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Soil microtopography on grazing gradients in Chihuahuan desert grasslands☆

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Abstract

The significant impacts of livestock in the creation of piospheres centered on water points is the loss of soil microtopography across a 'landscape' that has been influenced by many years of livestock grazing. The size, height, and spatial distribution of micromounds and surrounding depressions were measured by a modified erosion bridge at three distances (50, 450, and 1050 m) from water points in desert grassland pastures in the Jornada Basin, New Mexico, USA. Plots at 50 m had fewer micromounds and the mounds were smaller than those recorded on the more distant plots. Microtopography of plots at 450 m from water was not significantly different from that recorded at 50 m. Microtopography of plots that were 1050 m from water points was significantly different from that of plots nearer water points. Strong correlation between microtopography and the cover of long-lived perennial grasses ($R^2 = 91\%$) was found, such dependence could be used for assessing the trend in organic matter content that is in concordance with that of microtopography. Loss of microtopography from the impact of livestock in piospheres exacerbates erosion processes and contributes to desertification.

Keywords: Desertification; Grazing; Gradients; Microtopography; Piosphere

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1. Introduction

Microtopography describes variations in the soil surface elevation (millimeter or centimeter) for a scale of a few meters of horizontal distance. Small-scale (few centimeters) changes in vegetation communities synchronized with the elevation differences were observed in drained marsh (Zedler and Zedler, 1969). Vivian-Smith (1997) reported that species richness and evenness were significantly higher in areas characterized by small-scale heterogeneous microtopography. The amount of water available to vegetation is related to elevation; therefore, germination and seedling establishments are affected by the soil surface microtopography (Smith and Capelle, 1992).

In arid and semi-arid regions, it is well known that soil water and nutrients are spatially distributed in a pattern that is closely related to changes in elevation (Wondzell et al., 1990). In desert grasslands, water and nutrients accumulate in depressions between micromounds on which grass clumps or tussocks grow. Water and nutrient storage in depressions increases as the topography variability increases or the correlation length scale decreases (range of dependence in semi-variance; Huang and Bradford, 1990). Rainwater runoff from the micromounds accumulates in the depressions and grass fragments, insect frass and other organic matter fragments are transported from the micromounds into the depressions. If the microtopographhgy is flattened, microcatchments are lost and water runoff transports sediments and organic material off site (Dunkerley and Brwon, 1995, 1999).

It has been hypothesized that desertification, or degradation of Chihuahuan Desert grasslands, results in changes in spatial heterogeneity of soil resources (Schlesinger et al., 1990). Desert grasslands are characterized by fine scale patchiness of soil nutrients. Changes in fine scale patchiness may be the precursor of larger-scale changes leading to desertification. Livestock grazing has been shown to change the spatial distribution of grasses in the shortgrass steppe (Alder and Lauenroth, 2000). They attributed changes in the spatial heterogeneity of the dominant grass, *Bouteloua gracilis* primarily to grazing effects.

Studies of piospheres (areas of exponentially decreasing impact by domestic livestock centered on water points) focused on the effect of livestock on the vegetation characteristics of the piospheres (Lange, 1969; Graetz and Ludwig, 1978; Andrew and Lange, 1986; Fusco et al., 1995). Vegetation patterns on the piospheres examined in this study documented the exponential increase in grass cover at 1 km from water points (deSoyza et al., 1997; Nash et al., 1999). These studies did not report on microtopography on the grazing gradients. In Chihuahuan Desert grasslands, because of the apparent functional importance of microcatchments, we hypothesized that large numbers of livestock concentrated at water points destroys microtopography. We therefore, speculated that the impact of livestock is greatest on soil microtopography at the water point and decreases with distance. The loss of microtopography is hypothesized to be the initial change leading to desertification.

The main objective of this paper is, therefore, to perform a spatial analysis of microtopographic features and indices across a ‘landscape’ that has been influenced by many years of livestock grazing. To accomplish the above objective, we measured microtopography on plots established at fixed distances from water points in different paddocks. We calculated several measurements that characterized leveling of the microtopography: frequency of depressions/mounds, and the height of depressions/mounds from the '0' level reference that are equal or more than 3 cm. Microtopographic indices were determined from the above measurements in order to assess whether there is a change in soil microtopography pattern with increasing distances from the wells.

