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Biological soil crust effects must be included to accurately model infiltration and erosion in drylands: An example from Tabernas Badlands

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ABSTRACT

In dryland ecosystems, runoff is mainly generated in bare areas, which are also more susceptible to water erosion than vegetated areas. These bare areas are often covered and protected by biological soil crusts (BSCs), which modify numerous physicochemical surface properties involved in runoff and erosion processes. BSCs are considered as one of the most important stabilizing factors in the soil surface, but most previous research has concentrated only on patch or hillslope-scale effects of BSCs, and their effect at coarser scales has rarely been studied. In this article, we present a new approach based on previous surface cover quantification for including the effects of BSCs in physically-based runoff and erosion modeling. The Limburg Soil Erosion Model (LISEM) was used to parameterize and simulate the effects of BSCs on runoff and erosion in a small semiarid catchment characterized by fine-textured soils and predominantly covered by BSCs. Paired model simulations under two scenarios, with and without including the effects of BSCs, were run under different rainfall intensities to evaluate the effect of BSCs on runoff and erosion under different rainfall conditions. Runoff and erosion rates recorded in the field at the catchment outlet were predicted much more accurately when BSCs were included because there was less overestimation of runoff rate, maximum runoff peaks and erosion rates in the areas dominated by BSCs. The proposed approach enables BSCs to be included in spatially distributed runoff and erosion models, improving their predictions, and may be used for evaluating how the effect of human activity on BSCs affects catchment-scale water erosion.

1. Introduction

Chronic water scarcity in drylands combined with poor economies and unsustainable land use has increased land degradation problems, which are one of the major environmental issues of the 21st century (MEA, 2005). Soil erosion by water is considered as one of the major forms of land degradation in these landscapes, affecting numerous ecosystem services, such as water quality, water storage and recharge, nutrient cycle and flood attenuation (CSFD, 2007), with strong economic implications for land users and local populations (Adhikari and Nadella, 2011). Understanding and predicting soil erosion in drylands are indispensable for proper management of semiarid ecosystems and policy decisions for reducing land degradation.

Dryland systems have sparse vegetation cover embedded in a heterogeneous bare soil matrix. In this system, runoff is generated in bare areas and may be redistributed to vegetated patches, which act as surface obstruction and sinks for water, sediments and nutrients (Ludwig et al., 2005; Puigdefábregas, 2005; Cantón et al., 2011). In the absence of human disturbance, when soil conditions are stable enough, bare soils are often colonized by a complex community of specialized organisms comprised of cyanobacteria, algae, microfungi, lichen, mosses and other microorganisms that live within or immediately on the top of the soil surface (Belnap, 2006). These communities are known as biological soil crusts (BSCs), and can cover over 70% of the soil surface (Belnap et al., 2005), especially in areas where vascular plant growth is limited, such as on steep slopes or shallow soils (Lázaro et al., 2008). BSCs modify numerous physicochemical soil surface properties with strong implications for runoff generation and erosion (Belnap, 2006; Chamizo et al., 2012a). For instance, BSCs modify soil porosity (Miralles-Mellado et al., 2011), aggregate stability (Chamizo et al., 2012b), soil cohesion (Knapen et al., 2007) and surface microtopography (Kidron, 2007; Rodríguez-Caballero et al., 2012). There are contradictory results on the role that BSCs play in the partitioning of water into infiltration and runoff, depending on the soil texture (Warren, 2003). Thus, some studies have shown that BSCs allow for runoff generation in highly permeable sandy soils like predominant soils in the Negev, Israel, or Shapotou Desert, China (Verrecchia et al., 1995; Eldridge et al., 2002; Li et al., 2002, 2005; Kidron et al., 2003, 2012). Moreover, this effect may result in an increase

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in water erosion, since runoff generation is the main limiting factor controlling water erosion in these systems (Kidron and Yair, 2001). On fine-textured soils, where, in the absence of BSCs, soil surface is often sealed (Catt, 2001), BSC colonization results in a reduction in runoff (Eldridge et al., 2010; Chamizo et al., 2012a; Cantón et al., 2014; Lázaro et al., 2014) and water erosion (Bowker et al., 2008; Chamizo et al., 2012a; Rodríguez-Caballero et al., 2013; Chamizo et al., 2015). These studies have shown that although BSCs are considered as one of the most important soil stabilizing factors in all ecosystems (Kidron, 2001; Kidron and Yair, 2001; Bowker et al., 2008), and may reduce flow connectivity (Lázaro et al., 2014) and runoff generation (Chamizo et al., 2012a; Rodríguez-Caballero et al., 2013), compared to vegetated areas, they may be considered as runoff sources. The excess water may be harvested by downslope vegetation (Eldridge et al., 2002), and sometimes promote downslope erosion (Eldridge et al., 2000). Moreover, the hydrological behavior of BSCs varies depending on rainfall (Chamizo et al., 2012c; Kidron et al., 2012; Rodríguez-Caballero et al., 2013, 2014a). Thus during low intensity rains on fine textured soils, runoff on BSC patches is strongly controlled by microtopography (Rodríguez-Caballero et al., 2012), but this effect is masked during high-intensity rainfall (Kidron et al., 2012; Rodríguez-Caballero et al., 2013). In contrast, on BSCs covering coarse-textured soils, runoff rates are controlled by the duration of short intense rain pulses, which limit flow connectivity among areas covered by BSCs (Kidron, 2011). At larger scales, other processes control runoff generation and water erosion (Kirkby, 2002), and the effect of BSCs on these processes depends on their interaction with vegetation, which is also strongly affected by rainfall characteristics (Rodríguez-Caballero et al., 2014a). Therefore, the effect of the runoff generated in BSC areas should be evaluated at catchment scale and under different rainfall conditions to assess the combined impact of these effects and the potential for water harvested from crusted areas nourishing adjacent vegetated areas (Valentin et al., 1999; Rodríguez-Caballero et al., 2013). The uncertainty about their influence at larger scales limits knowledge of their role in ecosystem functioning and leads to some uncertainty about how they protect against catchment-scale water erosion.

