Available online at www.sciencedirect.com
ScienceDirect
Geoderma 140 (2007) 106 – 118
GEODERMA
www.elsevier.com/locate/geoderma

Multi-scale variability in soil aggregate stability: Implications for understanding and predicting semi-arid grassland degradation

Simon B. Bird [a,*], Jeffrey E. Herrick [a], Michelle M. Wander [b], Leigh Murray [c]

[a] USDA-ARS Jornada Experimental Range, MSC 3JER, New Mexico State University, P.O. Box 80003, Las Cruces NM 88003-8003, United States
[b] Department of Natural Resources and Environmental Sciences, University of Urbana-Champaign, 1102 S. Goodwin Avenue, Urbana, IL 61801, United States
[c] University Statistics Center, MSC 3CQ, New Mexico State University, P.O. Box 30001, Las Cruces, NM 88003-8001, United States

Received 25 October 2005; received in revised form 15 February 2007; accepted 17 March 2007
Available online 19 April 2007

Abstract

Increased soil loss and redistribution are commonly associated with changes in soil structure, yet variability in soil structure in arid ecosystems has been little studied. Soil aggregate stability is a key indicator of soil structure and is correlated with erodibility and water infiltration capacity. In 2000, we compared soil aggregate stability of a complex of Simona (Loamy, mixed, thermic, shallow Typic Paleorthids) and Harrisburg (Coarse-loamy, mixed, thermic, Typic Paleorthids) soils in a Chihuahuan Desert grassland. We examined soil stability at plant and landscape scales by assessing percentage aggregate stability at four sites in two cover classes (plant vs. interspace) located within each of three grass cover and land disturbance classes. To increase measurement sensitivity to changes in soil structure and identify potential early warning indicators for monitoring, we used two different methods for quantifying wet aggregate stability: a laboratory method using a 0.25 mm sieve and a field method using a 1.5 mm sieve. As expected, soil aggregate stability was significantly higher under grass plants than in plant interspaces (44.2 vs. 38.4 for the lab test and 4.4 vs. 3.3 for the field test; $P<0.01$). The field test showed higher stability in plots with higher grass cover throughout the top 10 mm soil layer, while disturbance level only affected stability at the soil surface. The laboratory test was insensitive to differences in grass cover and disturbance.

Keywords: Rangeland degradation; Spatial scale; Soil heterogeneity; Early warning indicator; Soil carbon

1. Introduction

The degradation of arid and semi-arid grasslands in the southwestern United States over the past 150 years has been well documented (Buffington and Herbel, 1965; Hastings and Turner, 1965; York and Dick-Peddie, 1969; Hennessy et al., 1983; Grover and Musick, 1990; Gibbens et al., 1992; Bahre and Shelton, 1993; van Auken, 2000; Gibbens et al., 2005). Grasslands on coarse-textured soils originally dominated by perennial grass species such as *Bouteloua eriopoda* (Torr.) Torr. (black grama) have been almost completely replaced by shrub species such as *Prosopis glandulosa* Torr. (honey mesquite) (Buffington and Herbel, 1965; Gibbens et al., 2005). This shift in vegetative cover correlates with major soil changes. Previous studies have documented increased soil loss and redistribution, resulting in higher spatial heterogeneity of soil water content and nutrient resources, and microbial biomass increases at the plant-interspace scale (approximately 1 to 10 m) (Schlesinger et al., 1990; Gallardo and Schlesinger, 1992; Cross and Schlesinger, 1999).

Relatively little is known about how dynamic soil properties respond to changes in grass cover and disturbance in arid and semi-arid grasslands. Most studies on soil nutrient availability in semi-arid grasslands have been limited to the plant-interspace scale. A greater understanding of the spatial variability of these properties is needed to help identify ecosystem processes driving system change and the appropriate scales for monitoring and management. We chose to study soil aggregate stability because studies in other ecosystems have shown a) that it is functionally important and b) that it reflects the status of a number of other important ecosystem properties and processes. Stable soil aggregates are

* Corresponding author. Tel.: +1 347 535 0627; fax: +1 505 646 5889.
E-mail address: sbird@simbio.com (S.B. Bird).

0016-7061/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.geoderma.2007.03.010

more resistant to detachment and loss through erosion than less stable aggregates (Pierson and Mulla, 1990). By controlling soil porosity, soil aggregates enhance soil water infiltration and water holding capacity (Jastrow et al., 1998). The soil organic matter that helps bind aggregates together conserves soil fertility (Elliot, 1986). Soil aggregate stability reflects the status of other soil processes because soil aggregation depends on soil organic matter inputs and the activity of the soil biotic community (Tisdall and Oades, 1982; Zobeck, 1991; Monreal and Kodama, 1997). Individual soil particles are bound together into microaggregates by organo-mineral bonds. These microaggregates include complex organic molecules, such as humic and fulvic acids, that have relatively long turnover times (Wander, 2004). These microaggregates are bound to each other by fungal hyphae, fine roots, root exudates, and byproducts of microbial decomposition that are relatively labile. Variability in soil texture and mineralogy, soil organic matter inputs, and disturbance together determine soil aggregate stability at a particular point in the landscape.

Our general objectives were to quantify spatial variability of soil aggregate stability at the plant-interspace scale across the landscape in order to better understand its potential role in grassland degradation and recovery, and to evaluate its potential use as an indicator for monitoring and assessment. We hypothesized that stability would be greater under grass plants than that in bare interspaces due to the accumulation of resources that promote aggregation under plant canopies. We expected stability to be greater in areas where grass cover was higher and the degree of disturbance was lower due to the correspondingly higher soil organic matter (SOM) inputs at the plot level. We also expected soil stability to vary with soil depth, with higher stability occurring at the soil surface (the most biologically active soil zone in this system).

2. Study sites and methods

2.1. Study sites

The study was conducted on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center. The two research areas are located in the Jornada del Muerto Basin at the northern end of the Chihuahuan Desert in south-central New Mexico, U.S.A. (Fig. 1). Mean annual rainfall is 247 mm, approximately 50% of which falls between July 1 and September 30 (Gile et al., 1998), and occurs primarily as short, high intensity, localized convective storms. There are three distinct seasons: a hot, wet summer (from July to October), a cool, dry winter (from November to March), and a hot, dry spring (from April to June) (Virginia et al., 1992). Mean annual temperature is 15.6 °C, with July being the hottest month with a mean temperature of 26 °C, and January the coolest with a mean temperature of 6 °C (Gile et al., 1998). Mean elevation is approximately 1250 m.

Four sites within a vegetation community transition zone between *B. eriopoda* grassland and mesquite shrubland provided landscape replication for each of three grass cover/disturbance combinations: (i) high grass cover and low disturbance; (ii) high grass cover and moderate disturbance; and (iii) low grass cover and high disturbance. The four sites (experimental blocks) were located at least 4 km from each other. An approximately 1 ha plot located in each grass cover/disturbance area served as the experimental unit for each of the three treatments. Distance between plots within a site was minimized to limit the contribution of precipitation and soils to within-block variability and all three treatments were always located less than 2 km from each other. Measurements were completed in three randomly selected sub-plots in each plot, with a minimum of 50 m between individual subplots (Fig. 1). Power analysis determined that this experimental design was suitable for detecting the hypothesized differences in aggregate stability.

2.2. Disturbance and grass cover

All plots were located in pastures that have received light to moderate use (less than 30% utilization) for at least the past ten years (J. Holechek and E. Fredrickson pers. comm.). All plots were only lightly grazed during the study period. Current and historic use patterns within pastures contributed to the variability in disturbance and grass cover on which the grass cover/disturbance levels were based. A water source for cattle served as the epicenter of disturbance at each site (Fig. 1). High grass cover/low disturbance plots at Sites 1 and 2 were located within 25 year-old exclosures to cattle. These grass cover/disturbance level areas were located a minimum of 800 m from water at Sites 3 and 4. The low grass cover/high disturbance plots were located within 20 m of water sources. The high grass cover/moderate disturbance plots were located at intermediate distances in areas that are actively grazed, but have maintained grass canopy cover similar to that of the high grass cover/low disturbance plots.