Long-lived perennial grasses permit higher soil moisture, nutrients and litter in a desert ecosystem because of their stoloniferous morphology (deSoyza et al., 1997). Nash et al. (1992) documented the exponential spatial cross correlation between soil moisture and perennial grasses in this desert area. Higher cover of long-lived perennial grasses indicates higher water and nutrient retention in desert soil. We, therefore, hypothesized that microtopography and long-lived perennial grasses behaved similarly at a distance, and hence, we can use long-lived perennial grasses as a surrogate variable to assess the trend of organic matter at a distance from the water point. This later has its useful implication when organic matter measurements are not available.

2. Materials and methods

The study sites were located on the Chihuahuan Desert Rangeland Research Center approximately 40 km north of Las Cruces, New Mexico, USA (Mayfield Well and Camp Well) and on the USDA-ARS Jornada Experimental Range, 50 km north of Las Cruces, New Mexico (West Well). The well gradients were on soil with deep sandy, loams, with scattered mesquite (*Prosopis glandulosa*) shrubs. The percent of clay and sand in the top 10 cm profiled in soil on the three gradients was 7% and 85%, respectively (Table 1, Dr. Herrick, unpublished data). The climate is typical of a semi-arid region, with low relative humidity, and an average annual rainfall of 23 cm, usually occurring from July 1 to September 30; and the maximum and minimum temperatures are between 36°C (June) and 13°C (January).

We established three, 1-ha plots along each of the three disturbance gradients at a distance of 50, 450 and 1050 m from the stock watering points. Each hectare was divided into 100 subplots, and from these, 10 of the subplots were selected at random for microtopography measurements. A total of 10, 100-m transects that are parallel to the disturbance gradients (deSoyza et al., 1997) in each plot were used for vegetation cover measurements. The linear interception of vegetation (long- and short-lived perennial grasses) or bare patches to transect were recorded to determine the percentage of vegetation cover and average bare patches, measured in centimeters, for each plot (Table 1).

Microtopography was measured using a modified erosion bridge. The bridge consisted of a 4 m aluminum pipe with holes drilled at 3 cm intervals along 300 cm of the pipe. Solid metal pins (mm diameter) were inserted through each of the holes in the pipe. The height of each pin above the leveled reference pipe was recorded. These lengths were adjusted for plot slope by using the first and last pins as zero reference.

Table 1
Characteristics of three grazing gradients (piospheres) originating at water wells on the Chihuahuan Desert Rangeland Research Center (CDRRC) and the Jornada Experimental Range (JER) desert grasslands in southern New Mexico (from deSoyza et al., 1997)

Site code	Percent		Average bare patch size (cm)	Percent	
	Grass	Shrub		Clay	Sand
CW0	0.47	5.7	396.2	10.00	82.09
CW2	4.5	5.5	126.9	6.08	86.58
CW3	20.8	4.3	68.5	6.89	83.55
MW0	1.2	6.8	296.4	14.99	76.24
MW2	5.7	10.9	90.2	6.21	87.33
MW3	23.7	6.7	62.6	7.43	85.37
WW0	0.88	15.9	197.6	4.40	87.84
WW2	8.9	13.7	133.1	5.92	85.78
WW3	27.6	5.1	50.9	6.54	85.28

WW = West Well on the JER, CW = Camp Well on the CDRRC and MW = Mayfield Well on the CDRRC. 0 are plots 50 m from water, 2 are plots 450 m from water and 3 are plots 1050 m from water. Percent of vegetation cover of grass and shrub, percent of clay and sand for top 10 cm and average bare patch (cm).

The ends of the aluminum pipe were fastened into vertical end stands, which were driven into the soil at varying depths until the erosion bridge pipe was level, as indicated by a spirit-level placed on the center pipe.

