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Runoff and sediment yield relationships with soil aggregate stability for a state-and-transition model in southeastern Arizona

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ABSTRACT

Soil erosion has been identified as the primary abiotic driver of site degradation on many semiarid rangelands. A key indicator of erosion potential that is being increasingly implemented in rangeland evaluations is soil aggregate stability (AS) as measured by a field soil slake test. However, there have been few studies that test if decreasing AS is an indication of increasing soil erosion. A rainfall simulator experiment was conducted in southeastern Arizona to measure runoff and erosion, aggregate stability, and cover attributes on three vegetation states of the state-and-transition model (STM) of the Loamy Upland ecological site (R041XC313AZ). The states included the reference state (RS), a site encroached by mesquite (MN), and a site invaded by *Eragrostis lehmanniana* (ML). Within the context of the STM, runoff was only different between very high and low cover states. Erosion and AS values differentiated among states, particularly between the RS and MN states. Relationships between runoff and erosion with canopy cover and interspace bare soil suggest that certain cover levels exist where runoff and erosion have the potential to increase. The results also indicated that for this ecological site, AS < 4 may represent an increased risk of erosion occurrence.

1. Introduction

Rangelands covering approximately 312 million hectares of the United States serve as an important source of forage for livestock, wildlife habitat, natural beauty, wilderness, and recreational opportunities (National Research Council, 1994). Loss of this vital resource through degradation is an ongoing concern. As rangelands degrade, they can no longer perform their normal functions, vegetation is lost, and runoff and soil loss increases. Loss of soil through erosion can affect plant composition, deplete soil biodiversity, lead to losses of reservoir storage and wildlife habitat, disrupt stream ecology and cause flooding (Pimentel et al., 1995).

The need to inventory, evaluate, and manage this extensive resource has resulted in the United States Department of Agriculture (USDA) Natural Resources Conservation Service's (NRCS) establishment of a landscape classification system called ecological sites. An ecological site is an area of land that differs from other areas in its ability to produce a distinctive kind and amount of vegetation due to its specific physical characteristics (USDI BLM, 2001). Each site is the result of the environmental factors (e.g. soils, relief or topography, climate, and natural disturbances like fire, drought, and herbivory) responsible for its development (Boltz and Peacock, 2002), and may contain several plant communities, known as vegetation states. Although the dominant species in each of the plant communities are commonly used to describe the state, a state is truly defined by soil and vegetation properties and processes (Herrick et al., 2002). The variations due to climatic events and/or management actions that are associated with each ecological site are typically depicted using State-and-Transition Models (STM) (Fig. 1). These models consist of states, transitions, and thresholds. The states, represented by the boxes in Fig. 1, are relatively stable and able to absorb disturbance and stresses to retain their ecological structure, up to a threshold point. The movement from one state to another is referred to as a transition and can be triggered by natural events and/or management actions. These transitions can occur over long or short periods of time and represent a change in site function. Once a threshold is crossed, restoration of the state to a previous or more desirable state can no longer be reached through natural events or a simple change in management. Significant inputs of management resources (e.g.

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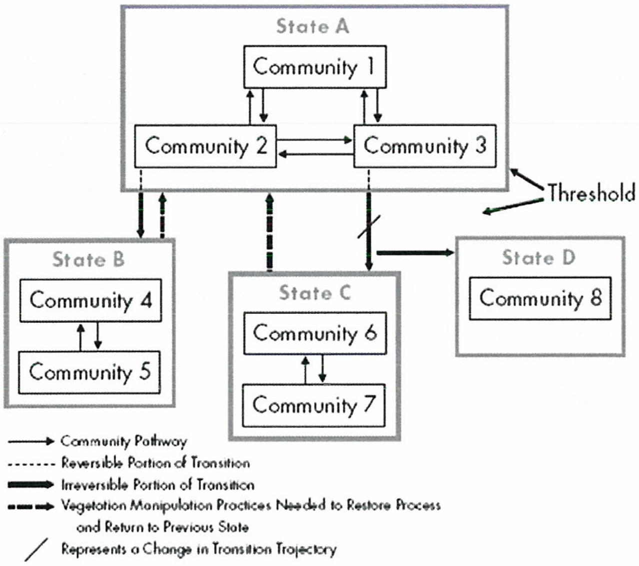

Fig. 1. State-and-transition model diagram for an ecological site (USDI BLM, 2001).

brush management and range planting) and energy are required, otherwise the transition becomes irreversible (USDI BLM, 2001).