Because the objective of this experiment was to study long-term differences in soil structure at the landscape scale, we were limited by the number of available grass cover/disturbance combinations. Thus, it is impossible to locate plots that would generate a complete factorial of grass cover/disturbance combinations. We were able to locate plots with similar grass cover and contrasting disturbance, allowing for a test of disturbance effects under similar vegetation. We were not able to hold disturbance constant for similar grass cover, weakening inferences about grass cover. This confounding issue is present, albeit rarely acknowledged, in nearly all grazing studies.

2.3. Soil characterization

The four replicate sites (blocks) were selected to minimize variability in relatively static soil properties that define potential range of variability in soil aggregate stability to management and vegetation. Because soil texture is frequently cited as the most significant static property, we confined the study to a single soil surface texture class: loamy sand. Initial site selection was based on hand texturing. These initial assessments were verified with 100-mm deep samples from each subplot using the

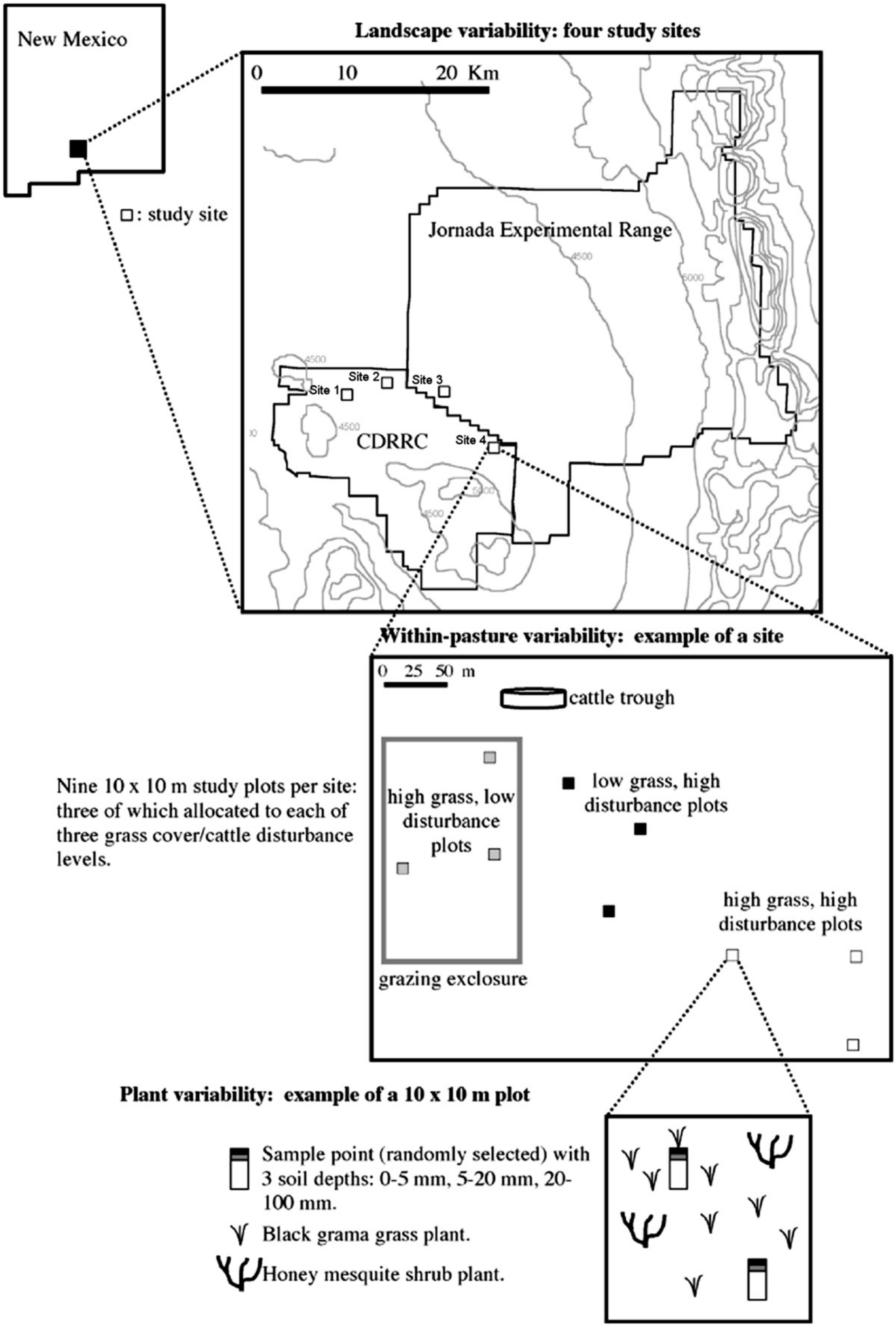

Fig. 1. Site location and plot layout. Landscape and site maps are to scale and spatially referenced, site and plot locations being derived from Global Positioning System (GPS) points plotted in ArcGIS®. Jornada Experimental Range and Chihuahuan Desert Rangeland Research Center (CDRRC) coverages are courtesy of B. Nolan.

hydrometer method (Gee and Bauder, 1986). We relocated three out of the thirty-six study plots to new randomly selected positions when sand (>0.05 mm) or clay (<0.02 mm) content differed by more than 4% from the other subplots within a site. Average sand content for the four sites ranged from 79–84%, while clay content ranged from 6–7% (Table 1). We also verified the soil series in each plot based on the soil texture data, a soil pit, and a minimum of 20 soil depth measurements at randomly selected locations. Based on these analyses (the soil map was incorrect), we concluded that the four sites are covered by a complex of Simona (Loamy, mixed, thermic, shallow Typic Paleorthids) and Harrisburg (Coarse-loamy, mixed, thermic, Typic Paleorthids) soils (Table 1; Bulloch and Neher, 1980). These two soils differ primarily in depth to a petrocalcic horizon. Based on this difference, the Simona is included in the Shallow Sandy ecological site (R042XB015NM), while the Harrisburg is in the Sandy ecological site (R042XB012NM). These two ecological sites have virtually identical vegetation and dynamics and the difference in depth does not directly affect soil structure in the top 100 mm.

2.4. Vegetation characterization

Plant canopy cover was measured in January, 2000 using the point intercept method on each of four randomly located 10-m long transects per subplot. Plant cover was recorded every 20 cm generating a total of 200 points per subplot. Grass cover was calculated as the percentage of those 200 points per subplot. *B. eriopoda* cover measurements confirmed that the high grass/low disturbance (51.9 ±8.5%) and high grass/moderate disturbance plots (48.3 ±6.8%) had similar grass cover, while the low grass/high disturbance plots (9.2 ±6.1%) had significantly lower grass cover than the other plots. Plant cover measurements confirmed that all four sites were in the early stages of mesquite invasion. The highest mesquite cover occurred in the low grass/high disturbance plots where it averaged 7.4±4.8%.

2.5. Soil sampling and analysis

Each subplot included two randomly selected sample points, one each under a *B. eriopoda* plant and in a plant interspace. Soil was removed from the top 0–5-mm depth with a modified masonry trowel, and from 5–20 and 20–100-mm depths with a 5-cm diameter soil corer. Soil collection occurred under grass canopies as close to the center of the plant as possible and at the approximate center of interspaces. Sampling was carried out between January 11th and 12th of 2000.

Soil samples were air-dried and passed through a 2-mm sieve to break down larger soil aggregates and remove plant litter. Between 3.5 and 4.5 g of each soil sample was placed in 0.25-mm sieves and immersed in deionized water for 5 min using a motorized platform that generated 1.5 cm of vertical movement at a rate of one cycle every two s (Kemper and Rosenau, 1986). Stable aggregates remaining on the sieves were dispersed in 5% sodium hexametaphosphate and washed through the sieve to allow both total and sand-free wet aggregate stability (henceforth referred to as laboratory aggregate stability) values to be calculated following Kemper and Rosenau (1986).

