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Combining 3D data and traditional soil erosion assessment techniques to study the effect of a vegetation cover gradient on hillslope runoff and soil erosion in a semi-arid catchment

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A B S T R A C T

In this paper, we examine the effect of vegetation on soil erosion, runoff generation and sediment transport on saline rangeland hillslopes. Rainfall simulations were conducted at a fixed 114 mm/h intensity on 6 m × 2 m erosion plots with varying degrees of vegetation. Plots were grouped into three categories (L, M and H) based on their canopy cover (L: < 5%, M: 5–19%, H: > 19%) and selected to limit variations in slope across canopy cover groups. Runoff and sediment samples were combined with three dimensional (3D) reconstruction data used to monitor soil surface microtopographic changes. Runoff initiation was significantly delayed on the L plots but cumulative runoff after 20 min of rainfall simulation indicated a positive effect of vegetation on infiltration processes. Cumulative sediment after 20 min of rainfall was similar across vegetation cover categories. The 3D data suggest that vegetation reduced net sediment delivery from the plots by primarily increasing opportunities for deposition while marginally affecting gross soil erosion. Plots with H vegetation cover experienced lower 3D-estimated erosion volumes but average erosion depth on L plots was lower than that on plots with M and H vegetation covers. Lower runoff volumes on M and H plots may have been compensated by greater runoff erosivity on these plots as runoff was concentrated in a narrower inter-patch space compared to L plots. This study highlights the need for an increased integration between traditional runoff measurement techniques and 3D reconstruction methods.

1. Introduction

Soil erosion and runoff on rangelands have historically been perceived as processes that adversely impact the proper functioning of rangeland ecosystems through loss of soil and water resources (e.g., Chartier and Rostagno, 2006; Herrick et al., 2006; Turnbull et al., 2012; Whitford et al., 1995). Nevertheless, soil erosion and runoff generation are often accompanied with water and sediment redistribution along the rangeland hillslope with potentially positive outcomes on rangeland function. Schlesinger et al. (1990) even proposed that sparsely vegetated rangelands may rely on resource (water, sediments and nutrients) redistribution during episodic events (rainfall, runoff, wind events) to ensure higher production than achievable by average annual inputs. According to these authors, an indication of such dependence of sparsely vegetated rangeland on resource redistribution is the observation that shrubs were more productive along intermittent streambeds and in local areas of water accumulation. Other studies supporting coupling between resource redistribution and rangeland ecosystem sustainability include modeling efforts from Buis and Veldkamp (2008), field observations, and rainfall simulation experiments showing strong decays in runoff with hillslope length by others (e.g., Bergkamp, 1998; Cerda, 1997; Puigdefabregas et al., 1999).

Abbreviations: CDR, Ratio of 3D-estimated volume of deposition over erosion in channels; CumQ, Cumulative runoff volume (L); CumQ20, Cumulative runoff volume (L) recorded the first 20 min of rainfall; CumS, Cumulative soil loss (kg); CumS20, Cumulative soil loss (kg) recorded the first 20 min of rainfall; CVD, Total volume of deposition estimated with 3D reconstruction in channels; CVE, Total volume of erosion estimated with 3D reconstruction in channels; CZD, Average depth of deposition estimated with 3D reconstruction in channels; CZE, Average depth of erosion estimated with 3D reconstruction in channels; Q_{ss}, Steady state runoff discharge (mm/h); Rdur, Rainfall duration; Ro. Dur, Runoff duration; Sed, Sediment concentration (g/L); SDR, Sediment delivery ratio; TDR, Ratio of 3D-estimated volume of deposition over erosion; TTR, Time elapsed between the start of rainfall and the initiation of runoff; TVD, Total volume of deposition estimated with 3D reconstruction; TVE, Total volume of erosion estimated with 3D reconstruction; TZD, Average depth of deposition estimated with 3D reconstruction; TZE, Average depth of erosion estimated with 3D reconstruction

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Most laboratory and field research on the effect of vegetation on runoff and soil erosion processes suggest an inverse albeit non-linear relationship between plant cover and runoff and sediment production (e.g., Cerdan et al., 2002; Nicolau et al., 1996; Polyakov et al., 2016; Rogers and Schumm, 1991) and this perception forms the foundation of rangeland erosion modeling (Nearing et al., 2011). At the patch scale, vegetation has a direct shielding effect against raindrop impact, reducing rainfall energy available for soil detachment (e.g., Abrahams et al., 1995; Parsons et al., 1992; Rostagno and Delvalle, 1988; Wainwright et al., 2000) and this shielding effect is further reinforced by the presence of litter and other vegetation debris under plant canopies (e.g., Gholami et al., 2013; Wang et al., 2014). Rainfall simulation experiments by Rogers and Schumm (1991) showed a quasi-linear inverse relationship between vegetative cover and sediment yield until a threshold of 15% vegetative cover is reached where vegetation and sediment yield appeared decoupled. Nicolau et al. (1996) noted that in addition to vegetative cover, another major controlling factor of runoff is the spatial arrangement of vegetation clumps as shrub circumventions by flow paths resulted in decreased runoff. In addition, when runoff concentrates in channels, the presence of litter and other vegetative materials contribute to the total soil shear strength (Blackburn, 1975; Cammeraat and Imeson, 1998; Pierson et al., 2014; Pierson et al., 2010; Williams et al., 2014a), reducing concentrated flow erosion. Increased soil loss associated with decrease in flow path tortuosity was also found on degraded tussock grasslands (Tongway and Ludwig, 1997). Other effects include the increase in effective soil surface roughness that reduces runoff velocity and promotes deposition (e.g., Al-Hamdan et al., 2013; Emmett, 1970; Pierson et al., 2007; Pierson et al., 2009; Siepel et al., 2002; Wainwright et al., 2000), reduction in total runoff through interception storage (Carlyle-Moses, 2004; Owens et al., 2006) and enhanced infiltration (Bhark and Small, 2003; Caldwell et al., 2012; Nulsen et al., 1986). In general, these factors and other processes opposing the delivery of resources (water, sediment and nutrients) across scales are lumped into the concept of connectivity (e.g., Bracken and Croke, 2007; Williams et al., 2014a; Williams et al., 2016a).

