Review Article

A review of concentrated flow erosion processes on rangelands: Fundamental understanding and knowledge gaps

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ABSTRACT

Concentrated flow erosion processes are distinguished from splash and sheetflow processes in their enhanced ability to mobilize and transport large amounts of soil, water and dissolved elements. On rangelands, soil, nutrients and water are scarce and only narrow margins of resource losses are tolerable before crossing the sustainability threshold. In these ecosystems, concentrated flow processes are perceived as indicators of degradation and often warrant the implementation of mitigation strategies. Nevertheless, this negative perception of concentrated flow processes may conflict with the need to improve understanding of the role of these transport vessels in redistributing water, soil and nutrients along the rangeland hillslope. Vegetation influences the development and erosion of concentrated flowpaths and has been the primary factor used to control and mitigate erosion on rangelands. At the ecohydrologic level, vegetation and concentrated flow pathways are engaged in a feedback relationship, the understanding of which might help improve rangeland management and restoration strategies. In this paper, we review published literature on experimental and conceptual research pertaining to concentrated flow processes on rangelands to: (1) present the fundamental science underpinning concentrated flow erosion modeling in these landscapes, (2) discuss the influence of vegetation on these erosion processes, (3) evaluate the contribution of concentrated flow erosion to overall sediment budget and (4) identify knowledge gaps.
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Contents

1. Introduction

Hillslope runoff and soil erosion processes play a vital role in rangeland ecosystem sustainability due to their control on resource mobility (Hassan, Scholes, & Ash, 2005) but they also have significant implications in off-site resource transport. Nichols, Nearing, Polyakov, and Stone (2013) found for example that hillslope processes contributed to 85% of sediment delivery from a 43.7 ha semi-arid shrub-dominated watershed. The influence of vegetation on hillslope runoff and sediment production forms the basis of current hydrology and erosion modeling technologies on rangelands (Nearing et al., 2011). Early attempts to apply empirical soil erosion models derived primarily from cropland data, such as the Universal Soil Loss Equation – USLE and the Revisited Universal Soil Loss Equation – RUSLE, on rangelands yielded unsatisfactory and contested results (Blackburn, 1980; Foster, Simanton, Renard, Lane & Osborn, 1981; Hart, 1984; Johnson, Savabi & Loomis, 1984; Mitchell & Roundtable, 2010; Spaeth, Pierson, Weltz & Blackburn, 2003; Trieste & Gifford, 1980). Weltz, Kidwell, and Fox (1998) point to the lumped nature and rigid structure of these empirical models as a key deficiency when applied to rangelands where biotic and abiotic interactions play a strong control on surficial processes.

The advent of physically-based soil erosion models such as the Water Erosion Prediction Project model-WEPP (Laflen, Lane, & Foster, 1991) offered the opportunity to develop the scientific framework necessary to provide insight into the relationship between hydrologic processes and rangeland condition. These research efforts led to the Rangeland Hydrology and Erosion Model (RHEM) (Al-Hamdan et al., 2015; Nearing et al., 2011), developed from experimental data specifically collected on rangeland sites across the Western U.S. As a process-based erosion model, RHEM models erosion and hydrology using the same fundamental principles as WEPP. Runoff generation and erosion on the hillslope are modeled in response to hydrological inputs and hydraulic parameters that are adjusted based on soil intrinsic properties and land surface conditions.

In both WEPP and RHEM, the hillslope is divided into (1) interrill areas, where rainsplash detachment and sheetflow transport occur and (2) concentrated flow areas where flow is deep and fluvial processes dominate. Accurate partitioning of hillslope erosion into interrill and concentrated-flow-dominated processes has a significant implication on rangeland erosion modeling especially following disturbances. Several studies (e.g, Al-Hamdan, Pierson, Nearing, and Williams (2012b), Pierson et al. (2013a, 2013b); Williams, Pierson, & Spaeth, 2016; Williams et al., 2014a, 2016a, 2016b) have demonstrated a significant increase in concentrated flow erosion when shrub-dominated rangeland are disturbed by fire or woody species encroachment compared to undisturbed conditions.

Concentrated flow erosion is a complex process because flow networks have a dual function of sediment and runoff production and storage as well as that of transport of these resources off-site. These intricately coupled functions are traditionally assumed to be controlled by rill flow hydraulics (Govers, Giménez, & Van Oost, 2007). In fact the presence of rills and gullies and the abundance thereof are key indicators of rangeland health (Pellant, Shaver, Pyke, & Herrick, 2005). As a surface process, concentrated flow erosion is directly influenced by biotic factors such as vegetation, forming feedback mechanisms that are seldom explored.

The aim of this paper is to review published experimental and conceptual research dealing with concentrated flow erosion processes on rangelands. In this paper, the term interrill erosion is used interchangeably with sheet and splash erosion to refer to the process of raindrop splash detachment and subsequent transport in sheetflow. Likewise, the term concentrated flow erosion encompasses a range of processes leading to the formation and erosion of rills and gullies, therefore these two terms were used to refer to specific forms of concentrated flow erosion. In this review we present (1) understanding of the fundamental science underpinning concentrated flow erosion modeling on rangeland with an emphasis on WEPP and advancements of the RHEM model, (2) the influence of vegetation on concentrated flow erosion, (3) the contribution of concentrated flow erosion to sediment budget and (4) knowledge gaps.

2. Physically-based modeling of concentrated flow erosion on rangeland

In physically based erosion models, overland flow in upland areas is a combination of concentrated flow (rill and gullies) and rainsplash sheetflow (interrill) (e.g., Laflen et al. (1991) and Nearing et al. (2011)). Concentrated flow is deeper and faster than overland sheetflow (Julien and Simons, 1985). In most cases the dominant form of overland flow on rangeland with adequate vegetation cover is sheetflow (e.g., Moffet, Pierson, Robichaud, Spaeth, and Hardegree (2007), Pierson et al. (2011, 2013a, 2008b), Pierson, Moffet, Williams, Hardegree, and Clark (2009), Williams et al. (2014, 2014b, 2016a)). However, continuous concentrated flowpaths play a significant role in amplifying soil erosion when they exist, especially on steep slopes or where ground cover is sparse. Therefore, predicting concentrated flow erosion on rangeland is paramount for physically based erosion modeling.

Concentrated flow plays two interactive functions in generating soil erosion. First, it can act as a transport agent for sediments detached by rainsplash and sheetflow. Second, it can act as a soil detachment agent and becomes a sediment source. Hydraulics of concentrated flow plays a key factor in both functions. For instance, flow velocity and rill width are required components to predict sediment detachment, entrainment, and transport (Line, & Meyer, 1988; Nearing, Foster, Lane, & Finkner, 1989). Therefore, modeling concentrated flow erosion requires accurate predictions of the hydraulic parameters. Here we present a description of approaches that have been used for modeling the physics of concentrated flow erosion on rangeland.