STMs are currently used to provide information about past vegetation changes to aid in anticipating and interpreting future change (Thacker et al., 2008; Chartier and Rostagno, 2006; Papanastasis and Chouvardas, 2005; Bestelmeyer et al., 2004) with the goal towards maintaining healthy and sustainable rangelands. The health of a rangeland is defined by "the degree to which the integrity of the soil and the ecological processes are sustained" (National Research Council, 1994). This is determined through ecological site level assessment of three main attributes: soil and site stability, hydrologic function, and biotic integrity. The first two attributes of soil and site stability and hydrologic function respectively represent the capacity of a site to limit redistribution and loss of soil resources by wind and water; and capture, store, and safely release water from rainfall and run-on while maintaining the ability to recover when a reduction in resources occurs. Biotic integrity describes the capacity of the biotic community (plants, animals, and microorganisms above and below the ground) to support ecological processes within the normal range of variability expected for the site, resist a loss in the ability to support these processes, and recover when losses do occur. These attributes are ecosystem components that cannot be directly measured, but can be approximated by a set of observable indicators of the component. There are a total of 17 indicators used to evaluate the three attributes. These indicators may be associated with single, two, or all three attributes (Pyke et al., 2002; Pellant et al., 2005). Utilizing several of these indicators (e.g. the formation of rills, litter dams and terracettes, bare ground patch size, plant community composition, or soil surface stability) to signal the approach of particular transitions, can aid managers by indicating the operation of processes that may be altered to inhibit or encourage these transitions to obtain or maintain the desired rangeland system (Bestelmeyer et al., 2003).

Soil degradation through accelerated erosion is extremely detrimental to rangeland health. This degradation damages not only the soil itself, but also disrupts nutrient cycling, seed germination, water infiltration, seedling development, and other ecological processes that are important components of rangeland ecosystems (National Research Council, 1994). On undisturbed rangelands, the dominant erosion process is primarily raindrop detachment with the detached soil particles being transported over a short distance and deposited on-site (Parsons et al., 2006). After a disturbance such as a prolonged drought, fire, overgrazing, or a combination of factors, the dominant process can change to sheet and/or concentrated flow detachment (generally referred to as "accelerated" erosion) that transports soil off-site (Pierson et al., 2009; Tongway and Ludwig, 1997).

One method of evaluating the soil's resistance to erosion is by measuring soil aggregate stability (AS). Surface AS, which is measured using a soil stability kit, is positively related to a soil's resistance to erosion (Pyke et al., 2002). The soil stability kit uses a slake test to assess the resistance of the soil surface to erosion. The slake test determines the stability of a soil ped by immersing it in water and applying a ranking ranging from one (unstable) to six (stable) based on the percent of soil remaining following immersion and/or wet sieving (Herrick et al., 2001). Although the slake test provides a measure of the likelihood erosion will occur, it does not provide any information regarding the amount of erosion that can or will occur.

Thus far, the slake test has not been widely validated on rangelands with runoff and erosion data. Two studies have measured soil AS using the soil stability kit and runoff and sediment generated using a rainfall simulator (Michaelides et al., 2009; Pierson et al., 2010). These studies focused on species specific responses, rather than a broader ecological site perspective. This study is approached from an ecological site context. Rainfall simulator experiments were conducted on the Reference State (RS) and two alternate states of the Loamy Upland ecological site (R041XC313AZ) (USDA, 2004) in southeastern Arizona. The STM for the Loamy Upland ecological site was developed through quantitative measurements of changes of vegetation composition and cover as a result of climate and management and qualitative observations of the presence or absence of erosional features (ex. rilling, pedestalling, etc). There has not been a systematic test of how hydrological processes are related to the STM or how changes in hydrologic processes are related to changes in AS. It is hypothesized in this paper that as a site moves away from reference state conditions, AS will decrease and runoff and erosion will significantly increase. Further, by pairing rainfall simulator data with vegetation and AS measures, it will be possible to identify the point where hydrological processes change and degradation risk increases as a result of changes in AS levels. Therefore, the objectives of this study were to: 1) quantify changes in runoff, erosion, and AS for vegetative states relative to the RS and 2) test whether changes in runoff and erosion are related to changes in AS.

2. Methods

2.1. Study sites

This study was conducted at seven sites at three locations; the Empire Ranch, the San Rafael Valley, and the Walnut Gulch Experimental Watershed (WGEW) (Table 1). All of the locations lie within Major Land Resource Area (MLRA) 41-3 Southeastern Arizona Basin and Range (USDA, 2006). Elevation ranges from 975 to 1525 m and the average annual precipitation ranges from 304 to 406 mm with 60% of the rainfall occurring between July and September. The study sites represent the reference state (RS) and two alternate states, Mesquite, Natives (MN) and Mesquite, Lehmann (ML), within the Loamy Upland 12–16" precipitation zone ecological site (R041XC313AZ) (USDA, 2004). A simplified depiction of the STM for Loamy Uplands is shown in Fig. 2.

The Empire Ranch, which is operated by Bureau of Land

Table 1
Study site description. RS = Reference State, MN = Mesquite, Natives, ML = Mesquite, Lehmann.