In order to measure the microtopography alone, we removed the slope effect by extracting the residuals from the regression line (Proc Reg; SAS, 1998) of the erosional bridge measurements. Residuals were noisy and needed to be smoothed (Fig. 1) for better visualization and ease of calculating the height and frequency of mounds and depressions. Residuals for each transect were smoothed using local regression (Proc Loess, SAS, 1998) as a non-parametric regression. It was determined that microtopography features (Fig. 2) include a number of depressions/mounds and height of depressions/mounds from the ‘0’ level reference that are equal to, or more than, 3 cm. Microtopography features number of depressions/mounds and height of depressions/mounds from the ‘0’ level reference that are equal or more than 3 cm were determined. Depth of 3 cm is the minimum depth that retain litter following windy season and therefore, depression of less than 3 cm will not have that much of effect on ecological processes such as seedling establishment (field observation; Whitford). A microtopography index was calculated as: (1) the sum of the absolute value of the depressions and mounds (Fig. 3a), (2) the frequency of depressions and mounds (Fig. 3b), and (3) the sum of depressions and the sum of mounds (Fig. 3c). Analyses of variances for the main effect (wells and distance) of the above three topographic indices were done using GLM (SAS, 1998). For multiple comparisons, the means for the height of mounds and depressions were done using GLM with Lsmeans options to account for the unequal number of measurements per plot (Fig. 4).

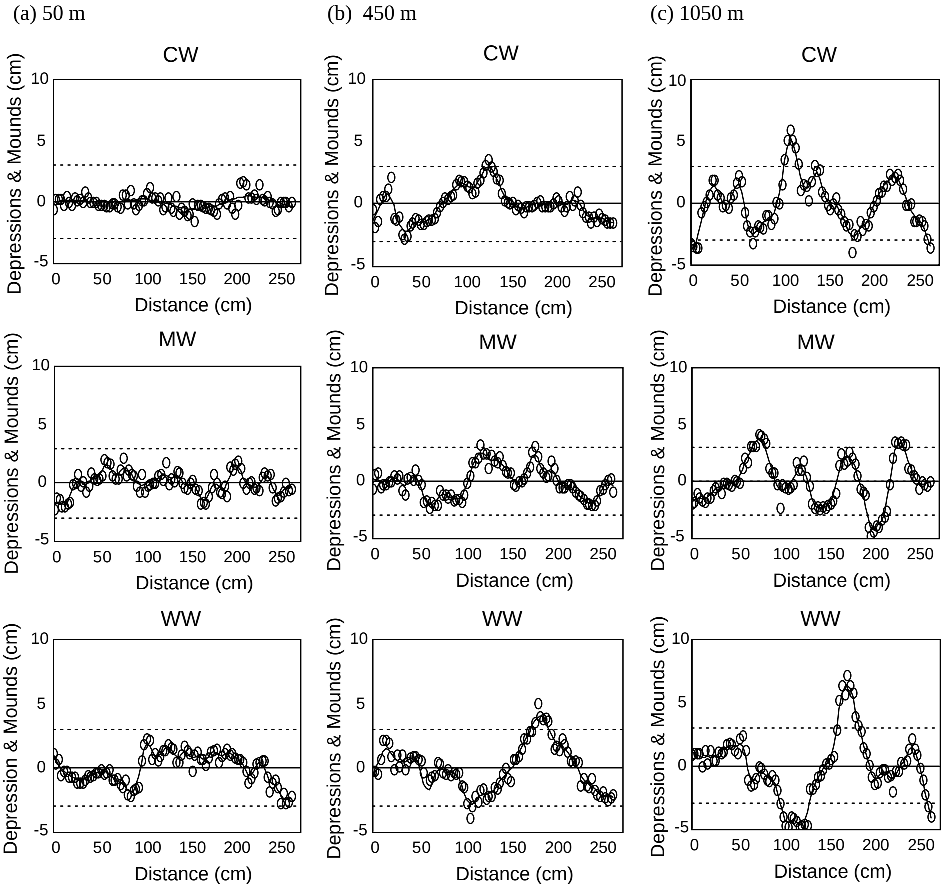

Fig. 1. An example of smoothing (solid line) the microtopography data (open circles) along grazing gradients at: (a) 50 m, (b) 450 m, and (c) 1050 m from water points at three wells, Camp Well (CW), Mayfield Well (MW), and West Well (WW). Dashed horizontal line is the 3 cm cut-off value for the effective height of mounds and depressions.

Soil organic matter was not measured in depressions between mounds to explore their relationship with microtopography along grazing disturbances. In lieu, long-lived perennial grass cover that was measured in each plot along the same grazing gradient (deSoyza et al., 1997) was used in regression (Proc Reg; SAS) with the microtopography index (sum of the absolute values of depression and mound). The dependence of the latter on the former will be used to assess the trend in organic matter along the grazing gradients from the water point.