2.1. Concentrated flow hydraulics

Many of the physically based erosion models use open channel flow hydraulics concepts such as Manning's equation to model hydraulics in concentrated flow (e.g., De Roo et al. (1994), Foster (1982b), Hairsine & Rose (1992) and Morgan et al. (1998)). In such concepts velocity V (ms^{-1}) of concentrated flow is related to the geometry of the flow channel and the hydraulic roughness of the channel surface:

$$V = \frac{R_h^{2/3} S^{1/2}}{n} \tag{1}$$

where R_h is the hydraulic radius (m) which equals the area divided by the wetted perimeter, S is slope gradient, n is Manning's number which represents the channel surface hydraulic roughness.

Other physically based erosion models use the Darcy–Weisbach roughness coefficient (f) to relate flow rate to flow geometry (i.e., Laflen et al. (1991)):

$$V^2 = \frac{8gR_hS}{f} \tag{2}$$

where g is gravitational acceleration.

The Darcy-Weisbach approach requires quantification of flow-path geometry such as the flowpath width. Flow width is usually predicted using empirical equations that relate flow geometry to flow rate. For example, the WEPP model (Flanagan, & Nearing, 1995; Laflen et al., 1991) predicts rill flowpath width using the following equation from Gilley, Kottwitz, and Simanton (1990):

$$w = 1.13Q^{0.303} \tag{3}$$

where w is flow width (m) and Q (m^3 s^{-1}) is flow discharge.

Historically, rangeland model parameterization of concentrated flow processes was based on the extensive studies conducted to describe rill or concentrated flow hydraulics on croplands (e.g. Foster, Huggins and Meyer (1984a), Foster, Huggins and Meyer (1984b), Gilley et al. (1990), Giménez and Govers (2001), Gimenez, Planchon, Silvera and Govers (2004), Govers (1992), Hessel, Jetten and Guanghui (2003), Lane and Foster (1980), Line and Meyer (1988), Nearing et al. (1997), Takken, Govers, Ciesiolka, Silburn and Loch (1998) and Weisheng and Tingwu (2002)). Such approaches can result in poor predictions as rangeland and croplands have different soil and vegetation cover characteristics (Moffet et al., 2007). In the past few years, efforts have been increased to develop physically-based overland flow erosion models, such as RHEM, specifically parameterized for rangeland processes (Nearing et al., 2011; Al-Hamdan et al., 2015; Williams, Pierson, Robichaud et al., 2016a). Although RHEM models hydrology and erosion using the same fundamental concepts as WEPP, RHEM applies different hydrologic and erosion parameterizations and uses different hydraulics predictions that were developed specifically for rangelands (Al-Hamdan et al., 2015). The current version of RHEM uses the following equation developed by Al-Hamdan et al. (2012a) to predict the concentrated flow width (w):

$$w = \frac{2.46Q^{0.39}}{S^{0.4}} \tag{4}$$

This equation is an advancement over Eq. (3) in that it captures the effect of slope as well as discharge on concentrated flowpath width for rangelands.

2.2. Soil detachment rate

In most physically-based models soil detachment rate for concentrated flow is predicted using hydraulic parameters such as shear stress and stream power. In such approaches, concentrated flow erosion is often considered to be a threshold phenomenon where the soil detachment rate can be related to the exceedance of a hydraulic parameter value with respect to its critical value. The general formula for these models is:

$$D_c = K_{HP}(HP - HP_c)^a \tag{5}$$

where Dc is concentrated flow detachment rate capacity (kg s^{-1} m^{-2}), K_{HP} is the soil erodibility factor based on the hydraulic parameter HP, HP_c is the threshold value where D_{cf} is insignificant before HP exceeds it, and a is the power exponent. Several forms of Eq. (5) have been developed, using different hydraulic parameters such as: flow shear stress (τ_s) (kg s^{-2} m^{-1}) (e.g., Flanagan and Nearing (1995) and Nearing et al. (1989)), stream power (ω) (kg s^{-3}) (e.g., Elliot and Laflen (1993), Hairsine and Rose (1992) and Nearing et al. (1997)), unit stream power (Ω) (m s^{-1}) (e.g., Moore and Burch (1986) and Morgan et al. (1998)), unit length shear force (Γ) (kg s^{-2}) (e.g., Giménez and Govers (2002)), and unit discharge (q) (m^2 s^{-1}) (e.g., Line and Meyer (1989)). Most of these equations were obtained from research

conducted on cropland soils in field and/or laboratory studies using flumes.

Evaluation of performance for these hydraulic parameters to predict concentrated flow detachment rate in various experimental conditions (Al-Hamdan et al., 2012b; Wirtz et al., 2013) resulted in no single parameter consistently best-fitting observed detachment rates. However, Al-Hamdan et al. (2012b) showed that stream power provides the best relationship among these five hydraulic parameters to describe concentrated flow detachment rate for disturbed rangeland. Al-Hamdan et al. (2012b) also found that when concentrated flow occurs that the threshold value (HP_c) can be ignored and the exponent of relationship (a) is not significantly different than 1, reducing the equation when using stream power to:

$$D_c = K_\omega(\omega) \tag{6}$$

The current version of RHEM uses this equation to calculate detachment capacity. Al-Hamdan et al. (2012) provided parametrization equations for estimating erodibility factor ($K\omega$) based on site vegetation cover condition and soil texture ((Eqs. (7) and 8)).

$$\log(K_\omega) = -4.05 - 0.81 \cdot cover - 11.87 \cdot clay + 5.19 \cdot silt \tag{7}$$

$$\log(K_\omega) = -3.29 - 2.25 \cdot cover - 1.82 \cdot rock + 3.95 \cdot silt \tag{8}$$

where $cover$ is the fraction of the soil surface covered by plant stems and residues, $rock$ is the fraction of soil surface covered with rocks, $clay$ and $silt$ are respectively the clay and silt contents of the soil. Eq. (7) is used on undisturbed rangelands while Eq. (8) is used on burned rangelands. One can note the negative coefficients of $cover$ in both equations, indicative of the beneficial effect of vegetation in reducing concentrated flow erodibility.

