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Short-term soil moisture response to low-tech erosion control structures in a semiarid rangeland☆

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ABSTRACT

Although rock check dams have been used for centuries to control erosion and support subsistence agriculture on western US rangelands, there is a lack of measured data to quantify their impact on soil moisture distribution. This study was conducted to measure and document soil moisture response to loose rock structures and wire bound rock structures in comparison with untreated control sites during the first rainfall season following construction. A field experiment was conducted on a degraded alluvial fan in southeastern Arizona where erosion control structures were built on three small ephemeral channels. Soil moisture was measured three times per week at depths ranging from 15 to 46 cm at six points on the upstream side of 5 loose rock structures, 5 wire bound structures, and at 5 untreated control sites throughout the 2006 summer monsoon season. Rainfall and runoff during 2006 were above average, and soil moisture was significantly higher through the channel bank soil profiles in proximity to loose rock and wire bound check dams than soil moisture measured at control sites. Erosion control structures are expected to increase local soil moisture in response to water impoundment. These results quantify this response and will be useful in designing rangeland restoration strategies that rely on soil moisture to improve vegetative cover.

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1. Introduction

Rock check dams have been used for centuries in the western United States (US) for a variety of functions including supporting subsistence agriculture (Norton et al., 2002), altering surface water hydrology (Doolittle, 1985), and controlling erosion (Heede, 1976). During the 1930s and 1940s, thousands of check dams were constructed by the Civilian Conservation Corps with the primary objective to control erosion (Gellis et al., 1995). These landscape manipulations were a direct means of mitigating land degradation problems and with very few exceptions did not incorporate any measurement or monitoring to evaluate their impacts on hydrologic or ecologic processes.

During the past decade there has been renewed interest in the southwestern US in using low-tech erosion control structures to meet a variety of watershed improvement objectives. Currently, most of the available guidance both for construction (Heede, 1976; NRCS, 2002) and expectation of impacts specific to the US rangelands dates to the mid 20th century. Although improving water quality by controlling upland erosion, increasing vegetative cover, and improving hydrologic function are commonly cited as justifications for constructing check dams, there is a distinct lack of (and need for) data to quantify their impacts. The results of specific field experiments to quantify the impacts of erosion control structure are needed to inform decisions related to both land management and use of soil and water conservation funds.

Check dams are physical barriers constructed in eroding channels or concentrated flow paths to induce sediment deposition. Where runoff volumes and rates are relatively low, and channel entrenchment or headcut development have not advanced to require engineered structures for stabilization, hand built check dams offer a low-tech approach to improving degraded landscapes. By inducing deposition, the structures can be used effectively for grade stabilization and erosion control. However, in addition to exerting geomorphic control, the same structures serve to alter and improve ecosystem function primarily through their control over the redistribution of water. Moisture is the principal limiting factor to vegetation growth in semi-arid rangelands. Rainfall amounts and spatial distribution are highly variable in semiarid regions (Goodrich et al., 1997), and in southeastern Arizona most runoff is generated during the summer monsoon season, which is also the primary growing season. Check dams are a mechanism for redistributing rainfall by altering runoff. Retaining runoff at specific points on the landscape (check dam sites) and for longer time periods (stored in the soil at the check dam sites) is expected to induce a feedback loop whereby

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increased water resources lead to plant growth and increased vegetative cover results in increased infiltration and soil moisture.

A limited number of studies have been published quantifying the impacts of check dams on sediment retention (Heede, 1976), their role in erosion and geomorphic control (Castillo et al., 2007; Romero-Diaz et al., 2007; Xu et al. 2004), and their effectiveness for gully control (Nyssen et al., 2004). In addition, many anecdotal descriptions of vegetative response have been proffered; however, the authors are not aware of any studies specifically quantifying soil moisture impacts. A field experiment was initiated in 2006 to better understand whether non-engineered erosion control structures (check dams) do alter soil moisture patterns in addition to their primary use for erosion control. We report field observations and soil moisture measurements from a degraded semiarid grassland site following construction of check dams as a restoration technique. The specific objective of this study is to quantify and compare soil moisture affected by loose rock and wire-bound rock check dams.