It is clear that vegetation interacts with sediment and water transport processes in a source-sink interrelationship that varies as a function of vegetation community type (Magliano et al., 2015; Merino-Martín et al., 2012). Studies in hydrodynamic research on the effect of vegetation patches on fluvial processes (e.g., Meire et al., 2014; Rominger and Nepf, 2011) showed that flow deflections by vegetation patches are associated with deposition features upstream patches. Furthermore, these regions of deposition can promote new vegetation growth in the long-term (Meire et al., 2014). On rangelands, it is important to understand how vegetation patches influence water and sediment transport processes to devise land management techniques that target specific processes to achieve desired outcomes. Traditional techniques used to evaluate the effect of vegetation on transport processes often involve quantifying changes in runoff or sediment concentration with hillslope length (Bergkamp, 1998; Cerda, 1997; Puigdefabregas et al., 1999). However, the complexity arising from scale and spatial connectivity of rangeland erosion and hydrologic processes (e.g., Pierson et al., 2009; Sadeghi et al., 2013; Williams et al., 2016b) render the interpretation of such vegetation-induced changes in runoff and sediment concentration difficult especially in the presence of active rills. Techniques that can explicitly and simultaneously quantify erosion, deposition in relation to hydrologic input and vegetation cover are likely to yield better results in linking vegetation to sediment transport processes.

The emergence and accessibility of three dimensional (3D) reconstruction techniques now offer new opportunities to study sediment transport processes in a more spatially explicit manner (Gillan et al., 2016; Nouwakpo et al., 2016a; Prosdocimi et al., 2017). When these 3D techniques are combined with traditional soil erosion and runoff measurement methods, interactions between vegetation and sediment transport processes can be examined with greater details (Nouwakpo et al., 2017). Nouwakpo et al. (2017), found that vegetation controlled surface processes by constraining runoff into the bare interspace between vegetation plants and promoting deposition. Nevertheless, Nouwakpo et al.'s (2017) study was not specifically designed to study vegetation effect on surface processes as other factors such as slope, vegetation type, litter and soil type varied between sites and treatments. The aim of the current study is to clarify the role of vegetation cover amount in controlling detachment, transport and redistribution of sediment on sparsely vegetated rangelands by combining soil surface 3D change information with traditional erosion assessment methodologies during simulated rainfall events. Unlike the Nouwakpo et al. (2017) paper, experiments in the current study were conducted on a single site using one rainfall intensity with only vegetation cover varied between treatments.

2. Materials and methods

2.1. Study site and plot selection

The study site is located near the city of Ferron in the state of Utah, USA (Fig. 1). Soils at the site are developed in the Mancos Shale geologic formation with high soil salinity and erodibility. The soil is mapped as a complex of Chipeta series (clayey, mixed, active, calcareous, mesic, shallow typic torriorthents) and Badland. This soil was derived from weathered clayey shale, forming a paralithic restrictive layer at a depth varying between 0.1 and 0.5 m. Soil texture at the site was classified as silt loam (USDA Taxonomy) with 11.5% sand, 66.7% silt and 21.8% clay. The study site is part of the warm central desertic basins and plateaus of the United States. Average annual precipitation in this region ranges between 150 and 255 mm mostly occurring as convective thunderstorms during the period of July to September. Vegetation at the study site was dominated by the shrub *Atriplex corrugata*.

Three hillslopes were identified at the study site to represent low (L, canopy cover < 5%), medium (M, 5% < canopy cover < 19%) and high (H, canopy cover > 19%) vegetation covers. Potential hillslopes were selected by visually identifying three contrasting densities of *Atriplex corrugata* on the site (Fig. 2). Hillslopes of similar slopes and soil characteristic were picked to minimize confounding effects of these factors on soil erosion processes. Four plots were randomly selected on each hillslope, giving a total of twelve plots to conduct the rainfall simulation experiments.

2.2. Materials

The experimental protocol used in this study is similar to that used in previous studies at the same site (e.g., Cadaret et al., 2016; Nouwakpo et al., 2017) except that in the current study, only one rainfall intensity was applied to each plot. On each plot selected, a rainfall of 114 mm/h intensity was applied. This intensity was determined from precipitation frequencies published by the United States National Oceanic and Atmospheric Administration (Atlas 14) (Bonnin et al., 2006) by selecting the 25-year storm and multiplying its 5-minute depth by 12 to get a depth per hour. Rainfall was simulated with the computer-controlled Walnut Gulch Rainfall Simulator (Paige et al., 2004). The simulator nozzles were pressured at 55 kPa at a height of 2.44 m which allow raindrops to approach terminal raindrop velocity (Paige et al., 2004).

Ground and vegetation cover on each plot were assessed using a laser point frame (VanAmburg et al., 2005). The laser point measurement consisted in a laser line vertically projected on the ground and visually tracked by an observer to determine intersecting vegetation canopy and ground cover (litter, bare soil, rocks, and biological crusts). In our study this laser measurement was made on a 0.5 m × 0.1 m grid (or 220 sample points) per plot and provided information on canopy cover, litter cover, rock content and the fraction of bare ground.