Site	Location (lat., long.)	State	Average slope (m m^{-1})	Simulation year	Management
RS1	31°45′23″N 110°40′45″W	Reference State	0.11	2010	Exclosure since 1987
RS2	31°27′7″N 110°38′1″W		0.08	2010	Fire in 2006, no grazing from 2004 through 2009
RS3	31°41′36″N 110°35′18″W		0.13	2010	Fire in 2002, drought 2003–2008, grazed
MN1	31°45′51″N 110°33′34″W	Mesquite, Native	0.13	2005	Grazed
MN2	31°47′44″N 110°37′7″W		0.04	2006	Grazed
MN3	31°47′44″N 110°37′3″W		0.04	2006	Grazed
ML	31°44′10″N 109°56′36″W	Mesquite, Lehmann	0.11	2010	Drought 2003–2008, Lehmann increase starting in 2006, grazed

Management (BLM), is located within the Las Cienegas National Conservation Area in the Sonoita Valley of southern Arizona and contains five of the seven study sites (RS1, RS3, MN1, MN2, and MN3). These five sites are located on the White House (fine, mixed, thermic, Ustollic Haplargids) soil series (USDA, 1979; USDA, 2003). The vegetation is dominated by *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama), *Bouteloua eriopoda* (Torr.) Torr. (black grama), *Aristida* spp., *Eragrostis intermedia* Hitchc. (plains lovegrass), *Dasyocholoa pulchellus* (Kunth) Willd. ex Rydb. (fluffgrass), and *Chloris virgata* Sw (feather fingergrass). Some *Prosopis* L. (mesquite), *Isocoma tenuisecta* Greene (burroweed), and various forbs were also present. All of the Empire sites were being grazed at the time of rainfall simulation with the exception of the RS1 site which has been excluded from grazing since 1987. RS1 and RS3 are classified as RS. The RS3 site had a wildfire in 2002 that was followed by a prolonged drought from 2003 to 2008. The other three sites are classified as the Mesquite, Native state (Fig. 1). The MN2 and MN3 sites are adjacent to each other. The difference between the two is that the plots on MN2 were selected to have at least one mesquite plant on the plot while the plots on MN3 did not have mesquite.

The RS2 study site is located in the San Rafael Valley approximately 15 km southeast of Patagonia, Arizona. This site is also found on the White House soil series and is dominated by *B. eriopoda*, *E. intermedia*, and *Bothriochloa barbinodis* (Lag.) Herter (cane bluestem). Small amounts of *B. gracilis*, *Bouteloua curtipendula* (Michx.) Torr. (sideoats grama), and various forbs were also present. This site is classified as an RS, is at the upper end of the elevation and precipitation range of MLRA 41-3, and was burned by a wildfire in 2006. It was not grazed three years before and after the fire and was being grazed in 2010 at the time of the rainfall simulation experiment.

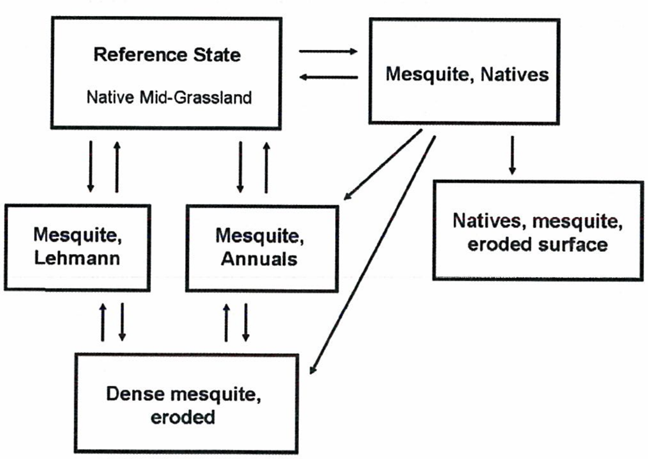

Fig. 2. Simplified depiction of state-and-transition model for MLRA 41-3, Loamy Upland 12–16″ precipitation zone (R041XC313AZ) (USDA, 2004).

The ML study site is in the eastern portion of the USDA Agricultural Research Service (ARS) Southwest Watershed Research Center (SWRC) maintained WGEW in southeastern Arizona. The soils at this site are a complex of Stronghold (coarse-loamy, mixed, thermic Ustollic Calciorthids), Elgin (fine, mixed, thermic, Ustollic Paleargids), and McAllister (fine-loamy, mixed, thermic, Ustollic Haplargids) soils, with Stronghold being the dominant soil (Emmerich and Verdugo, 2008). *Eragrostis lehmanniana* Nees (Lehmann lovegrass), *D. pulchellus*, small amounts of *B. curtipendula*, *B. eriopoda*, and various forbs compose the majority of the site's vegetation. This site was classified as an RS prior to 2006 at which time a change from native grasses to *E. lehmanniana* occurred as a result of a prolonged drought. At the time of rainfall simulation (2010) *E. lehmanniana* was the dominant warm season grass and the area was being grazed.