2. Methods

2.1. Study site

The site for this research is located in a rangeland watershed where prior land use in combination with highly variable climate has resulted in a degraded landscape characterized by an eroded soil surface and exposed soil. However, both onsite native grasses as a seed source and an eroding channel network that has not downcut sufficiently to require engineered structures for controlling further degradation typify conditions where low-tech structures can effectively be used as a restoration tool. In addition, current land management objectives include increasing vegetative cover on the landscape.

The Hay Mountain Watershed above the study site encompasses approximately 44 km^2 of semiarid rangeland in Cochise County, Arizona. The headwaters originate in the Mule Mountains, and the watershed generally conveys runoff that emerges from the mountain canyons across a broad alluvial fan to lower slopes approaching the Whitewater Draw. Historically, the watershed has supported commercial cattle ranching operations, and this land use continues today. The study site is located within a 38 ha (95 ac) pasture on the alluvial fan at an elevation of 1330 m. Although drainage paths across the site vary in response to variable runoff volumes and dynamic flow patterns, the area contributing runoff to the study site is approximately 200 ha (500 ac).

Mean annual temperature in Tombstone, Arizona, which is located 24 km to the northwest, is 77.4 F (22.5 °C), and average annual precipitation for the past 112 years recorded in Tombstone is 35 cm (13.84 in.), with an average of 21 cm (6.21 in.) of precipitation occurring during the monsoon season months of July, August, and September.

In general, the alluvial fan has developed as drainage paths changed course when runoff was diverted in response to aggradation of sediment eroded from the mountains. Although no site specific measurements are available, sediment fluxes across this surface are observed to be high. Large areas of exposed soil currently are subject to erosion during sheet flow, and an extensive network of concentrated flow paths have begun to incise in response to high velocity runoff that has scoured the surface soils to create small channels. One of the management objectives is to improve vegetative cover by redistributing channelized runoff to interfluve regions and maximizing onsite water retention.

The study site is underlain by the Mallet–Hooks soil complex, which is composed of 45% Mallet and similar soils and 35% Hooks and similar soils. The soils consist of a brown sandy loam near the surface (0–5 cm) covering sandy loams grading from fine sandy to gravelly (Mallet) or dark brown silty clay loams (Hooks) (5–45 cm) (USDA, 2003). Although the site is characterized by bare soil, the dominant grass species measured by plant count at the study site were vine mesquite (*Panicum obtusum*) and Lehmann lovegrass (*Eragrostis lehmanniana*). Other species present at the study site include sideoats grama (*Bouteloua curtipendula*), sand dropseed (*Sporobolus cryptandrus*), Arizona cottontop (*Digitaria californica*), cane beardgrass (*Bothriochloa barbinodis*), plains bristlegrass (*Setaria vulpiseta*), burroweed (*Isocoma tenuisecta*), desert broom (*Baccharis sarothroides*), bush muhly (*Muhlenbergia porteri*), silverleaf nightshade (*Solanum elaeagnifolium*), threeawn (*Aristida* sp.), whitethorn acacia (*Acacia constricta*), and mesquite (*Prosopis glandulosa*).

2.2. Experimental design

A detailed topographic survey was conducted prior to the monsoon season. Topographic data were used to develop digital elevation models, determine locations for check dam construction, and characterize pre-runoff channel profile and cross section geometry. Channel profile and cross section geometry were surveyed prior to construction (Table 1).

Three channel reaches were selected at random from among the drainage channels crossing a 38 ha (95 ac) fenced pasture. Within each channel reach, locations for structures were flagged. These locations were determined as described below based on site topography. Treatments consisting of: 1) loose rock erosion control structures, 2) wire bound rock erosion control structures, or 3) untreated control areas (Fig. 1) were assigned at random to flagged locations. Each of the three treatments was replicated 13 times for a total of 39 treated locations.

Backwater extents of ponded runoff were calculated based on channel and structure geometry. A spacing of 30 m between treatment sites to eliminate backwater effects was generally followed, with modification for site specific conditions. For example, an aggradation zone extending for 140 m within Channel 2 was not included when selecting the locations for treatments.