Al-Hamdan et al. (2012b) introduced a dynamic computational structure in RHEM for concentrated flow erosion modeling on freshly burned rangelands that start with an initially high $K\omega_{Max}$ to which an exponential decay function is applied to reduce $K\omega$ with cumulative runoff. This dynamic erodibility concept addresses the observation that soil erodibility and sediment availability are greatly increased immediately after a freshly disturbed site (Al-Hamdan et al., 2012b). Observed interrill and concentrated flow soil erosion observed immediately following such disturbances were consequently high but decline rapidly over the course of the first few rainfall events due to various factors including decrease in sediment availability. The following equation was proposed to estimate $K\omega$ and $K\omega_{Max}$:

$$K_\omega = K_{\omega Max}e^{\beta q_c} \text{ and}$$
$$\log(K_{\omega Max}) = -3.64 - 1.97 \cdot cover - 1.85 \cdot rock - 4.99 \cdot clay + 6.06 \cdot silt \tag{9}$$

where β is a constant and q_c is cumulative runoff.

The detachment capacity is used to calculate the detachment rate (D_r) (kg s^{-1} m^{-2}) in RHEM by (Foster, 1982a):

$$D_r = \begin{bmatrix} D_c\left(1 - \dfrac{CQ}{T_c}\right), CQ \leq T_C \\ \dfrac{0.5V_f}{Q}(T_c - CQ), CQ \geq T_C \end{bmatrix} \tag{10}$$

where C is the sediment concentration (kg m^{-3}), Q is the flow discharge (m^3 s^{-1}), Tc is the sediment transport capacity (kg s^{-1}), and V_f is the soil particle fall velocity (m s^{-1}) that is calculated as a function of particle density and size (Fair, Geyer, & Okun, 1971). Soil particle fall velocity is calculated using the mean particle size (D_{50}) of the soil texture. In this equation concentrated flow detachment rate (D_r) is calculated as the net detachment and deposition rate.

To calculate the transport capacity (T_c) in RHEM, the empirical

equation developed by Nearing et al. (1997) is used:

$$\log_{10}\left(\frac{10T_C}{w}\right) = -34.47 + 38.61\left(\frac{\exp[0.845 + 0.412\log(1000\omega)]}{1 + \exp[0.845 + 0.412\log(1000\omega)]}\right) \tag{11}$$

Methods of estimating concentrated flow erosion in RHEM have evolved over the last several years. The earliest version of RHEM used a shear stress approach and provided satisfactory estimates of total soil erosion (Belnap, Wilcox, Van Scoyoc, & Phillips, 2013; Hernandez et al., 2013, Felegari, Talebi, Dastorani & Rangavar, 2014; Weltz et al., 2014). The most recent version of RHEM include the dynamic erodibility concept described above and is based on the stream power to estimate concentrated flow erosion. The new approach has improved erosion estimates for concentrated flow erosion with a satisfactory range of error (Al-Hamdan et al., 2015).

3. Effect of vegetation on rangeland hydrology and erosion processes

Vegetation affects rangeland concentrated flow processes through its influence on water availability for runoff and sediment transport, regulation of sediment availability, routing of overland flow, and control of overland flow velocity and erosive energy (Al-Hamdan et al., 2012a, 2012b, 2013; Emmett, 1970; Pierson et al., 2009; Wainwright, Parsons & Abrahams, 2000; Williams et al., 2014a). Here, we provide an overview of these ecohydrologic relationships. We focus on the effects of vegetation in controlling not only runoff generation and erosion processes, but also its influence on infiltration and sediment deposition. Formation of concentrated flow is strongly dependent on the spatial connectivity of runoff and sediment sources across point ($<1\ m^2$) to patch scales (10 s square meters) (Pierson et al., 2010, 2013a; Williams et al., 2014a, 2016a). We therefore initiate our discussion at the point scale and progress with discussion of point scale contributions to concentrated flow processes at the patch to hillslope scales.

3.1. Vegetation effects on water input and runoff generation

Vegetation and associated ground cover strongly regulate concentrated flow formation by limiting water available for runoff and sediment transport. Sediment delivery from rangelands is governed by the connectivity of runoff and erosion processes and the availability of erodible soil (Al-Hamdan et al., 2015, 2012; b Williams et al., 2016a). Vegetation disrupts connectivity of runoff through interception and storage of water input. The percentage of event rainfall captured by vegetation and associated ground cover generally decreases as rainfall intensity increases (Carlyle-Moses, 2004; Owens, Lyons, & Alejandro, 2006). For low-intensity, short-duration rainfall events, most of the precipitation is captured by plant canopies, litter, and other ground cover and is lost to evaporation (Dunkerley, 2008; Owens et al., 2006). Water input during high-intensity or prolonged rainfall events usually exceeds interception storage capacity, resulting in delivery of water to the ground surface via throughflow and stemflow (Carlyle-Moses, 2004; D. Dunkerley, 2000; D.L. Dunkerley, 2008; Wainwright, Parsons, & Abrahams, 1999; Whitford, Anderson, & Rice, 1997; Martinez-Meza and Whitford, 1996). Interception by individual shrubs and conifers commonly averages 50–60% of water input for low-intensity rainfall events and 5–35% for high intensity or pro-longed rainfall events (Hamilton & Rowe, 1949; Owens et al., 2006; Rowe, 1948; Skau, 1964; Taucer, Munster, Wilcox, Owens & Mohanty, 2008; Tromble, 1983). Water arriving at the ground surface during an event either ponds at the soil surface, is stored in the litter layer, infiltrates into the soil, or is transferred downslope as runoff. Organic matter

contributions and soil fauna activity are typically greater in vegetated and litter covered areas relative to bare areas and facilitate macropore development and soil properties associated with enhanced infiltration (Blackburn, 1975; Cammeraat & Imeson, 1998; Imeson, Lavee, Calvo, & Cerdà, 1998; Puigdefabregas et al., 1999; Belnap, Welter, Grimm, Barger, & Ludwig, 2005; Dunkerley, 2002; Ludwig, Wilcox, Breshears, Tongway, & Imeson, 2005). Litter layers underneath vegetation also trap water input and thereby delay runoff generation. Prolonged storage at the ground surface allows water to slowly infiltrate, even in the presence of water repellent soils (Leighton-Boyce, Doerr, Shakesby, & Walsh, 2007; Pierson et al., 2010; Pierson et al., 2013a; Pierson, Robichaud, Moffet, Spaeth, & Williams, 2008; Pierson, Williams, Kormos, & Al-Hamdan, 2014; Williams et al., 2014). Hydraulic conductivity and infiltration rates can be as much as 25- to 30-fold lower for water repellent versus wettable soils (DeBano, 1971; Madsen, Chandler & Belnap, 2008). The litter layer in vegetated areas buffers repellency effects on infiltration by trapping water input and allowing it to slowly infiltrate via macropores and breaks in the water repellent layer or slow wetting of the soil profile (Doerr, Shakesby & Walsh, 2000; Meeuwig, 1971; Pierson et al., 2008a; Williams et al., 2014a). Collectively, interception and enhanced infiltration in vegetated areas commonly results in two- to more than 20-fold less event runoff relative to bare or sparsely vegetated areas across the point to patch scales (Pierson & Williams, 2016).