2.2. Data collection and analysis

Rainfall simulation runs were conducted on the study sites on four 2 × 6.1 m plots using the Walnut Gulch Rainfall Simulator (WGRS). The WGRS is a computer-controlled variable-intensity rainfall simulator with four VeeJet 80100 nozzles attached to an oscillating boom (Paige et al., 2003). The simulation run sequences were as follows. All plots had a dry run at initial soil moisture conditions followed by a wet run 45 min after the cessation of runoff from the dry run. The dry run consisted of a constant intensity of 60 mm h^{-1} for 45 min. The wet run consisted of a sequence of application rates from 60 to 178 mm h^{-1} in increasing increments of intensity. For all the runs with multiple application rates, the rates were changed after runoff had reached steady state for at least 5 min. Runoff depth at the downslope outlet of the plots was measured using an electronic staff gage and a pre-calibrated flume and was converted to a discharge using the flume's stage-discharge relationship. Sediment was measured using grab samples that were dried and weighed to compute sediment concentrations.

Measurements of approximately 400 points of surface and foliar canopy cover were made on each plot on a 15 × 20 cm grid using a green laser pointer and the line-point intercept method (Herrick et al., 2005). Vegetation was classified by species, and surface cover characteristics under and outside canopy cover were identified as soil, litter, plant crown, gravel, or rock. Surface (0–5 mm) soil aggregate stability samples were collected at the 50, 150, 250, 350, 450, and 550 cm marks along three transect lines placed 50 cm apart spanning the length of each rainfall simulator plot for a total of 18 samples per plot. Aggregate stability was measured using the slake test as described by Herrick et al. (2001) and assigned rankings from 1 to 6 based on the stability class (Table 2). Canopy gap was measured as the distance (>10 cm) between plant canopy

Table 2
Stability class ratings from Herrick et al., 2001.

Stability class	Criteria for assignment to stability class
1	50% of structural integrity lost within 5 s of immersion in water
2	50% of structural integrity lost 5-3- seconds after immersion
3	50% of structural integrity lost 30–300 s after immersion, or <10% of soil remains on sieve after five dipping cycles
4	10–20% of soil remains on sieve after five dipping cycles
5	25–75% of soil remains on sieve after five dipping cycles
6	75–100% of soil remains on sieve after five dipping cycles

along the same transects used for the aggregate stability sampling.

All statistical analysis was done using Statistix for Windows (Analytical Software, 2003), SigmaPlot for Windows (Systat Software, 2006), and JMP_{IN} statistical software (SAS Institute, 2008). One-way Analysis of Variance (ANOVA) and Least Significant Difference pairwise comparison tests were performed to assess differences in plot cover attributes, soil aggregate stability class, final infiltration rates, and runoff and sediment yield ratios. The sediment yield ratios were log transformed to normalize the data and back transformed for reporting. The final infiltration rate was computed as the difference in the maximum rainfall rate (~180 mm h^{-1}) and the corresponding steady state runoff rate. The runoff ratio, Q_*, was computed as Q = Q/P where Q = the total runoff (mm) and P = total rainfall (mm). The sediment yield ratio, SY_* (g mm^{-1} m^{-2}), was computed as SY_* = SY/PAS₀ where SY = total sediment yield (g), A = plot area (m^2), and S₀ = plot slope (m m^{-1}). Regression analysis was used to examine relationships among soil aggregate stability class, the runoff and sediment yield ratios, and plot cover attributes. In all statistical tests, $\alpha = 0.05$ was used.

3. Results and discussion

3.1. STM cover attributes

The Loamy Upland Ecological Site Description provides a range of canopy and ground cover attributes for the RS (Table 3). Slope gradient for the site can range from 1 to 15%. The STM only details canopy cover amounts and changes in vegetation composition (mid-grass, short grass, annuals, etc.) and does not provide information on ground cover amounts. The initial classification of the study sites into the states of the STM (Fig. 2 and Table 1) was based on the visual inspection of the vegetation cover and composition of the hillslopes where the plots were installed and verified with the plot canopy and ground cover measurements. In the case of the RS, the basis was the dominance of native perennial grass species and the absence of a significant number of shrub species or mesquite; for the MN state, the basis was the presence of native grasses and greater than 2% mesquite; and for the ML state, the basis was the dominance of *Eragrostis lehmanniana*. Overall, the measured canopy and ground cover attributes for the RS and the canopy cover for the MN and ML states conformed to values in Table 3. In addition, there were significant statistical differences between the RS and MN states in both canopy and ground cover. The measured grass cover for the MN sites (~20%) was significantly lower than the RS (47–64%) and ML (44%) sites (Table 4). Lehmann lovegrass made up over 80% of the total perennial grass at the ML site. The amount of litter was correspondingly lower for the MN sites (≤25%) and significantly greater (>65%) at the RS and ML sites. The total bare soil percentage for the RS and ML sites were very low (6–13%) due to the high amounts of litter cover while the amount of bare soil was significantly greater (42–64%) for the MN sites. The interspace (outside canopy cover) bare soil followed the same trend as total bare soil. The percent of canopy gap greater than 25 cm ranged from ≤1% for the RS sites to 61% for the MN1 site.