The erosion control structures were built using onsite rock and local labor. The geologic source of most of the rock used for construction was limestone debris shed from the Mule Mountains. Weathered limestone rocks ranging in size from 10 to 30 cm diameter were picked up from the soil surface and carried to the structure sites. In general the rocks were angular with rounded corners resulting from weathered in situ. Loose rock structures were constructed by placing rocks across and perpendicular to the channel to a depth of 2/3 of the channel bank height. Wire bound rock structures were constructed by trenching across the channel and into the banks with a 61 cm (24 in.) backhoe bucket to a depth of approximately 20 cm (8 in.) below the channel bottom. A wire cage was placed in the trench, filled with rock to a depth of approximately 2/3 of the channel depth, and closed with wire ties. Both structure types incorporated a low point near the center and were protected from overfall scour with loose rock placed to armor the channel on the downstream side of the structure.

2.3. Soil moisture measurement

Within the 39 treated locations, a subset of 15 was selected for measuring soil moisture. Five locations from among the 13 replications of each of the 3 treatments were selected at random. Soil moisture was measured from 7/17/2006 through 10/24/2006 using an AquaPro Soil Moisture sensor (http://www.aquapro-sensors.com/). The AquaPro is

Table 1
Summary of characteristics for each of three channels treated with erosion control structures.

	Channel 1	Channel 2[a]	Channel 3
Reach length	410 m	600 m	340 m
Reach average slope	0.99%	1.13%	0.85%
Ave. cross section width/depth	5 m/0.7 m	3.8 m/0.3 m	4.6 m/0.6 m

[a] Channel 2 contains a zone of aggradation that was not treated.

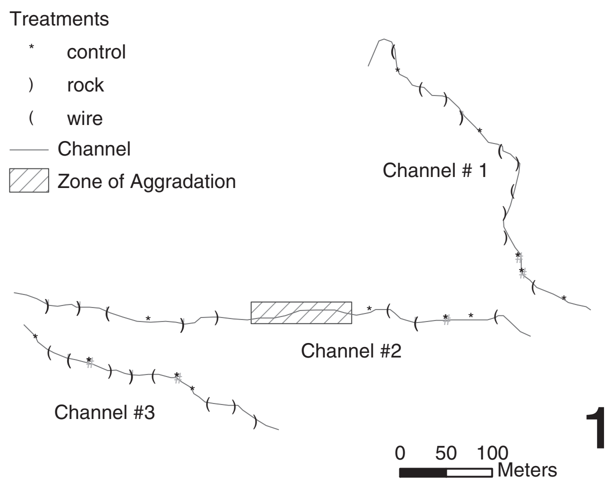

Fig. 1. Schematic showing erosion control treatment layout. Shaded shapes indicate treatments where soil moisture was measured.

a capacitance (radio-frequency) sensor that returns soil moisture measurements on a percent scale between 0 (air dried soil) and 100 (in water or saturated soil). Relative AquaPro measurements were converted to volumetric soil moisture content based on a field calibration and an average measured bulk density of 1.21 g/cm^3.

A total of 90 polycarbonate tubes were installed. Six tubes were installed at each of the 15 soil moisture measurement sites to a depth of approximately 0.75 m on a 2 m horizontal grid on the upstream side of each structure. At each site, two tubes were installed in the channel centerline and two tubes were installed on the left and right channel banks. Measurements were taken three times per week at four depths (15.2 cm, 22.9, 30.5, 45.7 corresponding to 6, 9, 12, and 18 in.) within each of the 90 tubes. Maintenance during the experiment was limited to removing organic debris from around the polycarbonate tubes. In addition to soil moisture, rainfall was monitored with four tipping bucket rain gages distributed with elevation through the watershed.

2.4. Analysis methods

The impact of erosion control structures on soil moisture was analyzed using analysis of variance to test the null hypothesis that the soil moisture measured at each of 4 depths through the bank soil profile was equal among the treatments.

For a given measurement day, the four soil moisture measurements taken on the banks at each of the 15 soil moisture measurement sites were averaged to produce a single average soil moisture value at each of 4 depths for each treated site. The same procedure was followed to produce a single soil moisture value for each measurement day at each of 4 depths in the channel centerline.