3.2. Vegetation effects on sediment availability for concentrated flow processes

Vegetation regulates sediment availability for concentrated flow erosion through protection of the soil surface from raindrop impact and the erosive energy of overland flow. Surface protection and soil stabilization by cover elements are paramount in minimizing erosion given that raindrop impact is the primary sediment contributor to shallow overland flow and ultimately a source for concentrated flow (Kinnell, 2005; Wainwright, Parsons, & Abrahams, 2000; Williams et al., 2016a). Vegetation and ground cover can reduce rainfall erosivity by nearly 50% (Wainwright et al., 1999). In addition to reducing raindrop impact, vegetation and ground cover facilitate roughness elements that trap and slow runoff and promote sediment deposition (Al-Hamdan et al., 2013; Emmett, 1970; Parsons, Abrahams & Wainwright, 1996; Pierson et al., 2007, 2009; Wainwright et al., 2000). Plants and associated organic material also contribute to the soil shear strength by anchoring soils and promoting aggregate stability (Blackburn, 1975; Cammeraat et al., 1998; Cerdà, 1998; Puigdefabregas et al., 1999; Pierson et al., 2010, 2013a, 2013b; Pierson et al., 2014; Williams, Pierson, Al-Hamdan et al., 2014). Parsons, Abrahams, and Simanton (1992); Parsons, Abrahams, and Wainwright (1994) evaluated the effect of cover elements on rainsplash erosion during high intensity rainfall simulations. Parsons et al. (1992, 1994) found the rainsplash erosion rate on arid, well-vegetated grassland was 0.01–0.04 $g\ m^{-2}\ min^{-1}$ for 73–86 $mm\ h^{-1}$ rainfall intensities. The same studies measured 0.34 $g\ m^{-2}\ min^{-1}$ erosion rate on a degraded arid shrubland for a simulated event with 145 $mm\ h^{-1}$ intensity (see Wainwright et al. (2000)). Rainsplash during the shrubland experiments eroded about 1.6-fold more sediment from areas between plant canopies than from areas underneath plant canopies (Parsons et al., 1992). Results from numerous other studies indicate that erosion rates from rainsplash and sheetflow at the point scale can be two-fold to more than three orders of magnitude greater for bare areas than areas underneath vegetation or with litter cover (Pierson & Williams, 2016). Actual differences vary with cover, soil, rainfall, and topography characteristics. Erosion from combined rainsplash, sheetflow, and concentrated flow processes is typically negligible where ground cover exceeds 50% (Gifford (1985), Pierson et al.

(2009, 2011, 2013a, 2013b), Weltz et al. (1998), Williams, Pierson, & Robichaud (2014); Fig. 2(A)).

3.3. Effects of vegetation community structure on concentrated flow processes

In arid and semiarid rangelands, where vegetation is typically sparse, a synergistic relationship has traditionally been observed between spatial distribution of vegetation and runoff structuring. This vegetation driven spatial heterogeneity (VDSH) stems from differential soil development and evolution processes between areas under canopies and bare ground (e.g., Bhark and Small (2003), Caldwell, Young, McDonald, and Zhu (2012), De Ploey (1984), and Nulsen, Bligh, Baxter, Solin, and Imrie (1986)) resulting in feedback mechanisms perpetuating or further accentuating the bare ground – under canopy soil dichotomy (Puigdefabregas et al., 1999). In addition, observations in semiarid rangelands suggest that deposition mounds form upstream of plant clumps as a result of energy losses and changes in transport capacity that accompany overland flow diversion by plant stems (e.g., Meire, Kondziolka, and Nepf (2014) and Rominger and Nepf (2011)). The entrapment of nutrients along with sediments in these mounds creates areas of nutrients concentration where plants thrive spatially alternated by bare or poorly vegetated zones of water and nutrient depletion, forming the premise of the "resource islands" or "vegetation island" concept (e.g., Li, Zhao, Zhu, Li, and Wang (2007) and Ridolfi, Laio, and D'Odorico (2008)).

From a hydraulic standpoint, these "vegetation islands" can further exacerbate the concentrated flow process (Fig. 1). Examples of this negative feedback loop are seen most often in shrub-dominated landscapes in the United States, which have formed coppice dunes such as sagebrush (Artemisia spp.), saltbush (*Atriplex* spp.), creasotebush (*Larrea tridentate*, DC. Coville), mesquite (*Prosopis glandulosa* Torr.), greasewood (*Sarcobatus vermiculatus,* Hook. Torr.) and in pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodland dominated areas in arid and semi-arid rangelands (Li et al., 2013; Davenport, Breshears, Wilcox & Allen, 1998; Eldridge et al., 2004; Pierson, Van Vactor, Blackburn & Wood, 1994; Schlesinger, Raikes, Hartley & Cross, 1996; Spaeth, Weltz, Fox & Pierson, 1994).

Experimental research at the Walnut Gulch Experimental Watershed in southern Arizona revealed that coarsening of the spatial structure of vegetation in shrublands led to increase in flow concentration and erosion rates (Abrahams, Parsons, & Wainwright, 1995; Parsons, Abrahams, & Wainwright, 1996; Wainwright et al., 2000). VDSH influences not only runoff partitioning into sheet and concentrated flow processes but also seems to control flow characteristics in hillslope rills and channels. The same landscape with uniform disturbance may experience significantly more runoff and soil loss from a similar runoff event due to increased connectivity of bare soils and formation of well-organized concentrated flowpaths. These organized flowpaths rapidly accelerate runoff velocity and the ability of water to erode and transport sediment downslope (Davenport et al., 1998; Urgeghe, Breshears, Martens & Beeson, 2010; Wilcox, Davenport, Pitlick & Allen, 1996). Tongway, and Ludwig (1997) found for example that on degraded tussock grasslands, overland flow was concentrated in long straight paths between the grasses. In the good condition grassland overland flow was tortuous, uniformly distributed, and produced less soil loss.