3.2. STM aggregate stability

AS was calculated as the average of the AS measured inside and outside vegetation canopy. The AS for the RS sites all were greater than 5 (Table 5) consistent with the value given in the ecological site description (Table 3). The mean values for the MN and ML sites were significantly lower than the RS and ranged from 4.0 to 4.6. With the exception of RS3 and MN2 sites, there was no significant difference between the aggregate stability measured under canopy and in the interspace areas. Because of the high amount of canopy cover for the RS1 and RS2 sites, less than 10% of the samples were taken in the interspace areas. For the MN and ML sites, about 50% were taken in the interspace areas. The coefficient of variation (c.v.) for the AS was lowest for the RS sites (average c.v. = 0.19) and highest for the MN sites (average c.v. = 0.44). In general, the c.v. for the under canopy aggregate stability was lower than the c.v. for the interspace aggregate stability.

3.3. STM hydrologic variables

Runoff began at the lowest rainfall intensity (~60 mm h^{-1}) of the wet run at all of the sites. The flow at the lower rainfall intensities tended to follow discrete flow paths that merged into broad sheet flow at the higher intensities. Ponded water was observed on terracettes upstream from grass plants at all of the RS sites. Both the final infiltration rates and runoff ratios showed a clear distinction between the highest and lowest cover sites and less of a difference for the other sites. The highest infiltration rates were for the two sites with the highest cover, RS1 (119 mm h^{-1}) and RS2

Table 3
Cover attributes (%) and aggregate stability values for the Loamy Upland 12–16 p.z. (R041XC313AZ) State and Transition Model from the Ecological Site Description (USDA, 2004).

State	Canopy		Ground			Aggregate stability
	Grass	Mesquite[a]	Litter	Rock[b]	Bare soil	
RS	25–55	0–5	10–60	5–40	15–25	>5
MN	16–55	2–10	NS[c]	NS	NS	NS
ML	30–50	5–15	NS	NS	NS	NS

[a] >0.6 m high.
[b] 6–76 mm.
[c] Not specified.

Table 4
Mean cover attributes (%) and basal gap (%) by site. Attribute means followed by a different letter are significantly different ($\alpha = 0.05$). Each attribute mean calculated from ($n = 4$) plots.

Site	Grass	Shrub	Total canopy	Litter	Rock	Total bare soil	Interspace bare soil	Canopy Gap >25 cm
RS1	64a	0a	76a	91a	0.3a	6a	1a	0.3a
RS2	60a	0a	68b	90a	2a	7ab	3ab	0.3a
RS3	47b	0a	50c	67b	21b	11ab	8bc	1a
MN1	22c	4b	26f	14d	39c	42c	31d	61b
MN2	20c	11c	35e	25c	10d	63d	40e	22c
MN3	26c	2a	38de	20cd	12d	64d	39e	6ad
ML	44b	1a	45cd	71b	16bd	13b	10c	9d

Table 5
Mean hydrologic and aggregate stability variables by site. Means for hydrologic variables and site, unprotected, and protected aggregate stability followed by a different letter are significantly different ($\alpha = 0.05$). Protected aggregate stability followed by** is significantly different ($\alpha = 0.05$) than the unprotected aggregate stability.

Site	Final infiltration rate mm hr^{-1}	Runoff ratio	Sediment yield ratio g m^{-2} mm^{-1}	Site aggregate stability	Unprotected aggregate stability	Protected aggregate stability
RS1	119a ($n = 4$)	0.23a ($n = 4$)	6.5a ($n = 4$)	5.8a ($n = 72$)	5.7a ($n = 9$)	5.8a ($n = 63$)
RS2	61b ($n = 4$)	0.57b ($n = 4$)	7.2a ($n = 4$)	5.3b ($n = 71$)	5.3a ($n = 8$)	5.3b ($n = 63$)
RS3	17c ($n = 4$)	0.83cd ($n = 4$)	8.6a ($n = 4$)	5.4ab ($n = 72$)	4.7ab ($n = 20$)	5.7ab** ($n = 52$)
MN1	30cd ($n = 4$)	0.75c ($n = 4$)	30.1b ($n = 4$)	4.0d ($n = 70$)	3.8bc ($n = 33$)	4.2c ($n = 37$)
MN2	11c ($n = 4$)	0.92d ($n = 4$)	32.3b ($n = 4$)	4.3cd ($n = 36$)	3.5c ($n = 20$)	5.3ab** ($n = 16$)
MN3	11c ($n = 4$)	0.93d ($n = 4$)	27.1b ($n = 4$)	4.1d ($n = 71$)	3.7bc ($n = 35$)	4.4c ($n = 36$)
ML	43bd ($n = 4$)	0.62b ($n = 4$)	16.1ab ($n = 4$)	4.6c ($n = 72$)	4.6ab ($n = 39$)	4.7c ($n = 33$)