The SAS (SAS, 2005) ANOVA mixed models procedure was run with channel as a random effect to evaluate the fixed effects of structure type on soil moisture. The mixed models procedure was necessary to accommodate potential spatial correlations among the data. In addition to treatment comparisons, soil moisture measurements were used to produce plots of moisture distribution with time through the 2006 monsoon season.

3. Results and discussion

3.1. General hydrology and response of structures

The summer "monsoon" season began with a rainfall event on 6/21/2006 and ended on 10/24/2006. During this period, there were 41 days with precipitation totaling 27.6 cm (10.8 in.).

The 2006 monsoon season was relatively wet. A total of 21.5 cm (8.5 in.) of precipitation was recorded during the study period, which began on 7/17/2006. This total stands in sharp contrast to both the 8.9 cm (3.5 in.) average recorded during the three years prior, and the 35.6 cm (14 in.) long term average annual precipitation recorded at the National Weather Service gage in nearby Tombstone, Arizona. In addition to the above average precipitation, the study site also experienced above average runoff during the measurement period. There were 11 runoff events in the study area during this period. Runoff was observed onsite as broad sheet flow over substantial portions of the 38 ha (95 ac) pasture with concentrated flow in the existing channels.

As expected, the general effect of the structures was to pond water and to induce sediment deposition. Both loose rock and wire-bound rock structures modified the channel bed gradient, primarily through deposition. During onsite field visits, some loose rocks were observed to shift during runoff, and although no structures failed completely, there were two loose rock structures that experienced some scour around the ends. In addition, two loose rock structures were completely buried with deposited sediment such that there was no difference in channel bed gradient relative to the structure location. In contrast, the remaining structures filled to capacity creating an abrupt change in channel gradient associated with deposited sediment.

Observations of physical response of the two structure types to runoff provide information of their effectiveness and role as restoration tools. In contrast to the wire-bound rocks, the loose rock structures were observed to dynamically adjust in response to flows. Minor adjustments in the positions of individual rocks are to be expected, and in the event that hydrostatic forces exceed the resistance of a loose rock dam, the structure can fail gracefully as rocks are redistributed by the flowing water. Rocks bound in wire can not respond in this manner and excess force may exacerbate downcutting as excess energy is dissipated through lateral erosion. Because they are designed to adjust in response to flows, loose rock structures are expected to be a more temporary feature on the landscape. However, wire plays a crucial role in the integrity of the structure and this is especially important if skill and care are not applied when constructing loose rock structures. In addition, although subject to deterioration through oxidation, wire will remain on the landscape for a long time. Because both types of check dams are subject to failure, maintenance is crucial to their successful use in restoration projects.

3.2. Soil moisture response

The temporal sequence of soil moisture averaged over all measurement sites for each treatment at each of four depths through the channel banks is shown in Fig. 2. Greater differences in measured soil moisture between the control sites and the sites with structures are seen early in the season (prior to mid August) and differences increase with depth during this time. As the monsoon season progressed, differences in soil moisture were smaller. This trend is likely a consequence of complex infiltration dynamics and moisture distribution within the soil profile. Soil moisture measurements and depth were used to generate interpolated contour plots of the temporal patterns of soil moisture through the monsoon season (Fig. 3).

For the entire measurement period (7/17/2006–10/24/2006) the SAS mixed model procedure indicated that soil moisture at 15 cm measured at the control sites differed from soil moisture measured at both the loose rock ($t = -4.43$, $p = <0.0001$, $alpha = 0.05$) and wire bound rock sites ($t = -4.25$, $p = <0.0001$, $alpha = 0.05$). There were no significant differences between measurements made at the loose rock and wire bound rock sites (Tables 2 and 3).

This pattern is repeated at 23, 30, and 46 cm depths (Table 3) where there were statistically significant differences in soil moisture associated both loose rock and wire-bound rock structures in comparison with the control sites at each of the four measurement depths. Although not statistically significant, there is generally a greater difference in the