3. Results

The microtopography indices behavior along a distance for the three wells is given in Fig. 3. All indices have a consistent pattern that are the smallest at the water point

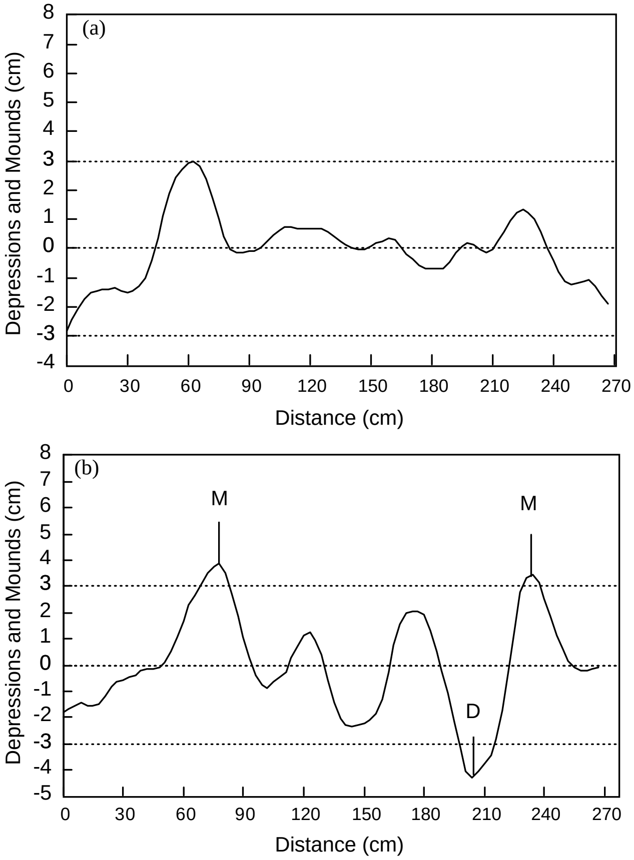

Fig. 2. Examples of depressions (D) and mounds (M) on plots at: (a) 50 m and (b) 1050 m from water points.

and increased with distance. The patterns of microtopography indices were similar for the three-piosphere gradients (df. = 2, 4; $F < 0.9$; $p > 0.5$), but they were significantly different with distance from the water point (df. = 2, 4; $F > 9.0$; $p < 0.03$). The number of mounds and depressions and the sums of the absolute deviations at the plots 1050 m from water points were significantly larger ($p < 0.03$, df. = 4) than those measured at plots 50 and 450 m from the livestock watering point. There were no significant differences in the sums of absolute deviations and the number of mounds and depressions at the 50 and 450 m distances in all wells ($p > 0.48$, df. = 4). The elevation deviations from the zero reference level of mounds and depressions were significantly larger at distance of 1050 m than at distance of 50 and 450 m distance on all ($p < 0.01$, df. = 4).

There were no significant differences in the average elevation deviation for zero level references for mounds at 50 and 450 m at three well gradients (df. = 4; $|t| < 1.75$; $p > 0.08$). However, for mounds at distance of 1050 m, the average elevation deviation at zero level references is significantly higher than at distance 50 and 450 m