Physically and spatially distributed runoff and erosion models are expected to be very useful in acquiring further knowledge of the effects of BSCs on drylands functioning due to their proficiency in simulating spatial patterns of water and sediment fluxes at catchment and ecosystem scales. Some of the most important and widely accepted spatially distributed models are the LISEM (Baartman et al., 2012), EROSION3D (Schmidt et al., 1999), Mefidis (Nunes et al., 2005) and MIKE-SHE (Refsgaard et al, 1995). All these models calculate runoff and sediment transport in each raster cell on a regular grid. Runoff and erosion generated in each cell are routed downstream towards the outlet using kinematic wave routing, providing a distributed image of runoff and sediment detachment and deposition. Although all erosion models have limitations in terms of representation of erosion processes, the Limburg Soil Erosion Model (LISEM) incorporates most soil properties and processes involved in runoff and erosion that have been demonstrated to be strongly modified by the presence of BSCs, such as surface storage in micro-depressions and overland flow (Rodríguez-Caballero et al., 2012), infiltration and vertical movement of water in the soil (Coppola et al., 2011; Chamizo et al., 2012a), soil porosity and water-holding capacity (Miralles-Mellado et al., 2011), cohesion (Knapen et al., 2007), aggregate stability and detachment by rainfall (Bowker et al., 2008; Chamizo et al, 2012b) and all their interactions. The LISEM can also simulate interception, infiltration and surface storage in different surface components as area-weighted fractions within a pixel. This is crucial to correctly model runoff generation and water erosion in drylands, where each pixel is usually a mixed cover of vegetation, BSCs and bare soil, with contrasting hydrological and erosional responses. This requires adequate continuous surface component distribution data and the resulting hydrological properties for accurate simulation of runoff and erosion patterns within a landscape. Although such data acquisition at landscape and catchment scales is too laborious and costly, especially in drylands, where vegetation cover and soil properties are highly variable (Ludwig et al., 2005), several other strategies may be adopted to generate spatially distributed maps of soil cover or properties (Sanchez-Moreno et al., 2014). The most common approach is to delineate different land or hydrological units from land use and soil type or texture class maps and assign representative values to vegetation properties and soil physical properties in the grid cells based on the classified information. However, because of their spatial heterogeneity, hydraulic soil properties in drylands are also highly variable, even within the same land unit. In such systems, assigning a representative value to soil cover or soil properties in each unit may hide land unit heterogeneity and mask the effect of spatial distribution of different surface components within the unit. An alternative to traditional land unit mapping strategies may be to characterize the soil properties of the different surface components in each pixel and then estimate the spatial distribution of the soil properties as measured in each surface component weighted by their relative fractions within a pixel. This methodology reduces the unrealistically sharp boundaries between land units and makes representation of spatial variability within land units, inherent to heterogeneous dryland systems possible.

Remote sensing provides spatially explicit information for characterizing the spatial distribution of different dryland surface components (Rodríguez-Caballero et al., 2014a), which is useful for erosion modeling (De Jong, 1994; Vrieling, 2006). However, it is difficult to apply traditional remote sensing techniques like spectral indices or hard classification in these heterogeneous systems, because as explained above, pixels often include a variety of different surface components such as different types of BSCs, bare soil and vegetation with contrasting hydrological and erosional behaviors (Alonso et al., 2014). Spectral mixture analysis (SMA) provides a means of detecting and representing subpixel surface components, and has previously been applied to quantify the relative cover of different types of BSCs, bare soil and vegetation (Rodríguez-Caballero et al., 2014b). SMA is based on the assumption that the pixel's spectrum is a linear combination of the spectrum of each cover type weighted by its relative proportion within the pixel (Smith et al., 1990), and provides an estimation of the proportion of the pixel belonging to each surface component (abundance). Such information may increase the accuracy of modeled runoff and erosion.

In this study, we used subpixel BSC cover data found by SMA (Rodríguez-Caballero et al., 2014a) for catchment-scale runoff and erosion modeling and evaluating the improvement in model predictions resulting from the consideration of this component of arid and semiarid ecosystems. To achieve this goal, we compared the modeling results when BSCs were included with those when they were not, and we also analyzed the interaction of water and sediments over bare soil, BSCs and vegetated areas within a small catchment characterized by fine-texture soils, to ultimately assess the global effect of BSCs on runoff and water erosion. We also attempted to answer some as yet unsolved questions required to find out the potential and the importance of including BSCs in modeling runoff and water erosion on fine-textured soils: i) Can the effect of BSCs on runoff and erosion be correctly parameterized using surface abundance images acquired by SMA? ii) Is the known plot-scale effect of BSCs strong enough to be reflected in the catchment output and also in runoff and sediment yield spatial patterns? iii) Do the effects of BSCs on runoff and erosion change under different rainfall intensities?

2. Material and methods

2.1. Study site

The study area is the El Cautivo experimental site, located in the Tabernas Desert in Almería, south-eastern Spain (N37°00′37″, W2°26′30″; Fig. 1). The Tabernas Desert is one of the most extensive badlands in Europe. The hydrological and erosion responses of this system have