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Quantifying decadal-scale erosion rates and their short-term variability on ecological sites in a semi-arid environment

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A B S T R A C T

Soil erosion rates on six semi-arid loamy upland rangeland sites located in southeastern Arizona were measured using a rainfall simulator and ^{137}Cs fallout methods. Site characteristics that have the greatest effects on soil erosion and runoff were identified. Long term (50 years) soil erosion rates as estimated using ^{137}Cs method varied between 5.1 and 11.0 Mg ha^{-1} y^{-1} and showed significant differences between Historic Climax Plant Community and Mesquite/Native states within the State and Transition Model. Erosion rates under simulated rainfall were measured between 0.9 and 17.2 g m^{-2} min^{-1} at 175 mm h^{-1} precipitation across all sites and varied as much as 8-fold at the same location, depending on the time of the simulation. Temporal variability of erosion rates within a site was in some cases much greater than inter-site differences. This variability was attributed to natural or management driven changes in plant community and soil characteristics. Bare soil area, an aggregate indicator for all types of cover combined, was the main controlling factor of erosion process across ecological sites. For meaningful interpretation rainfall simulation, results must be placed in the context of the range of possible vegetation and surface conditions within a given ecological site.

1. Introduction

Soil erosion affects the functioning of rangeland plant communities and has in many areas negatively impacted their ability to produce forage for stock and wildlife. The lack of quantitative data on soil erosion rates at the hillslope scale in arid rangelands hinders the development of erosion prediction tools and conservation efforts in the western United States. In addition, these data are necessary to better understand the effects of erosion on rangeland sustainability in the context of ecological sites within the State and Transition Models (STM).

An ecological site is a landscape unit defined by a unique set of physical characteristics including climate, soil, and topography, which supports a range of possible plant communities different from those found on other landscape units (USDA, 2003; Briske et al., 2005). Ecological sites are convenient conceptual entities for implementing management decisions. The State and Transition Model (STM) is a conceptual model describing the characteristics and temporal dynamics of ecological sites in response to disturbances (Westoby et al., 1989; Stringham et al., 2003). An ecological site within the STM can either remain stable when disturbances are minor, or transition into other states when disturbances are significant.

There are structural and functional thresholds that exist between different states within the STM (Briske et al., 2005). Functional thresholds defined by ecohydrological processes have been studied using rainfall simulation (Chartier and Rostagno, 2006; Petersen and Stringham, 2008) but have not been quantified. It is unknown whether these thresholds necessarily exist between all states of an STM (Stringham et al., 2003) or whether erosion rates necessarily differ between different states. Once the threshold is exceeded, an ecological site may undergo a transition to another state. Soil erosion is recognized as one of the key factors of this process; however the extent of its influence in comparison with other factors is not well understood. Erosion has the potential to remove organic matter and other nutrients from the soil, and also reduces its water holding capacity and fertility. Experimental data are needed to quantify erosion thresholds and provide understanding of the role of soil erosion within STM dynamics.

Rainfall plot experiments on rangelands have shown that state transition within ecological sites may be triggered by wildfire, drought, or invasive species (Chartier and Rostagno, 2006; Petersen and Stringham, 2008; Chartier et al., 2011). In addition, these disturbances may lead to changes in basic erosion mechanisms. Namely, raindrop detachment and short transport distance on undisturbed rangelands (Parsons et al., 2006) is succeeded as a dominant process by sheet and concentrated flow detachment on degraded sites (Petersen and Stringham, 2008).

It has been shown that in an arid or semi-arid grassland community a rapid increase in erosion rates due to decline in canopy and litter cover may occur during transition from native to invasive species (Polyakov et al., 2010b) after which the equilibrium is restored. The use of soil tracers such as ^{137}Cs may provide information on whether these short transition periods make significant contribution to overall soil loss at

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longer temporal (~60 years) scales. ^{137}Cs is an artificial radionuclide with half-life of 30.2 years introduced into the environment through fallout of atmospheric atomic weapons tests from the mid-1950s through 1963 (Walling and He, 2000). The technique is based on the property of ^{137}Cs to strongly and irreversibly adsorb onto clay particles in the upper soil layer. As a result, soil redistribution due to erosion can be estimated from a ^{137}Cs budget relative to a reference inventory using a variety of conversion models (Walling and He, 1999). Erosion and deposition rates calculated by this method represent time-integrated average rates since the peak of ^{137}Cs fallout in 1963. The ^{137}Cs activity in soil has been widely used to study soil redistribution (Ritchie and McHenry, 1990) including that on semiarid croplands where vegetation was one of the main controlling factor of soil erosion (Sadiki et al., 2007) and on arid rangelands (Chappell, 1999; Nearing et al., 2005; Ritchie et al., 2005; Foster et al., 2007).