Larger aggregate stability was measured with a field stability kit method (Herrick et al., 2001). This method combines the slaking effect of immersion of dry soil in water (Emerson, 1967) with agitation similar to that used in laboratory aggregate stability tests (Kemper and Rosenau, 1986). A small aluminum

Table 1
Study site soil characteristics and vegetation cover percentages

	Surface texture [a]				Mean percentage vegetation cover [b]		
	% Sand	% Silt	% Clay	Soil series	High grass	High grass	Low grass
	(>50 μm)	(2–50 μm)	(<2 μm)	Composition [c]	Low disturbance	Moderate disturbance	High disturbance
Site 1	82.05 (2.43)	11.41 (1.93)	6.53 (0.89)	70% Simona [d]			
Interspace				30% Harrisburg [d]	45.3	53.7	77.0
Black Grama					54.7	44.7	19.3
Mesquite					0.0	1.7	3.7
Site 2	79.33 (2.86)	14.27 (2.67)	6.39 (0.51)	75% Simona			
Interspace				25% Harrisburg	53.0	57.0	96.0
Black Grama					47.0	39.0	3.0
Mesquite					0.0	4.0	1.0
Site 3	80.91 (2.08)	11.82 (1.89)	7.26 (0.74)	25% Simona			
Interspace				75% Harrisburg	35.3	46.0	88.7
Black Grama					64.3	53.3	8.0
Mesquite					0.3	0.7	3.3
Site 4	84.19 (1.79)	9.56 (1.77)	6.25 (0.26)	50% Simona			
Interspace				50% Harrisburg	58.0	43.7	78.7
Black Grama					41.7	56.0	6.3
Mesquite					0.3	0.3	15.0

[a] Mean percentages (with standard errors in parentheses, $n=9$) from the hydrometer test of Gee and Bauder (1986) performed on a composite of nine 100 mm deep random samples taken in each of nine 10×10 m subplots per site.
[b] Determined using two randomly selected line point intercept transects per subplot; 50 20 cm points per transect; 9 subplots per site.
[c] Mean percentages generated from soil probes in each subplot rounded to nearest 5%. Series identified using Bulloch and Neher (1980).
[d] Coarse-loamy, mixed, thermic, shallow Typic Paleorthids.

sampling scoop was used to gently lift 8–10-mm diameter, 3–4-mm thick soil fragments from 0–5, 5–20, and 20–100-mm depths as close to the laboratory aggregate stability sampling points as possible. Each sample was assigned to a stability class from 1 (low) to 6 (high) (Herrick et al., 2001):

Stability class 0: soil too unstable to sample;
Stability class 1: 50% of structural integrity lost within 5 s of insertion in water;
Stability class 2: 50% of structural integrity lost within 5 to 30 s of insertion in water;
Stability class 3: <10% of soil remains on sieve after five dipping cycles;
Stability class 4: 10–25% of soil remains on sieve after five dipping cycles;
Stability class 5: 25–75% of soil remains on sieve after five dipping cycles;
Stability class 6: >75% of soil remains on sieve after five dipping cycles.

2.6. Statistical analysis

ANOVA was used to test for overall fixed effect differences in laboratory aggregate stability between sites, grass cover/disturbance levels, and soil depths. Because stability kit data were non-normally distributed, we used Kruskall–Wallis and Mann–Whitney non-parametric tests to identify effects of site, vegetation type, grass cover/disturbance level, and soil depth on stability kit values.

3. Results

Stability was consistently higher under grass plants compared to within plant interspaces for both laboratory (44.2 vs. 38.4; ANOVA $P<0.01$) and field stability kit values (4.4 vs. 3.3; Kruskall–Wallis $P<0.01$) (Tables 2 and 3). Grass cover/disturbance level significantly affected stability kit values ($P=0.02$). Grass cover/disturbance level did not significantly affect laboratory aggregate stability ($P=0.97$) (Tables 2 and 3; Figs. 2 and 3). Stability kit values were higher with more grass cover than with less grass cover (Figs. 2 and 3). Soil depth had a significant effect on both laboratory aggregate stability and stability kit values (Tables 2 and 3; Fig. 4). Stability kit values were higher at the soil surface ($P<0.01$), but not different between the 5–20-mm and 20–100-mm soil depths, while laboratory aggregate stability was significantly lower at 20–100 mm compared to the top 20 mm ($P=0.01$) (Fig. 4).

Significant variability between study sites was detected with laboratory aggregate stability ($P<0.01$) (Table 2), but not stability kit values ($P=0.54$) (Table 3). The highest stability was recorded at Site 4 and the lowest at Site 1 (Fig. 5). No correlation existed between aggregate stability and percentage clay content ($R=0.04$). The only significant interaction detected by ANOVA was between site and grass cover/disturbance level ($P=0.01$) (Table 2), where stability was lower in less disturbed plots in Sites 1 and 2. Although absolute values of soil stability varied between sites, stability was greater under grass plants than in plant interspaces across the landscape (Fig. 6).

Soil stability in the top 100 mm did not vary greatly between grass cover/disturbance levels in either the interspace or grass microsites (Fig. 7). As grass cover increased, mean laboratory aggregate stability increased in interspaces and decreased under grass, while stability kit values were lower both under grass and in interspaces in the low grass/high disturbance plots (Fig. 7). When considering just the top 5-mm soil depth, interspace stability kit values were much higher in the high grass/low disturbance plots compared to the other two plot types and stability under grass was much lower in the low grass/high disturbance plots (Fig. 8).

Table 2
Summary of analysis of variance of laboratory-measured 0.25 mm aggregate stability

Source	SS	DF	MS	F	P
Plot[a]	4.1	2	2.0	0.0	0.97
Grass vs. interspace	2940.8	1	2940.8	40.7	<0.01
Depth	687.4	2	343.7	4.8	0.01
Site	3806.2	3	1268.7	17.5	<0.01
Site[b] × treatment	1606.8	6	267.8	4.0	0.01
Error	10384.5	144	72.2		
Total	416154.2	216			

Original raw data collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.
[a] Plot conditions: (1) high grass cover, low disturbance; (2) high grass cover, moderate disturbance; and (3) low grass cover, low disturbance.
[b] All other interactions were non-significant at $P=0.05$.

Table 3
Summary of Kruskall–Wallis analysis of field stability kit values

Effect	DF	H	P
Plot[a]	2	9.41	0.01
Grass vs. interspace	2	76.27	<0.01
Depth	2	13.64	<0.01
Site	3	2.15	0.54

Original raw data collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.
[a] Plot conditions: (1) high grass cover, low disturbance; (2) high grass cover, moderate disturbance; and (3) low grass cover, low disturbance.

4. Discussion

4.1. Plant resource islands and soil depth

Regardless of how aggregate stability was measured, results indicate that stability at the 0–100-mm depth was greater under *B. eriopoda* than in plant interspaces. Higher soil stability under vegetation compared to within plant interspaces at the soil surface is to be expected given the influence of individual plants and the concentration of biological activity at the soil surface in sandy-soiled, semi-arid rangelands. At the soil surface under plants, litter inputs and associated microbial activity have been shown to contribute to aggregation and aggregate stability in other ecosystems (Jastrow et al., 1998). In the Chihuahuan Desert, other studies have demonstrated that water, organic