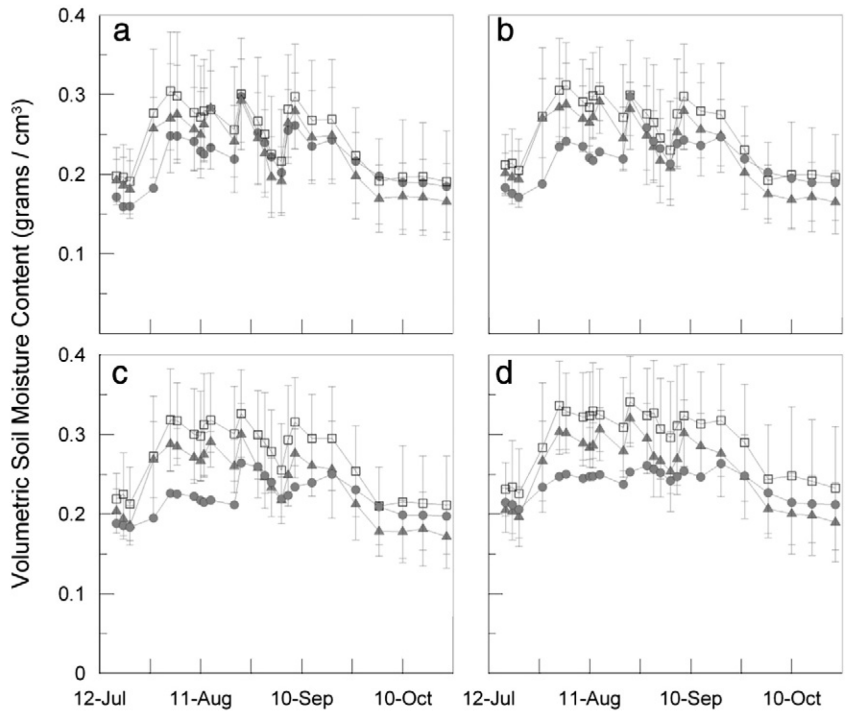

Fig. 2. Volumetric soil moisture vs. time at four measurement depths: a = 15 cm (6 in.), b = 23 cm (9 in.), c = 31 cm (12 in.), d = 46 cm (18 in.). Symbols: square = wire bound rock structure, triangle = loose rock structure, circle = control (no structure).

mean estimates at the deepest measurement depths between the loose rock structure sites and the wire bound rock structure sites.

The plots of average soil moisture for each treatment type show the largest differences in soil moisture from 7/17/2006 through 8/24/2006 (Fig. 2). A total of 19.0 cm of precipitation (of the 27.6 cm season total) and 8 or the 11 runoff events occurred during this period. From our observation, in many cases the wire acted to trap organic debris which contributed to ponding effectiveness. Because of the relatively sparse vegetation at the study site this result was not anticipated, however, the trapped organic material may play an important role in improving the ecological function of the treated site (Comiti et al., 2009).

As expected, backfilling at each structure site was rapid and most structures were filled to capacity after the first three flows. In contrast to the soil moisture measurement tubes installed on the channel banks, those installed in the channel were subject to reworking and hydraulic sorting of bed sediment. Recognizing that capacitance sensors may be affected by texture (Polyakov et al., 2005) and that the deposited sediment is often variable in profile bulk density and texture in response to hydraulic sorting (Conesa-García and García-Lorenzo, 2008), measurements taken in the channel bed offered inconclusive evidence that treated sites are different from the control sites and were not analyzed further.

4. Conclusions

The recent proliferation of proposed and funded projects throughout the western US that incorporate check dams for improving water quality by reducing sediment loads led this research to improve our scientific understanding of the broader process impacts. As mechanisms for physical restoration of an eroding land surface, both loose rock and wire-bound rock structures were observed to be effective in trapping sediment and modifying channel grade. However, degraded semiarid landscapes often require both physical and ecological restoration. Soil moisture is a crucial component of semiarid ecosystems (Noy-Meir, 1973). Although complex semiarid ecosystem pattern dynamics in response to variations in precipitation pulsing and soil moisture distribution is increasingly understood (D'Odorico et al., 2007; Hamerlynck et al., 2011; Moran et al. 2010), there has been much less attention paid to using this knowledge to improve applied techniques for restoring degraded regions. In general research to understand the impacts of check dams has focused on the geomorphic control of the sediment (Castillo et al., 2007; Lenzi and Comiti, 2003; Xu, et al. 2004). This study adds to the understanding of the potential for altering soil moisture to affect the structure and composition of vegetation in a water limited ecosystem.