Plant community physiognomy affects concentrated flow by controlling the connectivity of runoff and sediment sources and the energy of overland flow where it does occur (Williams et al., 2016a, 2014a, 2016b). On well vegetated rangelands, downslope transmission of runoff and erosion generated by rainsplash and sheetflow in isolated bare or sparsely vegetated patches is limited by ground cover or roughness elements that promote infiltration and deposition (Pierson et al., 1994, 2009; Reid, Wilcox, Breshears
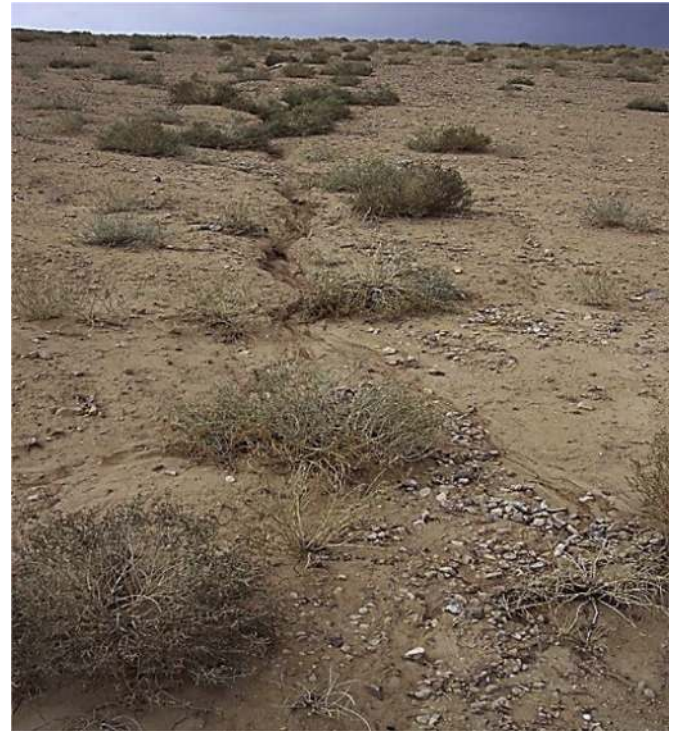

Fig. 1. Vegetation island redirecting concentrated flow around it resulting in deposition on the downslope side.

& MacDonald, 1999; Wilcox, Breshears & Allen, 2003). Soil detachment by concentrated flow is well correlated with flow velocity (Pierson et al., 2009, 2008b) and discharge (Al-Hamdan, Pierson, Nearing, & Williams, 2012; Govers et al., 2007; Nearing et al., 1997; Nearing, Simanton, Norton, Bulygin, & Stone, 1999), and flow velocity is strongly related to discharge (Al-Hamdan et al., 2012; Giménez et al., 2001; Govers et al., 2007; Govers, 1992; M. Nearing et al., 1997; M.A. Nearing et al., 1999). Grass clumps, plant bases, root mounds, and litter dams create topographic highs that may concentrate overland flow where runoff occurs, but the transport and erosive energy of concentrated flow are greatly reduced when flow intersects these roughness elements (Abrahams & Parsons, 1991; Abrahams & Parsons, 1994; Al-Hamdan et al., 2012b, 2012b, 2013; Bryan, 2000; Emmett, 1970; Nearing et al., 1997; Parsons et al., 1996; Wainwright et al., 2000). Reduced flow velocities and energy limit detachment and transport and allow surface runoff to disperse and sediment to fall out of suspension. Rangeland studies from the Great Basin Region, USA, have reported two-fold higher concentrated flow velocities for experiments on bare plots (80% bare ground) relative to well-vegetated plots 20–60% bare ground (Pierson et al., 2009, 2007). In those studies erosion from concentrated overland flow was four-fold to eight-fold greater for bare than well-vegetated plots. Sediment transported by concentrated flow where it does occur on well-vegetated sites often forms miniature alluvial fans adjacent to vegetative clumps (Emmett, 1970; Meire et al., 2014; Rominger & Nepf, 2011; Seyfried, 1991). These features indicate that concentrated flow does redistribute surface soil from bare areas to vegetated zones on hydrologically stable rangelands, but hillslope soil loss from this process is minor under such conditions (Pierson et al. (2009, 2007); Fig. 2(b)). Al-Hamdan et al. (2013) infers that the existence of a channel network is dictated not by hydraulic stresses exerted by runoff on bare soil but rather by the spatial distribution and structure of vegetation to which this network is in equilibrium. Concentrated flow becomes the dominant erosion mechanism on degraded rangelands where ground cover is sparse
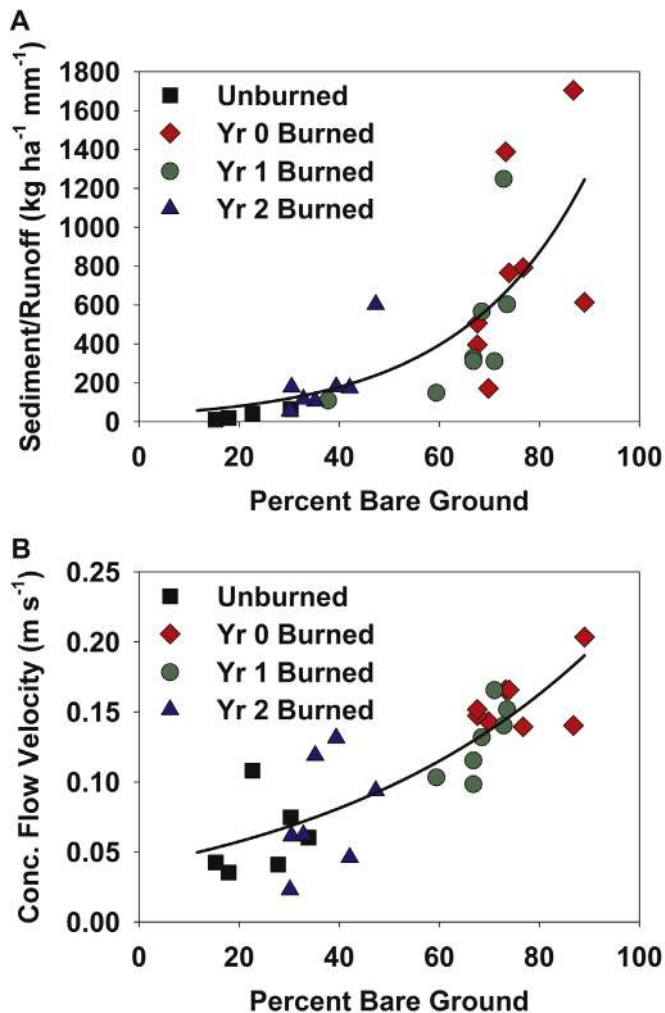
Fig. 2. Sediment per unit of runoff (A) and concentrated flow velocity (B) versus percent bare ground measured on rainfall simulation plots (32.5 m², 85 mm h⁻¹ raintall intensity) and concentrated flow experiments (12 L min⁻¹ flow release) on unburned and burned shrublands. Data from Pierson et al. (2009).