(61 mm h^{-1}) and the lowest rates for the two sites with the lowest cover, MN2 and MN3 (11 mm h^{-1}) (Table 5). However, the third lowest infiltration rate was for the RS3 site while the third highest rate was for the Lehmann dominated ML site. The final infiltration rate at high rainfall intensities should approach the maximum infiltration capacity of an area when all of the area is contributing to runoff (Yu, 1999; Stone et al., 2008). As such, the final infiltration rates listed in Table 5 can be interpreted as the potential maximum infiltration capacity for a given site given that the simulated rainfall rate was extremely high (180 mm h^{-1}). This rate is equivalent to the 10, 50, and >100 year return periods of the 5, 10, and 15 min maximum rainfall intensities respectively for the study areas (National Oceanic and Atmospheric Administration, National Weather Service Precipitation Frequency Data Server http://www.nws.noaa.gov/oh/hdsc/index.html). The runoff ratios varied from 0.23 for the RS1 site to over 0.90 for the MN2 and 3 sites. The runoff ratios for the RS2 and ML sites were similar at about 0.60 while the ratio was greater than 0.75 for RS3 and all of the MN sites.

The sediment yield ratios varied by a factor of five. In contrast with the hydrologic variables, the sediment yield ratio showed a clearer distinction among the states. The lowest ratio was for the RS1 site (6.5 g m^{-2} mm^{-1}) and the highest was for the MN1 site (32.3 g m^{-2} mm^{-1}) (Table 5). All of the low grass cover and high bare soil MN sites had significantly higher ratios than the other sites. Although none of the sites showed signs of concentrated flow erosion, pedestalling, an indication of sheet flow erosion, was observed at the MN2 and MN3 sites.

3.4. Cover relationships

AS and the runoff and sediment yield ratios were significantly correlated with all of the cover attributes (Table 4). The highest correlations were for grass and canopy cover and for total and interspace bare soil. All of these cover attributes were significantly different between the RS and MN states. The relationships of canopy cover and interspace bare soil with the variables AS and runoff and sediment ratios illustrate how these variables are related to differences in the states as reflected by differences in cover (Figs. 3–6). AS increased with increasing canopy cover and decreasing interspace bare soil. AS ranged from about 5 to 6 with decreasing canopy cover until canopy cover was less than 40% (Fig. 3a). Below 40% cover, AS primarily ranged from about 3 to 4.5 and even below 20% cover, the range in stability was high. Most of the stability values greater than 5 were for interspace bare soil less than 15% (Fig. 3b). For interspace bare soil greater than 20%, stability values were highly variable and primarily ranged from 3 to 5.5. The runoff ratio increased with decreasing canopy cover and increased with increasing bare soil. However, the variability in the runoff ratio was high over the range of measured canopy cover (Fig. 4a). The runoff ratio exceeded 0.5 at canopy cover values of 75% and frequently exceeded 0.8 for canopy values less than 50%. The variability of the runoff ratio was higher for interspace bare soil amounts less than 10% and decreased as the bare soil increased

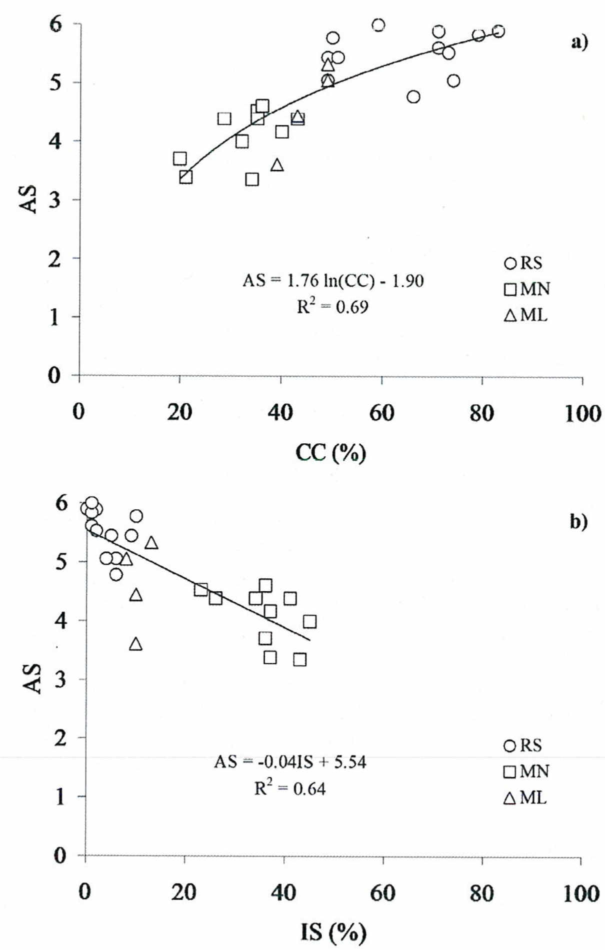

Fig. 3. Relationship of aggregate stability, AS, with a) canopy cover, CC (%), and b) interspace bare soil, IS (%). Both regressions are significant.