Despite the evidence that important interactions and feedbacks exist between vegetation change and erosion at different spatial (Chartier and Rostagno, 2006; Polyakov et al., 2010b) and temporal scales, quantitative information on the erosion dynamics, thresholds and transitions between different states within STMs is limited. The purpose of this study was to: a) quantify and compare runoff and erosion rates, as measured with a rainfall simulator and estimated using ^{137}Cs, on several semi-arid loamy upland rangeland sites located in southeastern Arizona in the context of ecological states and transition thresholds; b) determine which site characteristics have the greatest effects on soil erosion rates at these sites.

2. Methods

2.1. Location and site characteristics

Six ecological sites (R041XC313AZ) that belong to Major Land Resource Area (MLRA) 41-3 Loamy Upland (NRCS, 2013) were selected for the study (Fig. 1). Five sites are located at the historic Empire Ranch northeast of Sonoita, AZ and one site in the San Rafael Valley east of Patagonia, AZ (Table 1). The Historic Climax Plant Community (HCPC) encompasses three of the sites (Willow, ER2, and ER5). HCPC is comprised of plants adapted to natural disturbances including fire, while able to maintain natural equilibrium. Plant community in this state is represented by grasses of genera *Bothriochloa*, *Bouteloua*, *Ergrostis* and *Aristida* and native forbs. ER4S, ER4G, and ER3 sites are classified as Mesquite Natives Community. ER4S and ER4G sites are located in close proximity to each other and are very similar with respect to ecological characteristics.

Historically, the Empire Ranch has been heavily grazed, although the timing and extent are poorly documented. The ER5 site has been excluded from grazing since the mid-1980s but was grazed prior to that time. The ER2 was heavily grazed until the mid-2000's, and a wildfire swept through the area in 2000. The ER4S has established mesquites on the plots and the mesquites on ER4G had been mechanically removed. The Willow grassland location was burned by wildfires in 2005 and has regained vegetation cover.

The study area has a semi-arid climate dominated by the North American Monsoon (Sheppard et al., 2002). Precipitation is highly spatially and temporally variable with a pronounced peak in July through mid-September and a lesser increase in December through March. The annual precipitation at the Empire Ranch sites ranges between 300 and 400 mm y^{-1} and at San Rafael Valley is 450 mm y^{-1}. The average daily temperatures are 24 °C in July and 10 °C in January. The soils at all of the sites are gravely loams and belong to the White House (fine, mixed, thermic, Ustollic Haplargids) soil series (McGuire and Robinett, 2003). They were formed on alluvial fans and are characterized by a shallow A horizon underlain by deep argillic and calcic horizons.

2.2. Rainfall plots and simulation

Four 6 by 2 m long-term runoff plots were established on each experimental site. The plots had sheet metal borders installed at the top and sides to prevent lateral flow. Plot surface and vegetative cover were measured at 400 points on a 15 × 20 cm grid using the line-point intercept method (Herrick et al., 2005). Surface cover was

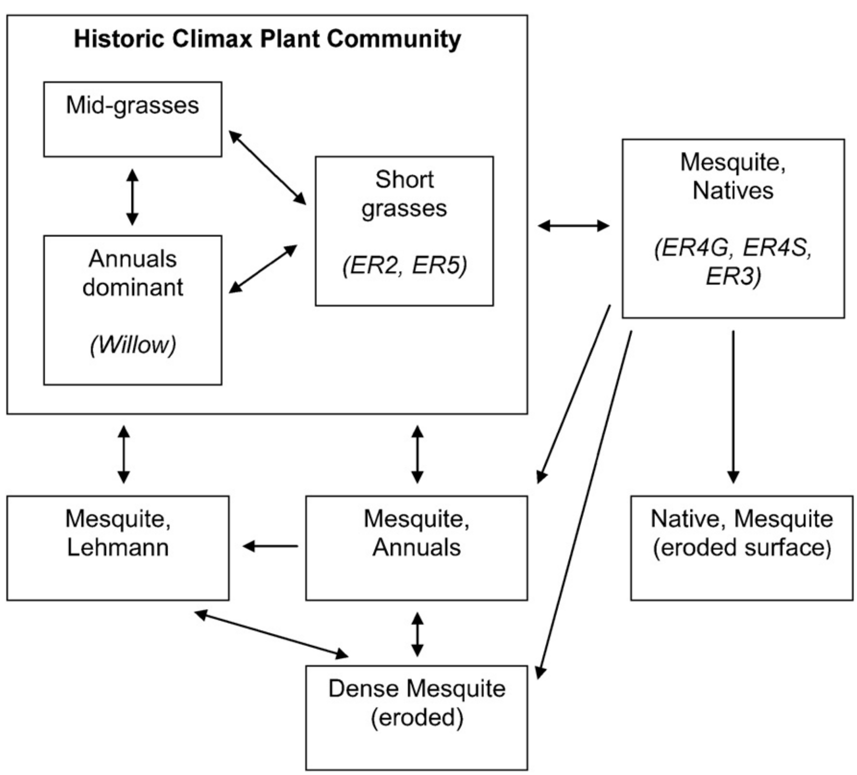

Fig. 1. Experimental sites within State and Transition Model for MLRA 41-3, loamy uplands (R041XC313AZ) (NRCS, 2013).