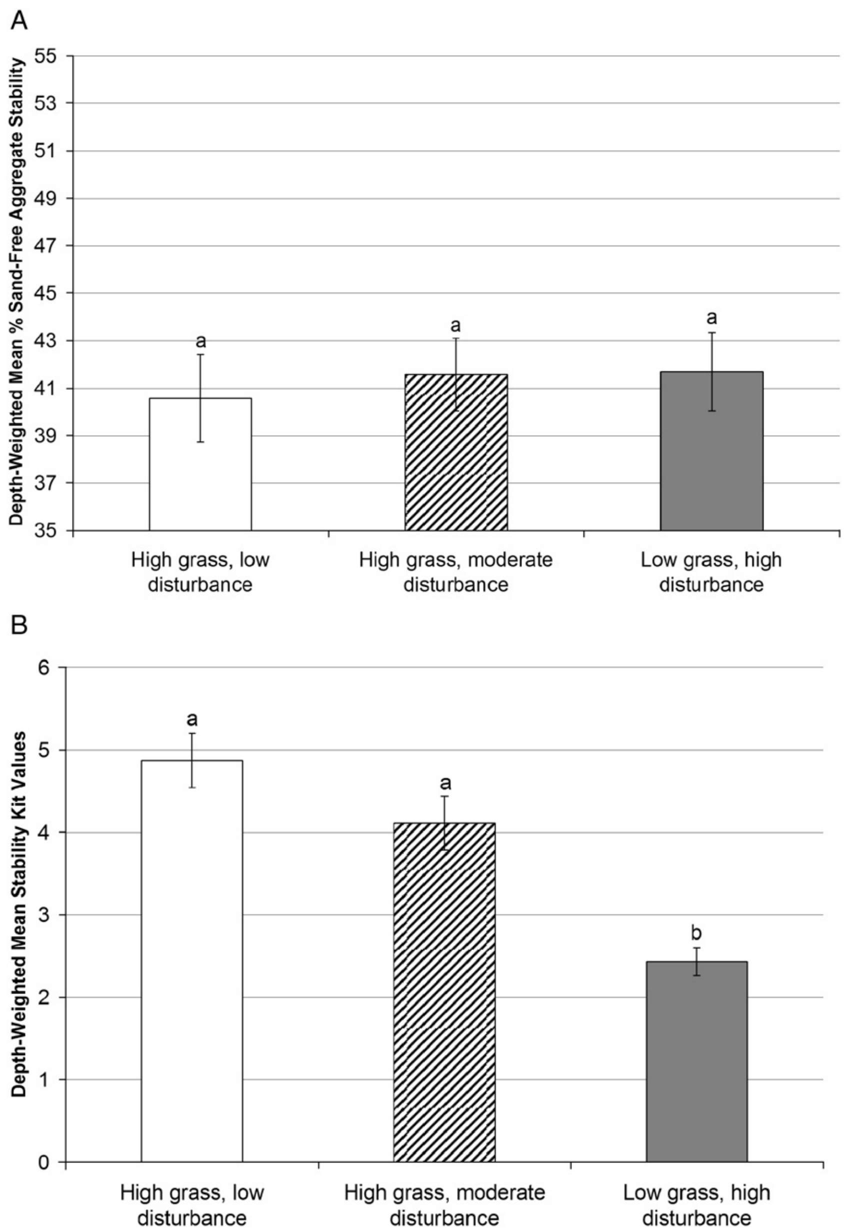

Fig. 2. Effect of grass cover/disturbance level on percentage laboratory sand-free aggregate stability (A) and field stability kit values (B) for the top 10-cm soil depth. Different letters above bars indicate significant differences between grass cover/disturbance levels ($P<0.05$) as detected by ANOVA and Tukey's post-hoc testing (percentage aggregate stability), or Kruskall–Wallis and Mann–Whitney non-parametric testing (stability kit). Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

matter, and mineral nutrients concentrate and wind-blown sediments and litterfall accumulate under plant canopies (Schlesinger et al., 1990, 1996; Cross and Schlesinger, 1999; Gill and Burke, 1999) potentially promoting aggregation and enhancing aggregate stability. Aggregate stability is also greatest when and where temperature and water content least constrain biological activity (Lavee et al., 1996). The physical buffering effects of plant canopies may further promote higher soil stability beneath them.

According to Belnap and Gillette (1998), aggregation at the soil surface in plant interspaces appears to be largely dominated by soil cyanobacteria. Cyanobacteria are visible as dangling threads of soil-on-soil surface fragments. A related study, however, showed that fungal-derived materials ("glomalin") are also present at the soil surface in interspaces, albeit at lower concentrations than under plants (Bird et al., 2002). Soil aggregation at the 5–20 and 20–100-mm depths was likely dominated by plant root-associated inputs such as exudates. The effects of plant roots on aggregation can be variable depending upon carbon inputs, the degree of penetration and mechanical disruption, mycorrhizal action, and root morphology (Denef et al., 2002).

4.2. Grass cover and disturbance

While it is difficult to separate the effects of grass cover and disturbance with our experimental design, some observations

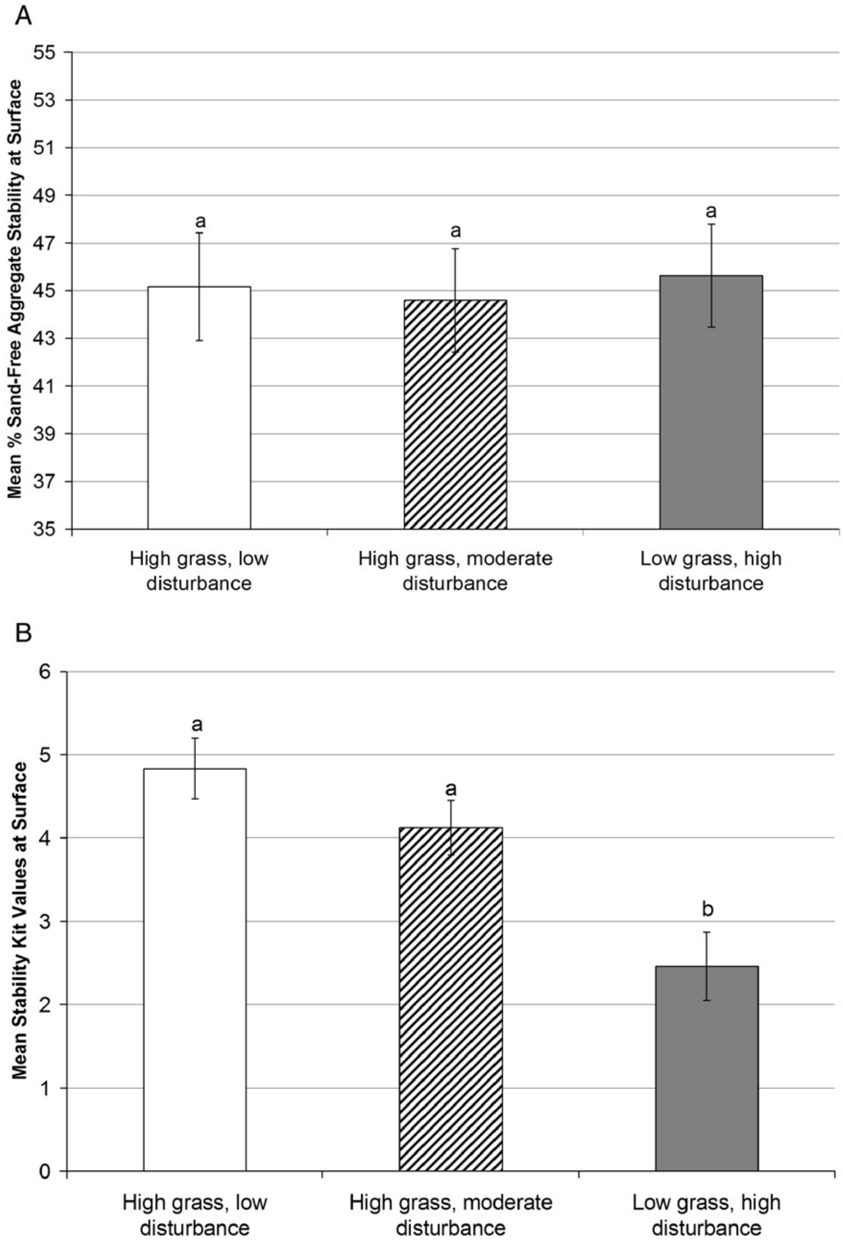

Fig. 3. Effect of grass cover/disturbance level on percentage laboratory sand-free aggregate stability (A) and field stability kit values (B) for the top 5 mm soil depth. Different letters above bars indicate significant differences between grass cover/disturbance levels ($P<0.05$) as detected by ANOVA and Tukey's post-hoc testing (percentage aggregate stability), or Kruskall–Wallis and Mann–Whitney non-parametric testing (stability kit). Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

can be made regarding the relative effects of each on aggregate stability. Interspace stability measured with the field kit was much higher at the soil surface in plots with lower disturbance. Stability under grass plants was lower in the low grass cover treatments. As grass plants are lost and the size of plant interspaces increases, those interspaces become increasingly susceptible to wind and water erosion, and temperature conditions become unfavorable for plant establishment and growth (Schlesinger et al., 1990). As interspace size increases, one would therefore expect that interspace soil surfaces would become denuded and aggregate stability would be lower, but that many of the resources would be concentrated under the remaining grass plants.