(Pierson et al., 2009, 2011, 2013a, 2008; Williams et al., 2014a, 2014b, 2016a).

3.4. Disturbance impacts on concentrated flow processes

Concentrated flowpaths rarely develop on undisturbed rangelands, but often become the dominant conduit for overland flow and sediment transport after disturbance (Moffet et al., 2007; Pierson et al., 2009; Williams et al., 2014b, 2016a). Such rangeland disturbance includes: animal grazing, fire- and non-fire-induced vegetation removal, vehicle traffic, etc. Sediment yield from concentrated flow processes is several orders of magnitude greater than that of sheetflow and rainsplash and can account for 50–90% of total sediment yield on slopes with sparse to no cover (Pierson et al., 2008b; Thornes, 1980; Wainwright et al., 2000). Following fire disturbance, reduced vegetation and ground cover interception, decreased infiltration rate, and amplified runoff facilitate formation of concentrated flowpaths (Al-Hamdan et al., 2013; Pierson et al., 2009; Williams et al., 2016a). These relationships are enhanced on steep slopes and where overland flow is promoted by soil water repellency (Pierson et al., 2011; Shakesby, & Doerr, 2006; Williams et al., 2014). Greater raindrop impact and increased sediment availability after canopy and ground cover removal result in increased soil detachment and transport from combined rainsplash

and sheetflow processes (Pierson et al., 2009, 2013b, 2014;, 2015; Williams et al., 2016, 2014a, 2016b). Reductions in ground cover (decreased surface roughness) abate surface retention of runoff, allowing flow to concentrate and move downslope with greater velocity, erosive energy, and transport capacity (Al-Hamdan et al., 2013; Pierson et al., 2009, 2013a, 2008b; Shakesby et al., 2006; Williams et al., 2014a, 2016a). The potential overall effect is a decrease in the time to runoff initiation and an increase in cumulative runoff and sediment yield over the duration of a storm event.

Cross-scale field experiments on infiltration, runoff, and erosion provide estimates of disturbance impacts on concentrated flow processes (Pierson & Williams, 2016). Pierson et al. (2009) found that moderate burning of a steeply sloping rangeland in Idaho, USA, increased runoff of simulated rainfall (85 mm h⁻¹) by two-fold on 0.5 m² shrub plots immediately following burning. The same storm simulated at the patch scale (32.5 m²) generated nearly seven-fold more runoff for the immediate post-fire condition. Increased runoff immediately following burning accumulated in high velocity concentrated flowpaths and generated more than 100-fold more sediment yield than measured for the unburned condition (Fig. 2). Concentrated flowpaths were not observed on unburned plots during the rainfall experiments. Concentrated flow experiments in the same study generated three-fold more runoff and six-fold more erosion for the immediately post-fire condition relative to unburned plots.

The dramatic increase in sediment delivery from the patch scale simulations and concentrated flow experiments were attributed to increased runoff and sediment availability and formation of high velocity flowpaths on the burned plots. Erosion rates and concentrated flow velocity on burned plots returned to near pre-fire levels when ground cover approached 60% two growing seasons after burning (Fig. 2). Pierson et al. (2008b) conducted similar concentrated flow experiments on burned and unburned plots within the first year after a high severity burn on steeply sloping shrublands in Nevada, USA. That study measured nearly 18,000 g of soil erosion on burned plots and 10 g of soil erosion on unburned plots. In another study, Williams et al. (2014a) measured a nearly three-fold increase in point-scale (0.5 m²) runoff of applied rainfall (102 mm h⁻¹) on burned conifer plots one year post-fire, but burning had no impact on runoff from degraded shrub and interspace (areas between shrubs and trees) plots. Burned plots generated three- to more than 30-fold more erosion than unburned plots. The highest erosion rates were measured on burned conifer and shrub plots with ample available sediment. The same rainfall event applied at the patch scale (13 m²) generated two-fold and more than 20-fold more erosion on burned shrub-interspace (plots with shrub and interspace coverage) and conifer plots respectively. The fire-induced increases in patch scale erosion were attributed to cross-scale connectivity of runoff and sediment sources, formation of concentrated flowpaths (Fig. 3), and an increase in available sediment following fire-removal of ground cover (Williams et al., 2014a). The experimental results from Pierson et al. (2009, 2008) and Williams et al. (2014a) illustrate the profound influence that concentrated flow processes have on erosion in the first few years following disturbances like burning (Fig. 2). The overall impact of disturbance on event concentrated flow processes depends largely on the rate or magnitude of water input, surface susceptibility to runoff and sediment detachment and entrainment, and the amount of sediment available (Al-Hamdan, 2012b; Williams et al., 2014b, 2016a).

Overall, on undisturbed arid and semiarid rangelands, it is often assumed that sheetflow and interrill erosion are the dominant processes while disturbances such as fire allow for increased flow concentration and severely weakened soil resistance to rill erosion (Moffet et al., 2007). This understanding of rangeland concentrated flow erosion processes is currently reflected in hydraulic parameterization equations for rill erodibility in RHEM. In fact Al-Hamdan et al. (2015) proposed a dynamic modeling framework to

Fig. 3. Concentrated flowpaths formed and are activity eroding as result of loss of protective vegetation and formation of hydrophobic surface soil layer following wildfire in Central Nevada.

match observed temporal declines in erosion rate with time following a major disturbance. In Al-Hamdan et al.'s (2015) model, rill erodibility was initially high immediately after disturbance and exponentially decayed with cumulative runoff over the course of rainfall events.