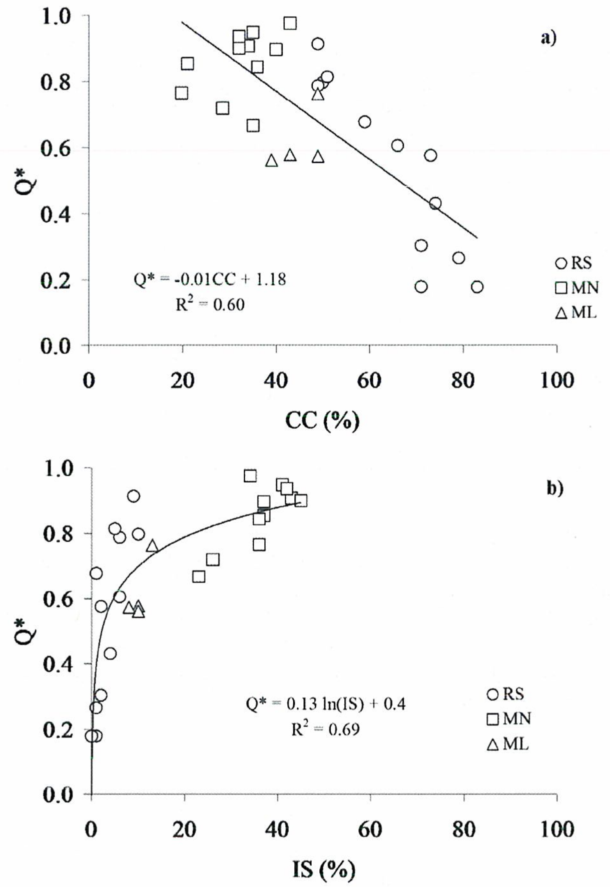

Fig. 4. Relationship of runoff ratio, Q*, with a) canopy cover, CC (%), and b) interspace bare soil, IS (%). Both regressions are significant.

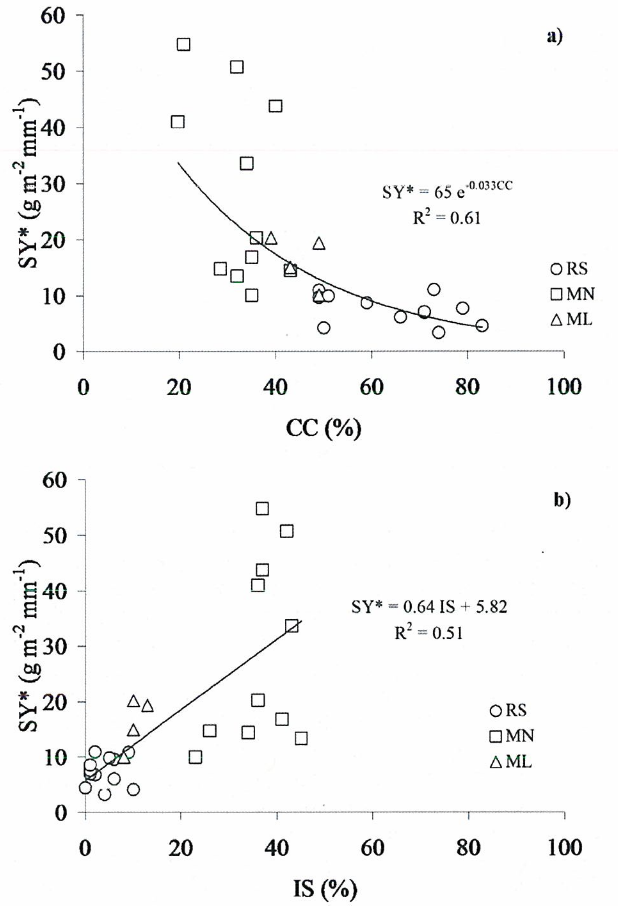

Fig. 5. Relationship of sediment yield ratio, SY* (g m^{-2} mm^{-1}) with a) canopy cover, CC (%), and b) interspace bare soil, IS (%). Both regressions are significant.

(Fig. 4b). The sediment yield ratio followed the same trends as for the runoff ratio, increasing with decreasing canopy cover and increasing bare soil. The variability of the sediment yield ratio increased for canopy percentages less than 40–50% (Fig. 5a) and interspace bare soil amounts greater than 20% (Fig. 5b). In contrast with the runoff ratio, the variability of the sediment yield ratio increased with increasing interspace bare soil amount.

3.5. AS relationship with runoff and sediment yield ratio

Both the runoff and sediment yield ratio decreased with increasing AS. However for the runoff ratio, the trend is a result of the very low ratio (<0.4) and high stability (>5.5) values for the RS1 site (Fig. 6a). When that site was omitted, there was no significant trend. For stability values greater than 5, the runoff ratio varied from 0.4 to 0.95 and for stability values less than 4 the range was 0.6 to close to 100% runoff. The sediment yield ratio was more closely related to AS than the runoff ratio. For stability values greater than 5.4, the sediment yield ranged from 4 to 11 g m^{-2} m^{-1} (Fig. 6b). The range in the sediment yield increased from 11 to 55 g m^{-2} m^{-1} for stability values less than 4.