Higher stability kit values under grass plants in the high grass cover/low disturbance plots suggest that soil stability is decreasing under vegetation, and not just in interspaces, during vegetation transition. We originally hypothesized that the difference in stability between interspaces and under grass would increase with less grass cover and a higher degree of disturbance. Since stability under grass plants was lower in areas with lower grass cover, this grass versus interspace difference was lower than expected in these areas. Plots with high grass cover and moderate disturbance showed the biggest contrast in stability kit values between interspaces and grass. While higher grass cover is maintained, therefore, stability under individual grass plants remains high even if interspaces

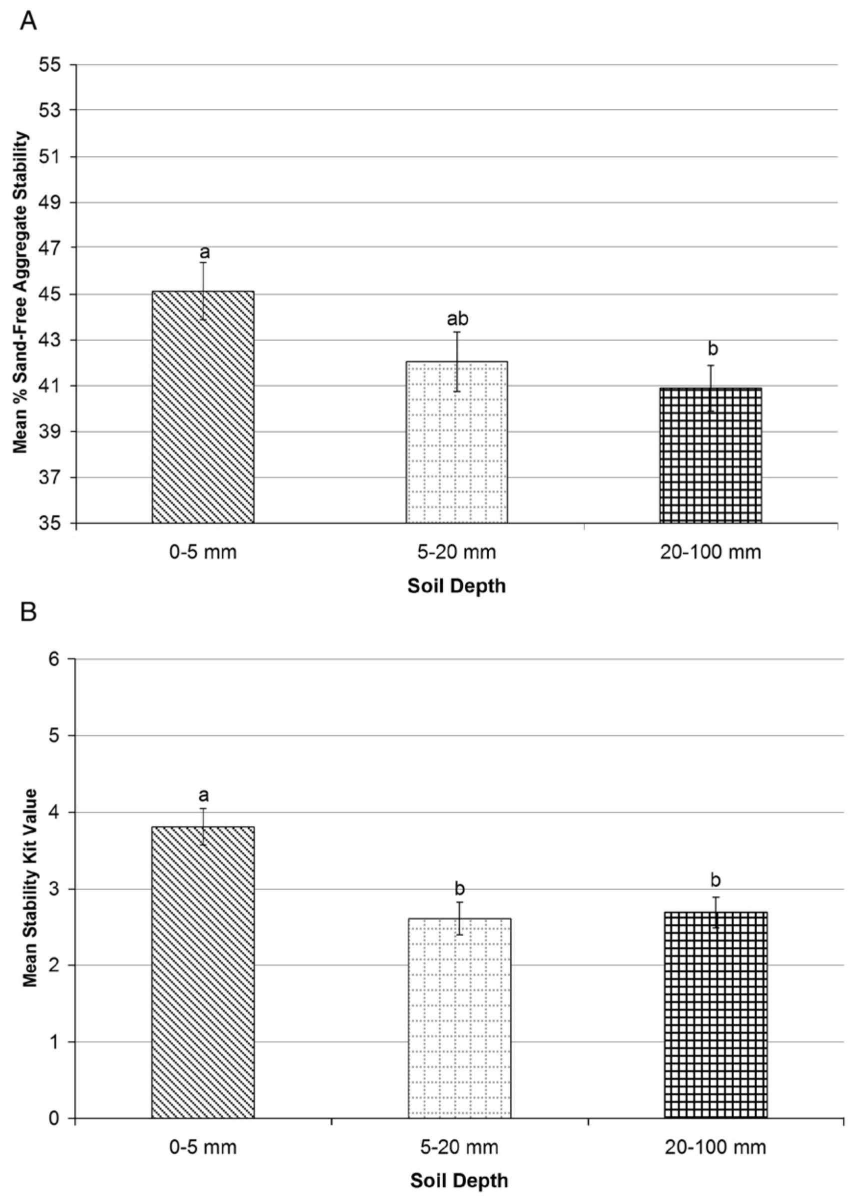

Fig. 4. Effect of soil depth on percentage laboratory sand-free aggregate stability (A) and field stability kit values (B). Different letters above bars indicate significant differences between soil depths ($P<0.05$) as detected by ANOVA and Tukey's post-hoc testing (percentage aggregate stability), or Kruskall–Wallis and Mann–Whitney non-parametric testing (stability kit). Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

are becoming less stable due to more frequent disturbance. As grass cover decreases, the stability of larger aggregates under grass declines along with interspace stability. Two comparable sites may have similar grass cover, but if one is subject to a higher level of disturbance, the risk of further decrease in grass cover may be greater. Stability kit measurements could potentially be used to detect this difference in condition.

Aggregate stability measured by the laboratory test using 0.25 mm sieves was generally more homogeneous across the three grass cover/disturbance treatments than the field test, which used 1.5 mm sieves. We suggest that there are two reasons for this difference between the two methods. The first is that laboratory transport and processing tends to degrade samples (data not shown). Because larger aggregates are more likely to be shattered during transport and processing, samples with a higher proportion of larger aggregates could be disproportionately affected. In future studies, this degradation effect could be measured to determine whether it would tend to reduce treatment differences.

The second proposed explanation for differences between the two methods is related to the nature of the soil degradation process. More labile carbon is responsible for binding small macroaggregates (laboratory test) to form larger macroaggregates (Elliot, 1986; Tisdall and Oades, 1982). Labile carbon is also the first to be lost when organic matter inputs decline (low grass cover) and disturbance increases (high disturbance). Consequently loss of large aggregate stability, reflected in the stability kit measurements is likely to occur before the component smaller aggregates are destabilized. Albeit at a finer scale, this may be the