This research has shown that check dams have a quantifiable impact on soil moisture distribution and that increases in soil moisture can be induced proximal to both loose rock and wire-bound erosion control structures. Soil moisture increases were the result of increased residence time of ponded water. Both loose rock and wire-bound rock structures were effective in increasing soil moisture. This is an important result suggesting that given similar soil moisture impacts, the decision to construct one type or the other should take into account factors such as cost, labor requirements, skill level of the constructors, and physical persistence of structures on the landscape.

The results of this study represent a short time period (one monsoon season) and a particular alluvial fan landscape and its underlying soils and overlying vegetative cover. Across the western US rangelands, soils and landscapes are highly heterogeneous. Even within a given landscape, soils and vegetation may exist in a mosaic pattern and surface hydrology can be spatially complex. Although this research has shown a statistically significant increase in soil moisture associated with check dams, the ecological significance of the increase will depend on a variety of site and species specific characteristics. Interpreting the restoration impacts of using check dams requires information and an understanding of the relation of relative soil moisture increases to species specific soil moisture, temperature, and humidity requirements for germination, establishment, and growth.

In summary, low-tech erosion control structures effectively alter soil moisture distribution. Additional research is needed to quantify the effects of increased soil moisture on species specific germination, establishment and growth to realize their full potential for restoring vegetative cover on degraded sites. Ongoing research is needed to