4. Contribution of concentrated flow to total erosion

Erosion processes occur on a continuum of scales from interrill to rill and gullies and large river systems (Wondzell & King, 2003). Once sediments are eroded and collected at the drainage (hillslope, catchment or watershed) outlet, the task of parsing total erosion into its different components becomes complex. Quantifying the contribution of concentrated flow erosion to total erosion often requires the use of techniques that take advantage of the unique morphology of these erosional features compared to the surrounding areas. Concentrated flowpaths are deep and expose lower soil layers to the surface compared to surrounding interrill areas. Environmental radionuclides have been used to estimate the contribution of concentrated flow processes to total erosion (Liu, Yang, Warrington, Liu, & Tian, 2011; Wilson, Papanicolaou, & Denn, 2012; Yang, Walling, Tian, & Liu, 2006). Natural and man-made fallout radionuclides are unevenly distributed within the soil profile so they can be used as effective sediment tracers. The most commonly used radionuclides are caesium-137 (Cs-137) and lead-210 (Pb-210), providing information on sediment redistribution over medium term timescales (25–100 years) (Walling, 2013). In recent years, beryllium-7 (Be-7, a radionuclide with half-life of 53.22 days) has received increased attention for its potential to trace sediments over timescales relevant to a single event, enabling an event-based partitioning of erosion into its components. Using a combination of Be-7 and Cs-137, Yang et al. (2006) found a dominance of interrill processes at the start of erosion and a gradual importance of concentrated flow processes once rills were formed, representing 54.3% of total soil loss on a cultivated plot and 61.4% on an uncultivated forest plot. The temporal shift of erosion processes from interrill-dominated at the start of erosion to channel-dominated in later stages of the erosive event has also been found by others (e.g., Liu et al. (2011) and Wilson et al. (2012)). The spatial scales at which erosion processes have been investigated with radionuclides varied from plot and hillslope (e.g., Jha, Schkade, and Kirchner (2015), Liu et al. (2011) and Porto and Walling (2014)) to whole watershed assessments (e.g., Geeraert et al. (2015), Gourdin et al. (2014) and

Wilson et al. (2014)). Meteorically-delivered radionuclides such as Be-7 have less often been used in arid and semiarid environments as a short-term sediment tracer because low and highly variable precipitation regimes hinder reliable interpretation of radioactivity measurement (Kaste, Elmore, Vest, & Okin, 2011).

Another commonly used method to quantify the contribution of concentrated flow processes in total erosion involves the estimation of rill and gully volume (e.g., Govers and Poesen (1988), Marzolff and Poesen (2009) and Nyssen et al. (2006)). Di Stefano, Ferro, Pampalone, and Sanzone (2013) conducted a study on a semiarid site to estimate the contribution of concentrated flow processes to total erosion during natural rainfall events. From manual cross-section surveys of rills and gullies with a mechanical rillmeter and a total station, these authors found that the contribution of concentrated flow processes ranged from 23.5% to more than 100%. Di Stefano et al. (2013) attributed the contribution higher than 100% to sediment delivery mechanisms whereby a portion of the eroded sediment in rills does not reach the hillslope outlet. It is important to note that the experimental sites used in Di Stefano et al. (2013) were maintained under cultivated fallow and therefore are considered disturbed.

5. Knowledge gaps and conclusions

5.1. Initiation and spatial distribution of concentrated flowpaths

Despite the advancement of modeling concentrated flow erosion on rangeland, as represented in RHEM, future work is still needed for improving the prediction of erosion processes. While the model can simulate detachment rate in concentrated flow, it does not model or predict concentrated flow formation or rill initiation. Even though rill density or spacing between concentrated flowpaths is currently a parameter in RHEM, the value of this parameter is usually set as a default value of 1 rill per meter (i.e. the spacing between concentrated flowpaths is 1 m). This value was suggested by Gilley et al. (1990) based on cropland experiments. Assuming a uniform distribution of rills or concentrated flowpaths on cropland might be logical given the uniformity of its characteristics. Rangeland overland flow processes on the other hand vary with vegetation, ground surface conditions, and hillslope topography (Pierson et al., 2011; Williams et al., 2014b). In most cases the dominant form of overland flow on rangelands with adequate vegetation cover is sheetflow. Concentrated flow emerges on steep slopes or where ground cover is sparse (Al-Hamdan et al., 2013; Pierson et al., 2009; Williams et al., 2016a). Using data from experiments conducted on rangeland with a wide span of characteristics, Al-Hamdan et al. (2013) showed that formation of continuous concentrated flowpaths at the plot scale is positively correlated with flow discharge per unit width, slope, and ground cover. Using the same data, the authors developed a logistic equation to estimate the probability of overland flow to become concentrated on rangeland:

$$P = \frac{\exp\left(-6.\,397 + 8.\,335S + 3.\,252bare + 3440q\right)}{1 + \exp\left(-6.\,397 + 8.\,335S + 3.\,252bare + 3440q\right)} \tag{12}$$

where S is slope (m m^{-1}), *bare* is fraction of bare soil to total area (m^2 m^{-2}), and q is flow discharge per unit width (m^2 s^{-1}).

In order to address the lack of concentrated flow network modeling for physically based models on rangeland, new approaches such as Eq. (12) might be needed. Alternatively, others have used topographic threshold concepts to predict the location of concentrated flow initiation. These concepts are based on the work of Vandaele, Poesen, Govers, and Wesemael (1996) who proposed an inverse power function between slope S and

contributing area A above channel heads (Eq. (13)).

$$S = \alpha A^b \qquad (13)$$

where α and b are constants.

Some authors have used this model to predict rill and gully location at watershed scales (e.g., Daggupati, Douglas-Mankin, and Sheshukov (2013), Dewitte, Daoudi, Bosco, and Van Den Eeckhaut (2015) and Millares, Gulliver, and Polo (2012)). With the advent of low-cost three-dimensional reconstruction technologies and the improvement in the degree of autonomy of Unmanned Aerial Vehicles, one can expect high-resolution topographic data to be increasingly available to accommodate the topographic threshold-based modeling approach. Nevertheless, Eq. (13) is static in nature and there is a need to develop a dynamic model structure that is suitable for event-based erosion modeling.

5.2. Improved linkage between concentrated flow processes and resource redistribution

It is well recognized that an increase in concentrated flow erosion leads to an increase in total erosion (e.g., Al-Hamdan et al., 2015; Pierson et al., 2009, 2011, 2013a, 2008; Williams et al., 2014a, 2014b, 2016a). What is not well understood however is the role of rill and gully formation in delivery of eroded material from interrill areas.

On rangelands, especially those in arid and semi-arid landscapes, vegetation can be sparse and a high degree of variability is observed in soil surface and subsurface conditions. In these ecosystems, the most notable spatial heterogeneity is imposed by plants. Soil under vegetated patches was shown to exhibit enhanced infiltration and greater water storage capacity (Bhark et al., 2003; Caldwell et al., 2012; De Ploey, 1984; MartinezMeza, & Whitford, 1996; Nulsen et al., 1986), increased soil organic carbon and nutrient inputs (Imeson, & Verstraten, 1989; Virginia, & Jarrell, 1983), promoting greater biological activity that further differentiates these areas as resource sinks while the bare interspace act as source of material and water.