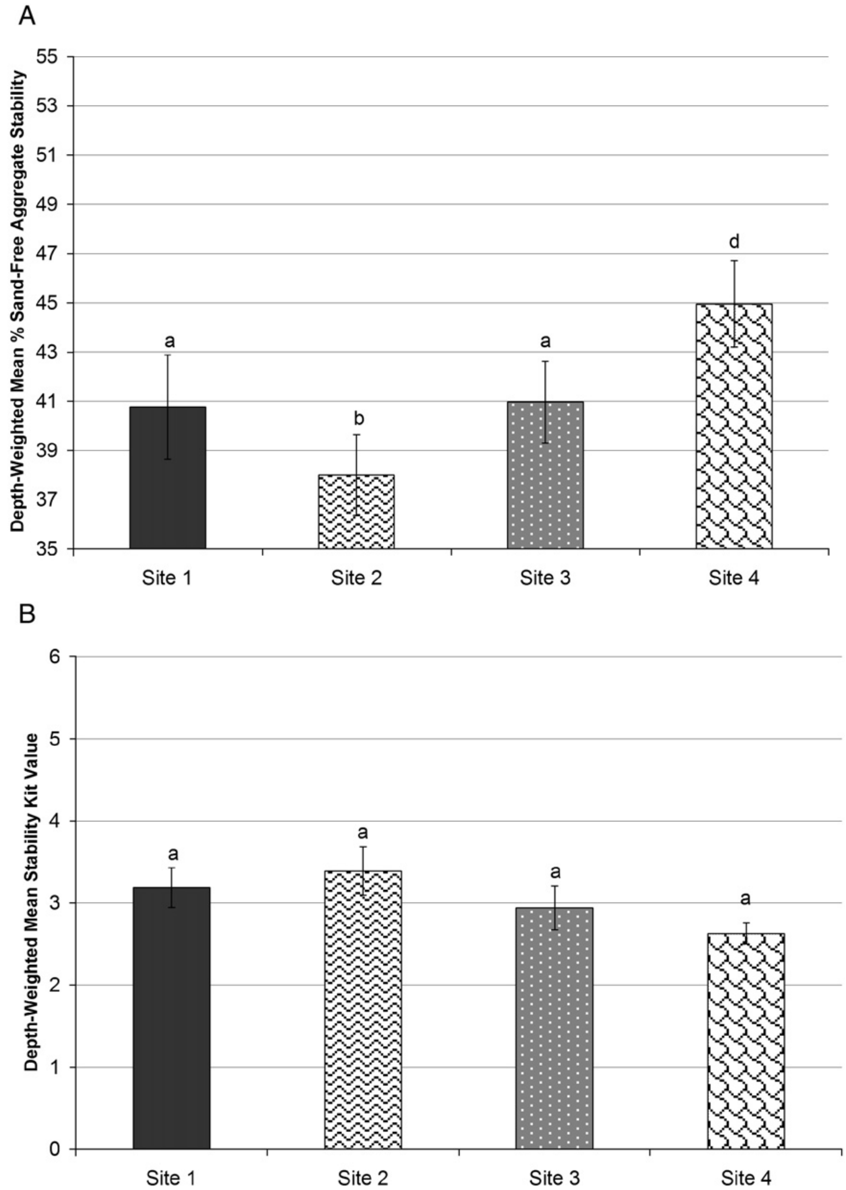

Fig. 5. Landscape variability in percentage laboratory sand-free aggregate stability (A) and field stability kit values (B). Different letters above bars indicate significant differences between study sites ($P<0.05$) as detected by ANOVA and Tukey's post-hoc testing (percentage aggregate stability), or Kruskall–Wallis and Mann–Whitney non-parametric testing (stability kit). Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

same phenomenon that has been observed in agroecosystems where cultivation treatments or the conversion of perennial to annual crops decrease the proportion of water-stable, higher-carbon-containing macroaggregates (>0.25 mm) and increase the proportion of microaggregates (<0.25 mm) (Cambardella and Elliot, 1993; Puget et al., 1995; Chantigny et al., 1997; Monreal and Kodama, 1997). The high sand content (>79% dry weight) of the soils included in this study could result in this process occurring at a coarser scale of aggregation.

4.3. Landscape-scale variability

Semi-arid rangeland landscapes are known to be highly patchy in terms of resource distribution at multiple scales. The spatial patterns observed in our aggregate stability data support this trend. At the patch level, soil depth and presence of vegetation significantly affected stability measured using both methods. The amount of grass cover and degree of disturbance at the within-pasture level consistently influenced stability kit values, particularly at the soil surface, while the response of laboratory stability to these factors was lower and variable. Landscape position only consistently affected laboratory stability, probably due to differences in soil mineralogy that have a greater effect on the stabilization of smaller aggregates.

Variability of soil stability between study sites reinforces the need to replicate at the landscape scale when studying soil processes in rangeland ecosystems. Several factors are known to influence aggregate stability at this scale. Higher soil clay

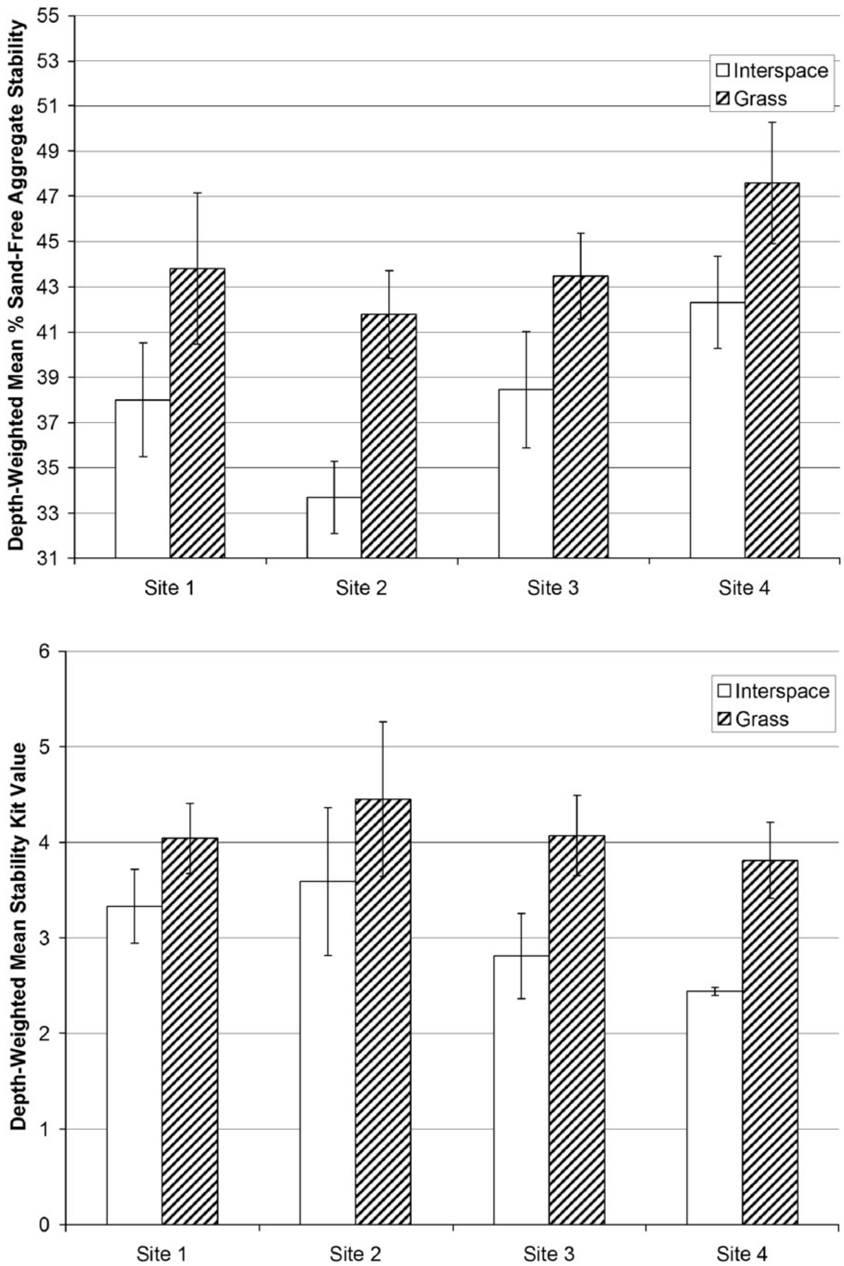

Fig. 6. Depth-weighted mean percentage laboratory aggregate stability and field stability kit values by vegetation type and site. Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

content tends to correlate with higher stability (Kemper and Koch, 1966), but our soil texture data did not explain between-site variation. Other factors potentially affecting landscape variability in soil stability include calcium carbonate and iron oxide content (Kemper and Koch, 1966). No correlation between aggregate stability and calcium carbonate was found at these study sites (Bird et al., 2002). Iron oxides were not measured, but could potentially explain some variability. We are limited to conclude that coarse scale variability of aggregate stability exists in this landscape and needs to be taken into consideration, but further study is required to explain what is driving that heterogeneity.