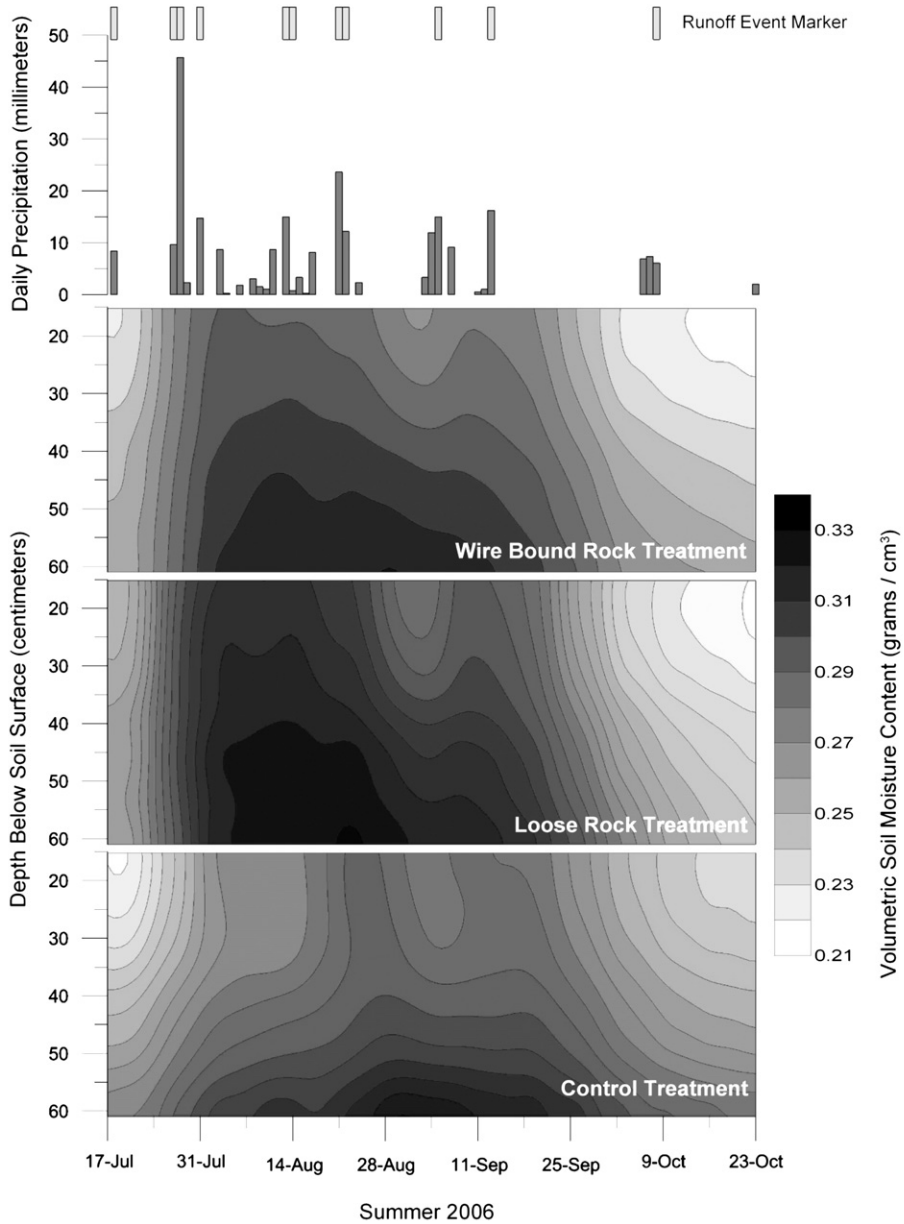

Fig. 3. Interpolated volumetric soil moisture with depth and 2006 monsoon precipitation with runoff events dates indicated.

Table 2

Summary of mean estimates of volumetric soil moisture among treatments at 4 depths for A) the entire period of measurement and B) the initial monsoon period.

All dates 7/17–10/24/06			Dates 7/17–8/14/06		
Treatment	Mean volumetric soil moisture	Standard deviation	Treatment	Mean volumetric soil moisture	Standard deviation
15 cm			15 cm		
Control	0.220	0.062	Control	0.210	0.059
Loose	0.229	0.060	Loose	0.241	0.058
Wire	0.248	0.073	Wire	0.258	0.072
23 cm			23 cm		
Control	0.221	0.062	Control	0.210	0.054
Loose	0.235	0.056	Loose	0.253	0.051
Wire	0.257	0.067	Wire	0.270	0.064
31 cm			31 cm		
Control	0.220	0.057	Control	0.208	0.046
Loose	0.240	0.052	Loose	0.253	0.048
Wire	0.274	0.066	Wire	0.279	0.066
46 cm			46 cm		
Control	0.239	0.044	Control	0.235	0.047
Loose	0.260	0.055	Loose	0.264	0.052
Wire	0.295	0.070	Wire	0.294	0.068

Table 3
Summary of statistically significant differences[a] among treatments indicated in bold typeface for A) the entire period of measurement and B) the initial monsoon period.

Depth (cm)	Treatment	Control	Loose
A. Soil moisture measurements 7/17/06–10/24/06			
15	Control		
	Loose	**−6.33**, **−4.43**, <**0.0001**	
	Wire	**−5.86**, **−4.25**, <**0.0001**	0.47, 0.34, 0.7317
23	Control		
	Loose	**−7.09**, **−4.86**, <**0.0001**	
	Wire	**−7.86**, **−5.59**, <**0.0001**	−0.77, −0.55, 0.5833
30	Control		
	Loose	**−7.71**, **−5.73**, <**0.0001**	
	Wire	**−10.89**, **−8.39**, <**0.0001**	−3.17, −2.45, 0.0147
46	Control		
	Loose	**−6.89**, **−5.49**, <**0.0001**	
	Wire	**−10.03**, **−8.29**, <**0.0001**	**−3.14, −2.60, 0.0097**
B. Soil moisture measurements 7/17/06–8/14/2006			
15	Control		
	Loose	**−9.21**, **−3.96**, **0.0001**	
	Wire	**−9.21**, **−4.11**, <**0.0001**	0.004, 0, 0.9984
23	Control		
	Loose	**−10.40**, **−4.75**, <**0.0001**	
	Wire	**−11.47**, **−5.45**, <**0.0001**	−1.07, −0.50, 0.6148
30	Control		
	Loose	**−10.38**, **−5.14**, <**0.0001**	
	Wire	**−13.21**, **−6.80**, <**0.0001**	−2.83, −1.45, 0.1505
46	Control		
	Loose	**−6.63**, **−3.28**, **0.0013**	
	Wire	**−9.94**, **−5.11**, <**0.0001**	−3.31, −1.69, 0.0931

[a] Differences of least squares means (estimated difference, t value, Pr>t, alpha = 0.05).

quantify the long-term persistence of the impacts of low-tech erosion control structures on soil moisture, sediment, and vegetation dynamics.

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