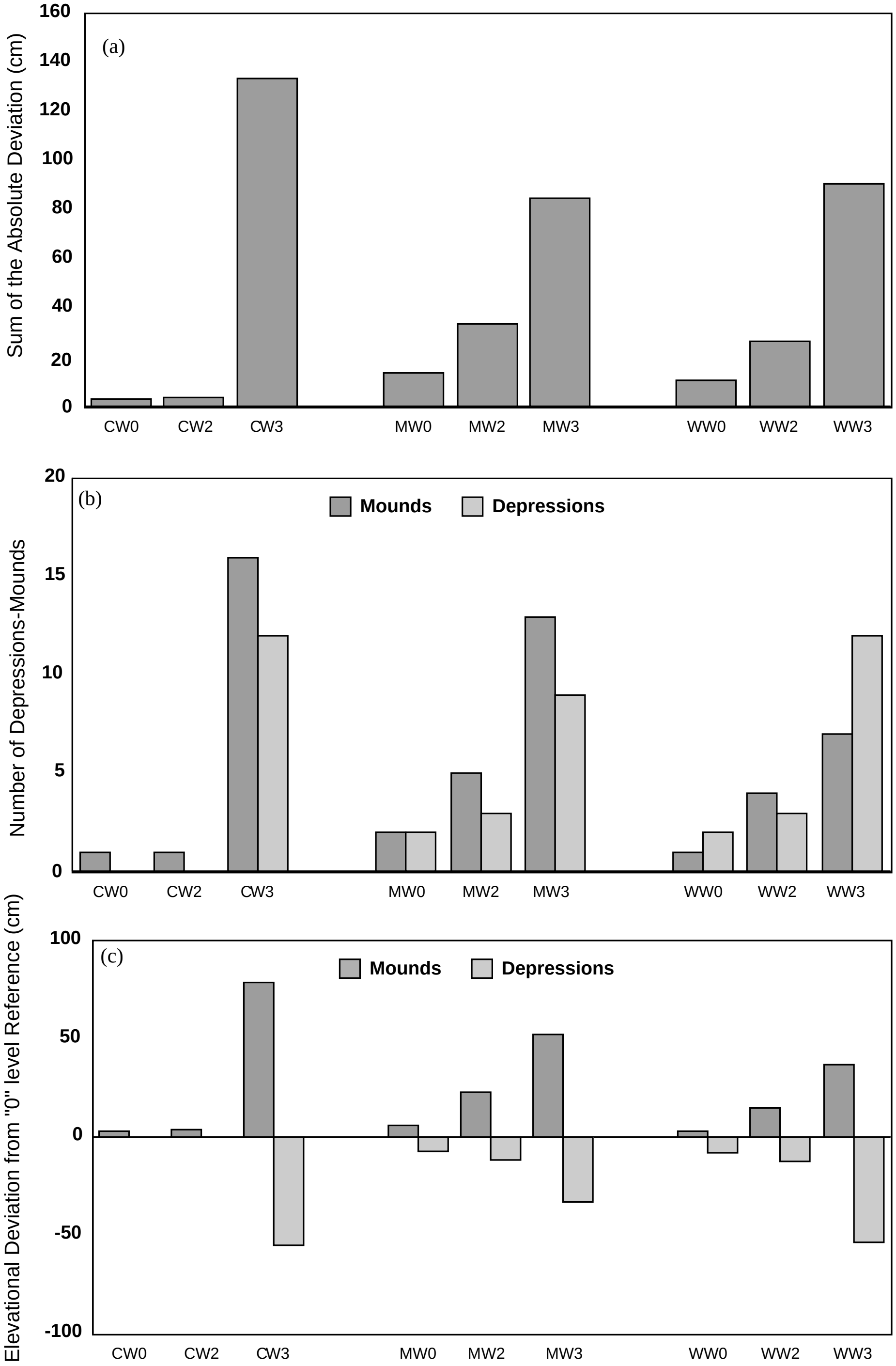

Fig. 3. Comparisons of three indices of microtopography: (a) sum of the absolute deviations from the zero reference (cm), (b) number of depressions and micromounds, and (c) mounds and depressions deviation (±cm) from the zero reference. CW = Camp Well, MW = Mayfield Well, and WW = West Well. 0 = plots at 50 m from water, 2 = plots at 450 m from water and 3 = plots at 1050 m from water.