4.4. Conclusions and implications for management and monitoring

Both the higher stability under grass canopies and the significant grass cover level effect reflect the importance of high grass cover for maintaining soil aggregate stability in desert grasslands. Because higher soil aggregate stability is correlated with lower soil erodibility, this should help limit soil loss and redistribution even during periods when canopy cover is temporarily reduced due to drought or herbivory. The plant-interspace and grass cover/disturbance patterns were relatively consistent across the landscape, despite differences in overall

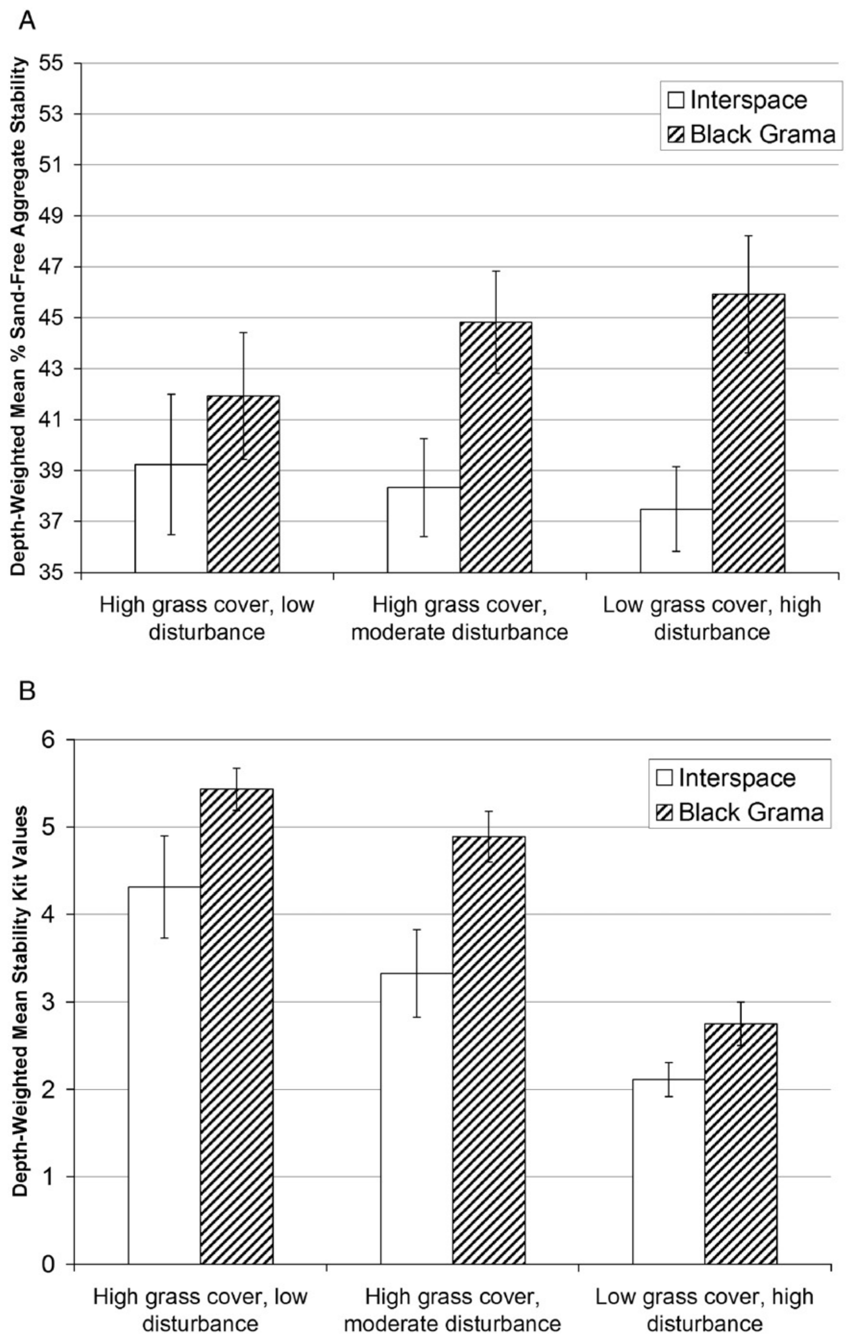

Fig. 7. Depth-weighted mean percentage laboratory aggregate stability (A) and field stability kit values (B) by vegetation type and grass cover/cattle disturbance level. Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

mean values; hence, we suggest that our conclusions regarding the effects of grass cover and disturbance on soil stability can be generally applied to grass–shrubland transitional communities on coarse-textured soils.

Soil aggregate stability is a potential early warning indicator of grassland degradation. Because it depends on the long-term balance between soil organic matter inputs (which tend to increase it) and disturbance (which tends to reduce it), it should integrate changes in plant production, utilization by herbivores and soil surface disturbance. Because soil aggregate stability is related to soil erodibility, it should reflect changes in ecosystem resistance and resilience. This study further suggests that the stability kit method is sensitive to differences in both grass cover and disturbance, while the laboratory test reflected relatively fewer treatment differences in the stability of smaller aggregates. Soil aggregate stability measured using the soil stability kit is therefore a potentially useful early warning indicator of soil surface dynamics that are relevant to ecosystem function. Using the stability kit also has the benefit of eliminating transport and laboratory costs, and minimizing the risk of sample damage during transport. A preliminary review of field kit data from over 5000 locations sampled throughout

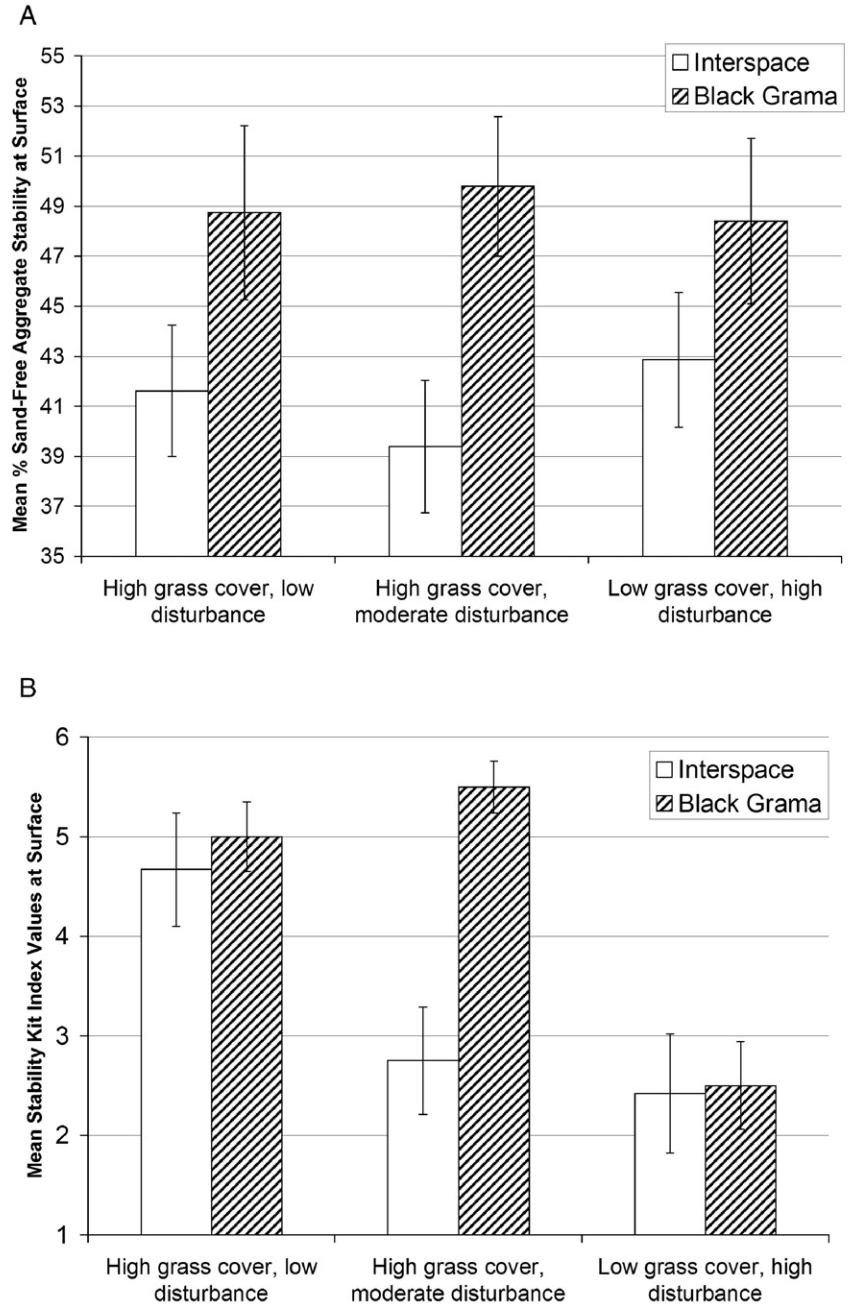

Fig. 8. Mean percentage laboratory aggregate stability and field stability kit (B) values at the soil surface by vegetation type and grass cover/cattle disturbance level. Error bars are standard errors. Raw data were collected in January, 2000 on the USDA-ARS Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center.

the western United States between 2003 and 2006 as part of the USDA National Resource Inventory program for rangelands (Spaeth et al., 2003) indicates that the results of the current study can be broadly applied to a number of other plant communities and soils in arid and semi-arid ecosystems (Spaeth et al., unpublished data).