4. Summary

The soil stability kit developed by Herrick et al. (2001) was designed to provide a rapid, repeatable means of obtaining a measure of soil aggregate stability in the field. A decrease in aggregate stability is a semi-quantitative indicator of potential increases in runoff and erosion. It was not developed to quantify specific rates or amounts but to be used in conjunction with other soil and hydrologic factors to determine the trend in hydrologic function of an ecological site. An ecological site's STM provides information about possible vegetation shifts to aid in anticipating and interpreting future change. In the case of this study, the unique dataset of coincident vegetation, soil aggregate stability, sediment yield, and runoff measurements from sites in multiple vegetation states provided the ability to evaluate erosion potential within the context of the STM for the Loamy Uplands ecological site.

A number of studies (Bird et al., 2007; Beever et al., 2006; Cerdá, 1999; Chartier and Rostagno, 2006; Loch, 2000; Castillo et al., 1997; Barthès and Roose, 2002; Cantón et al., 2009) have shown that there are three somewhat universal outcomes regarding how canopy cover relates to aggregate stability, erosion and runoff: 1) soil aggregate stability increases as canopy cover increases; 2) erosion decreases as canopy cover increases; and 3) runoff decreases as canopy cover increases. The results from our study followed these same relationship patterns. Strong significant negative relationships were found between canopy cover, Q* ($R^2 = 0.60$) and SY* ($R^2 = 0.61$) (Figs. 4a and 5a). Higher canopy cover provides decreased exposure to raindrop impact and detachment, as well as greater soil protection through the increased presence of plant roots and exudates. These protections serve to increase aggregate stability and decrease soil loss. Thus, significant negative relationships were also found between both SY* ($R^2 = 0.60$) and Q* ($R^2 = 0.29$) and mean aggregate stability class (Fig. 6). The trend

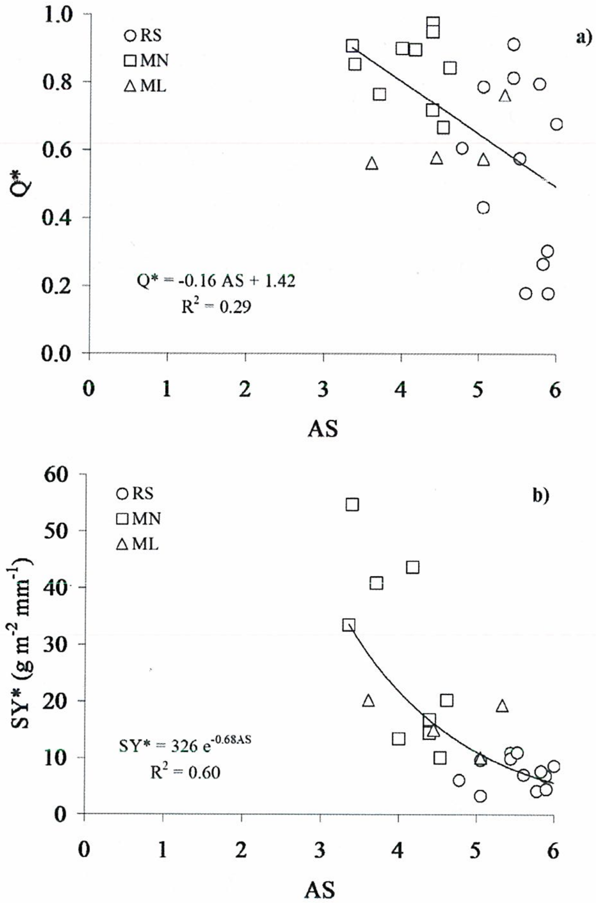

Fig. 6. Relationship of aggregate stability, AS, with a) runoff ratio, Q*, and b) sediment yield ratio, SY* (g m^{-2} mm^{-1}). Both regressions are significant.

shown in Fig. 6a suggests that below a stability value of 3, a site will produce close to 100% runoff for rainfall intensities that exceed the site's infiltration capacity. Significant rilling or sheet flow erosion was not observed at any of the sites which implies that the dominant erosion process was raindrop splash and sheet flow transport. For the states in which flow detachment is the dominant erosion process, the erosion rates would be significantly greater. The data suggest that accelerated erosion would occur for aggregate stability values less than 3 (Fig. 6b).

The sites used in this study represented states that tended to have higher canopy cover and aggregate stability values. The result is likely to be much different for the other states in the state-and-transition model. Future work needs to be conducted to obtain reasonable vegetation and sediment loss points of reference for the lower (1–3) end of the aggregate stability class scale. This could potentially be achieved by examining the three vegetation states not represented by this study. Together with vegetative cover, aggregate stability appears to be an inexpensive, rapid, repeatable means of obtaining a reasonable picture of erosion potential in semiarid rangelands. Though this study only looks at one ecological site type, the previously mentioned universal outcomes regarding how canopy cover relates to aggregate stability, erosion, and runoff were found to exist in several rangeland environments around the world. Given that this study observed similar outcomes, there is reason to believe the findings of this study could be extended to other dryland systems.

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