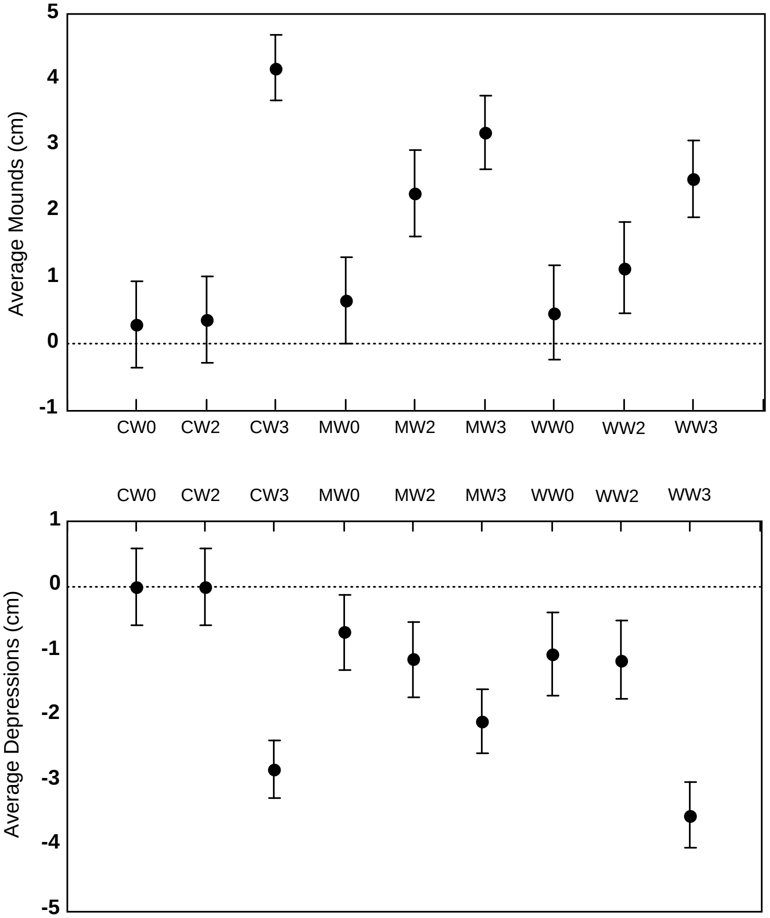

Fig. 4. Average heights of micromounds and average depths of depressions on plots on piosphere gradients in Chihuahuan Desert grassland. CW = Camp Well, MW = Mayfield Well, and WW = West Well. 0 = plots at 50 m from water, 2 = plots at 450 m from water and 3 = plots at 1050 m from water. Closed circles represent mean value and vertical lines represent standard error ($p \leqslant 0.05$).

at Camp Well (df. = 4; $|t| > 4.64$; $p < 0.0001$). Differences in average mounds were significant between 1050 and 50 m (df. = 4; $|t| > 2.22$; $p < 0.03$), but were not significant between 1050 and 450 m (df. = 4; $|t| < 1.51$; $p > 0.14$) for the Mayfield Well and West Well gradients.

There were no depressions that were equal to or greater than 3 cm in Camp Well (Fig. 4). The differences in the average elevational deviation at zero level references for depressions at the 50 and 450 m distance were not significant at Mayfield Well and West Well (df. = 4, $|t| < 0.51$, $p > 0.6$). Differences in the average elevational depressions for the 1050 m was significantly higher than that at 50 m at the Camp Well and West Well gradients ($|t| > 3.00$, $p < 0.003$). The average depressions at the

Mayfield Well were higher at the 1050 m and decreased consistently, but unsignificantly, toward the water point ($|t| < 1.8$, $p > 0.08$).

Long-lived vegetation helps stabilize soil and reduce the amount of erosion in the Chihuahuan Desert on these grazing gradients. Soil stability and long-lived vegetation cover were higher at distances from the water point (deSoyza et al., 1997). Nash et al. (1999) reported that the long-lived vegetation cover increased as the square distance increased; similar behavior was found for the microtopography index (Fig. 5) indicating the strong dependence of microtopography on the amount of perennial grass cover ($R^2 = 0.91$, df. = 1, 8, $F = 81.39$, $p < 0.0001$; Fig. 6). It is known that in a desert environment, soil moisture and nutrients are higher in microcatchments between mounds on which grass clumps or tussocks grow. Therefore, the relationship between microtopography and vegetation cover found above should reflect the increasing trend of soil moisture and organic matter from the water point along the grazing gradients.

4. Discussion

One effect of large numbers of livestock concentrated at water points is a marked reduction in plant cover as a result of their 'camping' behavior near water points. This study documented significant reductions in mound height and depth of intermound depressions on plots that were less than 450 m from a livestock water point. The destruction of the mound/depression microtopography eliminates the micro watersheds that are important for the maintenance of desert grassland. In semi-arid grasslands of Colorado, disturbance that increased bare space around

