemistry*, **45**, 21–34.

Shreve, F. (1942). The desert vegetation of North America. *Botanical Review*, **8**: 195–246.

Wainwright, J. (in press). Climate and climate variability at Jornada. In: Schlesinger, W.H., Huenneke, L. & Havstad, K. (Eds), *Jornada*, Oxford: Oxford University Press.

Wainwright, J., Parsons, A.J. & Abrahams, A.D. (1995). A simulation study of the role of raindrop erosion in the formation of desert pavements. *Earth Surface Processess and Landforms*, **20**: 277–291.

Whitford, W.G., Martinez Meza, E. & DeSoyza, A. (1996). Morphological variation in creosotebush, *Larrea tridentata*: effects on ecosystem properties. In: Barrow, J.R., Durant, E., Sosebee, R.E. & Tausch, R.J. (Eds), *Proceedings of the Symposium on Shrubland Ecosystem Dynamics in a Chaning Climate*, pp. 195–198, May 23rd–25th 1995, Las Cruces, N.M., General Technical Report. INT-GTR 338. Ogden, UT: U.S. Department of Agriculture, Forest Service Intermountain Research Station. 275 pp.