Further investigation is required to fully explain what drives the variability of soil stability in semi-arid landscapes at different spatial scales. This consideration is of broad applicability considering the high importance of soil stability for ecosystem structure and functioning, and hence for production, biodiversity, and potential soil erosion. The patterns of aggregate stability in plant interspaces versus under plant canopies in relation to grassland degradation processes appear to be complex and warrant further investigation. We found soil stability to be variable across a number of spatial scales. This heterogeneity must be taken into consideration when making management decisions that are likely to be impacted upon and/or influenced by soil stability.

Acknowledgements

We would like to extend thanks to Hanoch Lavee, Sarah Pariente, Joel Brown, and Deb Peters for advice and suggestions during this study. Thanks also go to Justin van Zee, Terese Flores, Barbara Nolan, Adrianne Ford, Laura Burkett, and the staff of the Jornada Experimental Range for lab, field, GIS, and administrative support. This research was made possible by a grant from the International Arid Lands Consortium.

References

Bahre, C.J., Shelton, M.L., 1993. Historic vegetation change, mesquite increases, and climate in southeastern Arizona. J. Biogeogr. 20, 489–504.

Belnap, J., Gillette, D.A., 1998. Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. J. Arid Environ. 39, 133–142.

Bird, S.B., Herrick, J.E., Wander, M.M., Wright, S.E., 2002. Spatial heterogeneity of aggregate stability and soil carbon in a semi-arid rangeland. Environ. Pollut. 116, 445–455.

Buffington, L.C., Herbel, C.H., 1965. Vegetation changes on a semidesert grassland range from 1958 to 1963. Ecol. Monogr. 35, 139–164.

Bulloch Jr., H.E., Neher, R.E., 1980. Soil Survey of Dona Ana County Area, New Mexico. USDA Soil Conservation Service and BLM. NM Agricultural Station, NM.

Cambardella, C.A., Elliot, E.T., 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Biol. Biochem. 57, 1071–1076.

Chantigny, M.H., Angers, D.A., Prevost, D., Vezina, L.-P., Chalifour, F.-P., 1997. Soil aggregation and fungal and bacterial biomass under annual and perennial cropping systems. Soil Sci. Soc. Am. J. 61, 262–267.

Cross, A.F., Schlesinger, W.H., 1999. Plant regulation of soil nutrient distribution in the northern Chihuahuan Desert. Plant Ecol. 145, 11–25.

Denef, K., Six, J., Merckx, R., Paustian, K., 2002. Short-term effects of biological and physical forces on aggregate formation in soils with different clay mineralogy. Plant Soil 246, 185–200.

Elliot, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.

Emerson, W.W., 1967. A classification of soil aggregates based on their coherence in water. Aust. J. Soil Res. 5, 47–57.

Gallardo, A., Schlesinger, W.H., 1992. Carbon and nitrogen limitations of soil microbial biomass in desert ecosystems. Biogeochemistry 18, 1–17.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis, In: Klute, A. (Ed.), Methods of Soil Analysis, Part I, second ed. ASA, Madison, pp. 383–411.

Gibbens, R.P., Beck, R.F., McNeely, R.P., Herbel, C.H., 1992. Recent rates of mesquite establishment in the northern Chihuahuan Desert. J. Range Manag. 45, 585–588.

Gibbens, R.P., McNeely, R.P., Havstad, K.M., Beck, R.F., Nolan, B., 2005. Vegetation changes in the Jornada Basin from 1858 to 1998. J. Arid Environ. 61, 651–658.

Gile, L.H., Gibbens, R.P., Lenz, J.M., 1998. Soil-induced variability in root systems of creosotebush (*Larrea tridentata*) and tarbush (*Flourensia cernua*). J. Arid Environ. 39, 57–78.

Gill, R.A., Burke, I.C., 1999. Ecosystem consequences of plant life form changes at three sites in the semi-arid United States. Oecologia 121, 551–563.

Grover, H.D., Musick, H.B., 1990. Shrubland encroachment in southern New Mexico, U.S.A.: an analysis of desertification processes in the American Southwest. Clim. Change 17, 305–330.

Hastings, J.R., Turner, R.M., 1965. The Changing Mile: An Ecological Study of Vegetation Change with Time in the Lower Mile of an Arid and Semiarid Region. University of Arizona Press, Tucson.

Hennessy, J.T., Gibbens, R.P., Tromble, J.M., Cardenas, M., 1983. Vegetation changes from 1935 to 1980 in mesquite dunelands and former grasslands of southern New Mexico. J. Range Manag. 36, 370–374.

Herrick, J.E., Whitford, W.G., de Soyza, A.G., Van Zee, J.W., Haystad, K.M., Seybold, C.A., Walton, M., 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. Catena 44, 27–35.

Jastrow, J.D., Miller, R.M., Lussenhop, J., 1998. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. Soil Biol. Biochem. 30, 905–916.

Kemper, W.D., Koch, E.J., 1966. Aggregate Stability of Soils from Western United States and Canada: United States Department of Agriculture Technical Bulletin no. 1355. USDA, Washington, D.C.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution, In: Klute, A. (Ed.), Methods of Soil Analysis, Part I, second ed. ASA, Madison, pp. 425–442.

Lavee, H., Sarah, P., Imeson, A.C., 1996. Aggregate stability dynamics as affected by soil temperature and moisture regimes. Geogr. Ann. 78, 73–82.

Monreal, C.M., Kodama, H., 1997. Influence of aggregate architecture and minerals on living habitats and soil organic matter. Can. J. Soil Sci. 77, 367–377.

Pierson, F.B., Mulla, D.J., 1990. Aggregate stability in the Palouse region of Washington: effect of landscape position. Soil Sci. Soc. Am. J. 54, 1407–1412.

Puget, P., Chenu, C., Balesdent, J., 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. Eur. J. Soil Sci. 46, 449–459.

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., Raikes, J.A., Hartley, A.E., Cross, A.F., 1996. On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77, 364–374.

Spaeth, K.E., Pierson, F.B., Herrick, J.E., Shaver, P.L., Pyke, D.A., Pellant, M., Thompson, D., Dayton, D., 2003. New proposed National Resources Inventory protocols on nonfederal rangelands. J. Soil Water Conserv. 53, 18A–23A.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates. J. Soil Sci. 33, 141–163.

van Auken, O.W., 2000. Shrub invasions of North American semi-arid rangelands. Annu. Rev. Ecol. Syst. 31, 197–215.

Virginia, R.A., Jarrell, W.M., Whitford, W.G., Freckman, D.W., 1992. Soil biota and soil properties in the surface rooting zone of mesquite (*Prosopis glandulosa*) in historical and recently desertified Chihuahuan Desert habitats. Biol. Fertil. Soils 14, 90–98.

Wander, M.M., 2004. Soil organic matter fractions and their relevance to soil function. In: Magdoff, F., Weil, R. (Eds.), Soil Organic Matter in Sustainable Agriculture. CRC Press, Boca Raton, pp. 67–102.

York, J.C., Dick-Peddie, W.A., 1969. Vegetation changes in southern New Mexico during the past hundred years. In: Ginnies, W.G., Goldman, B.J. (Eds.), Arid Lands in Perspective. University of Arizona Press, Tucson, pp. 157–166.

Zobeck, T.M., 1991. Soil properties affecting wind erosion. J. Soil Water Conserv. 46, 112–118.