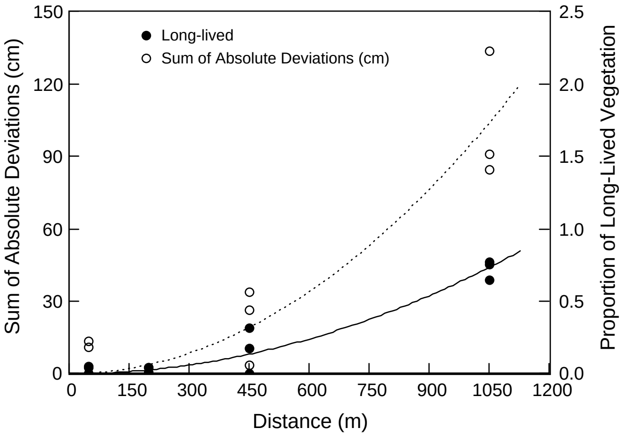

Fig. 5. Long-lived vegetation and a microtopography index with distance on piosphere gradients in Chihuahuan Desert grassland. Solid line is the fitted model for the proportion of long-lived vegetation ($y = 9.4E - 7x^2$, $R^2 = 0.94$, $F = 119$, $p < 0.0001$). Dashed line is the fitted model for the sum of absolute deviations with distance ($y = 6.643E - 7x^2$, $R^2 = 0.96$, $F = 282$, $p < 0.0001$).

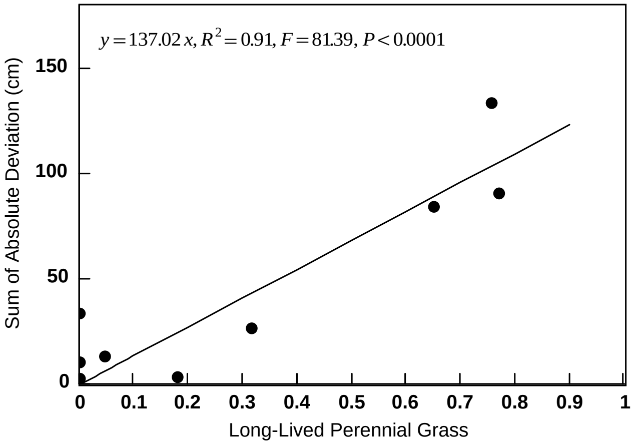

Fig. 6. The dependence of a microtopography index on the cover of long-lived perennial grasses on the grazing gradients. *Y* represents the sum of absolute deviations (cm) and *x* represents the cover of long-lived perennial grasses.

grass tussocks resulted in increased differences in height between plant crowns and bare soil openings (Martinez-Turanzas et al., 1997). The increase in height differences was related to greater soil redistribution with increasing bare soil patch size. The basal height of grass tussocks increases when the foliage causes deposition of wind transported material within a tussock. Although relatively small bare patches in short-grass prairie contributed to soil accretion in the grass tussock mounds, the extensive bare areas at the water points in the Chihuahuan Desert allowed deflation of mounds and reduction in microtopographic variation. The destruction of vegetation canopies by trampling and consumption by livestock eliminates the most important factor, the resistance of wind erosion (Van de Ven et al., 1989). They reported that if vegetation density, height and/or diameter are reduced, soil loss increases as the square of that factor. In our study, the areas around water points on the grazing gradients were almost completely devoid of perennial vegetation. Most micromounds on the plots closest to water points were not obviously associated with grass plants or even with dead grass-root crowns. Micromounds in the first zone of the piosphere were primarily the result of hoof action by the livestock. The reduction in height and the number of micromounds and the lack of plants plus soil compaction result in reduced infiltration, plus the depth of the standing water is shallow following rains. These factors combine to increase evaporation losses and reduced water storage when compared with soils in zones with functional microtopography.

In Chihuahuan Desert grasslands, areas at intermediate distances from water, and the larger bare patches (Whitford et al., 1999) contribute to soil accretion mechanisms described by Martinez-Turanzas et al. (1997). The exaggeration of micromound-depression microtopography at intermediate distances from water points probably contributes to the resistance and resilience of perennial grasses by favoring increased depth of soil water. Although the areas nearest water points exhibit significant reductions in numbers of micromounds and in mound height and depression depth, the reduced abundance of bunch grasses increases the area around the mounds contributing to water available to individual plants. This is a contributing factor affecting the higher survivorship of grasses at intermediate distances from water than at the largest distance from water where survivorship of grasses and small shrubs was measured (Whitford et al., 1999).

In a study of drought survivorship and recovery following drought, Whitford et al. (1999) reported higher survivorship and greater recovery of grass cover at distances greater than 450 m from the livestock watering point. The ability of grasses to survive drought is probably related to higher infiltration in the grass tussocks resulting from stemflow (Van Elewijck, 1989) and to the larger volumes of runoff water retained in the depressions between tussocks. The significant loss of microtopography in piospheres exacerbates erosion and contributes to loss of functional properties of desert grasslands.

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