Concentrated flow erosion when it occurs, is often confined within the interspace and its course dictated by the spatial arrangement of plants. In a sense, there seems to be a functional specialization of the interspace as flow concentration pathways where resources (primarily water) are collected and redistributed along the hillslope. In fact Schlesinger et al. (1990) proposed that sparse rangeland ecosystems such as shrubland exploit effectively an unpredictable and episodic source of water and nutrient supply to ensure higher production than allowable by average annual inputs. These researchers also noted that shrubs were more productive along intermittent streambeds and in local areas of water accumulation. Resource redistribution across the landscape seems to be an essential component of ecosystem dynamics in sparsely vegetated rangelands. Modeling efforts from Buis, and Veldkamp (2008) demonstrated that redistribution of water and possibly other resources might be key to long-term sustainability of these arid and semi-arid ecosystems.

Redistribution of water and sediment has been empirically understood and applied to mechanical water harvesting practices. An example is the Vallerani plowing technique used to create zones of water collection and flow concentration feeding vegetated patches (Fig. 4). The Vallerani plow creates a divot and pushes up soil to form a berm (i.e., bund) that traps water from the uphill slope (Gammon & Oweis, 2011). This mechanized water harvesting system provides additional water to the shrubs transplanted into the depression that is necessary for their survival. In addition, a ripping blade is part of the system that is pulled through the soil to improve water storage capacity. While this

Fig. 4. Degrade watershed that has been restored using Vallerani plow to interrupt concentrated flowpaths and reduce offsite runoff and sediment yield.

technique has proven successful in watershed restoration in Jordan and other countries in the Middle East and North Africa (Gammon & Oweis, 2011; Akhtar et al., 2006, 2010), it still relies on empirical and speculative knowledge on concentrated-flow-driven resource redistribution along the hillslope. More research is needed to develop a systematic conceptual and modeling framework that clarifies the role of concentrated flow processes in resource redistribution on the hillslope in order to support effective rangeland improvement practices.

Erosion and deposition processes are often scale-dependent. On rangelands, field observations and rainfall simulation experiments showed strong runoff decay with hillslope length (Bergkamp, 1998; Cerda, 1997; Puigdefabregas, Sole, Gutierrez, del Barrio, & Boer, 1999). The effect of scale on sediment concentration is not clearly understood as conflicting results have been found. Decrease in sediment delivery was shown by some (e.g., Sadeghi, Seghaleh, and Rangavar (2013)) while others found an increase in sediment delivery with coarsening of the spatial structure (Williams, Pierson, Robichaud et al., 2016). de Vente, Poesen, Arabkhedri, and Verstraeten (2007) proposed explanations for these conflicting results at broad watershed scales but concluded that overall watershed area is a poor predictor of area-specific sediment yield which is rather controlled by the relative dominance of specific erosion processes.

The more fundamental problem might be that erosion science today has provided ample data-based understanding of detachment and transport processes but has rarely specifically targeted deposition due to lack of simple adequate tools to quantify this process. In the Di Stefano et al. (2013) study for example, much of the eroded material in rills may have been deposited within the field, likely leading to the higher-than-one contribution of rills measured in this study. Recent work from Nouwakpo, Weltz, Champa and Fisher (in press) suggests that concentrated flow contributions estimated with three-dimensional reconstruction on a semi-arid vegetated hillslope were several orders of magnitude lower than predicted with RHEM (version 2.2) even though the experimental data showed a statistically significant association between channel volumes and sediment concentration. Currently, hydraulic parameters and soil properties are key factors in governing the processes of soil deposition along the hillslope. Unlike concentrated flow detachment, the process of deposition along the

Fig. 5. Release of a dye plume illustrating how runoff is redirect by vegetation clumps resulting in increased touristy and reduced sediment transport capacity.
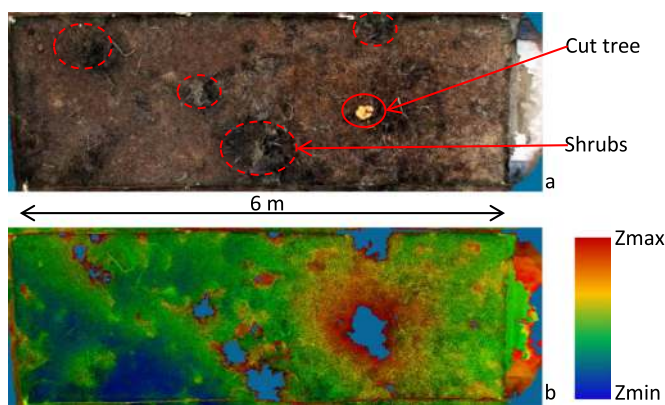

Fig. 6. Illustration of the effect of vegetation on soil surface microtopography showing a synoptic image of a 6 m × 2 m erosion plot (a) and a digital elevation model of the relative elevation in the plot (b).

hillslope in Eq. (11) is obtained from the WEPP model. This equation or concept has not been evaluated on rangeland yet. Perhaps improving understanding of the mechanics of deposition processes from measurements specifically targeting this surface process would help develop a more complete prediction tool for deposition. This experimental work would be useful to evaluate the validity of current deposition equations or develop other more appropriate approaches for modeling deposition on rangeland.

It is possible that on undisturbed rangeland hillslopes, the amount of erosion produced by rill-forming processes might be low but the presence of a rill network might substantially influence sediment delivery (Nouwakpo et al., in press). Knowledge on the feedback between interrill sediment delivery and concentrated flow processes is needed to improve hydrology and erosion modeling on rangeland. In many sparsely-vegetated rangelands, vegetation naturally structures runoff into the interspace between plants (Fig. 5). In these ecosystems, the soil supporting vegetated patches is often elevated compared to the surrounding area (Fig. 6) resulting in runoff being forced to flow between patches. Currently, flow concentration pathways are perceived as resource loss vessels that need to be minimized on both rangelands and croplands. This negative perception of channel network might limit a complete understanding of the role played by these processes on rangelands. A recent research in the Argentinian Dry Chaco woodlands (Magliano, Breshears, Fernandez, & Jobbagy, 2015) showed that rainfall intensity controlled runoff/runon redistribution patterns with sparsely vegetated rangeland patches were more effective than densely vegetated patches at capturing moisture under low intensity events while the denser patches performed better under high intensity events. While this study did not specifically address the role of concentrated flow erosion in the resource redistribution, it certainly highlights the sensitivity of rangeland ecosystems to resource redistribution. More research is needed to further clarify linkages between concentrated flow processes and resource redistribution mechanisms on rangelands.

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