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SMALL-SCALE GEODIVERSITY REGULATES FUNCTIONING, CONNECTIVITY, AND PRODUCTIVITY OF SHRUBBY, SEMI-ARID RANGELANDS

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ABSTRACT

Geodiversity has recently been attracting increasing attention as a measure of diversity for the physical components of natural environments. It has shown positive relations with biodiversity, as well as with several ecosystem services. Yet, so far, geodiversity studies have focused on relatively large spatial scales, ranging between hillslope, basin, and landform scales. It is proposed that either natural-induced or anthropogenic-induced, small-scale (centimeter-scale to few decimeter-scale) geodiversity has a large impact on the hydrological connectivity and overall functioning of semi-arid rangelands and other shrubby and woody drylands. It is further proposed that greater small-scale geodiversity increases the on-site retention of water and soil resources, decreasing the vulnerability of rangelands to prolonged droughts and climatic changes. Particularly, positive impact of moderate grazing intensity on rangelands functioning is demonstrated by the formation of livestock trampling routes, which transect hillslopes, increase ecosystem geodiversity, and modify the spatial redistribution of scarce water and soil resources at the patch scale. Numerical simulations of a mathematical model for vegetation patterns in water-limited systems show that the trampling routes increase the survivability of vegetation patches under prolonged droughts. In practical terms, the concept of small-scale geodiversity is relevant for the determination, monitoring, and assessment of land degradation, as well as for restoration projects of eroded lands and degraded ecosystems. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: environmental planning and management; patchy vegetation cover; source-sink ecosystems; structural versus functional connectivity; two versus three-phase mosaics

Geodiversity is defined as the natural heterogeneity of geological, geomorphic, and soil characteristics, and demonstrates the complexity of natural systems (Gray, 2005). The topic has been increasingly studied during the last decade, highlighting its relationship with natural diversity (Cañadas & Flaño, 2007), and particularly with vegetative biodiversity (Jačková & Romportl, 2008), ecosystem services (Gray, 2004, 2011; Hansom, 2012), hydrological cycles, and surface processes (Thomas, 2012). As such, geodiversity is clearly linked to the concept of hydrological connectivity, which is characterized as the extent to which materials are redistributed within a landscape unit (Okin *et al.*, 2015), and highlights the impact of both natural and anthropogenic types of ground surface cover on processes of water overland flow and soil erosion (Marchamalo *et al.*, in press). Understanding geodiversity is therefore a key requirement in a more sustainable future. However, the concept of geodiversity has not yet achieved the wide awareness that biodiversity has (Hansom, 2012).

Because geodiversity is scale-dependent, when assessing its occurrence and magnitude, the question of scale should be precisely defined. So far, the spatial range for studying geodiversity and its relationship with geo-ecosystems has focused on medium-scales to large-scales, ranging between the hillslope, basin (or watershed), and landform scales (Cañadas & Flaño, 2007; Jačková & Romportl, 2008; Thomas, 2012). In these scales, despite the potential impact of anthropogenic activities, such as land-use (change) and management practices – for example, vegetation clearing versus afforestation or reforestation – the focus has mainly been put on natural factors (i.e., factors not directly affected by human activities), such as lithology, topography, and pedology (Hudson & Inbar, 2012; Thomas, 2012). As such, the geodiversity-related terminology has been mainly directed at theoretical studies, aimed at understanding the inter-relations between this term and the rest of the physical and biotic components of geo-ecosystems. Yet, in practical terms, geodiversity provides an essential foundation to natural environments and is fundamental to the provision of a wide range of functions related to habitats and landscapes (Hansom, 2012). Regardless, geodiversity indices have been developed, aimed at comparing the geodiversity factor among different sites, as well as at enabling the extrapolation of analysis to data-limited sites. The indices consider several physical components, including geology, geomorphology, hydrology, pedology, and surface roughness of the selected sites, to a scale of 1 km^2 resolution (Cañadas & Flaño, 2007; Parks &

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Mulligan, 2010). However, these indices are not applicable for smaller-sized aerial units and cannot be utilized for monitoring smaller-scale geodiversity.

In addition to hillslope-scale geodiversity, basin-scale geodiversity, and landform-scale geodiversity, it is claimed here that smaller-scale geodiversity has a large impact on geo-ecosystems, because of its effect on the geo-ecosystem functioning, which is defined as the geo-ecosystem's capacity to retain scarce resources and control their loss to the outside of its boundaries (Tongway & Ludwig, 2003). This is particularly relevant for water-limited environments, such as semi-arid undulate and hilly shrublands and woodlands (Kropfl *et al*., 2013; Papanastasis *et al*., in press). Because of the limited water availability, such ecosystems do not consist of full vegetation cover but rather of two-phase mosaics, which are composed of vegetation patches and interpatch bare spaces. It has been widely acknowledged that the vegetation patches act as sinks for water that is generated as runoff in the interpatch spaces, controlling its leakage from the hillslopes (Cerdà, 1997; Kropfl *et al*., 2013). Over time, the sporadic vegetative patchiness is modified through a self-organization mechanism, into a spatial pattern, of which its vegetation patches occur to certain shapes, dimensions, and intervals (Ludwig *et al*., 1999). Together with the vegetative component, the soil of such ecosystems becomes spatially patterned, demonstrating considerable pedogenic differences between the source areas and sink patches (Cerdà, 1997; Kropfl *et al*., 2013). As opposed to such productive and self-sustained source-sink ecosystems, it has been shown that the clearing of shrubby or woody vegetation from these lands, for example, in order to negate competition with herbaceous vegetation for scarce water resources, has transformed them into net-source areas of resources, with the consequent accelerated soil erosion and land degradation (Oostwoud Wijdenes *et al*., 2001).

In addition to the vegetation cover, also the ground surface's rock fragment cover was reported to regulate water infiltration, and therefore, the spatial redistribution of water and sediments in hilly, semi-arid lands (Cerdà, 2001). The surface roughness and its associated pedogenic pattern in stony shrublands are affected by the percentage of the rock fragment cover (Valentin, 1994) and its positioning on the ground surface (Poesen & Ingelmo-Sanchez, 1992). In this regard, the relevant size fraction of rock fragment was reported to be ~1 cm and larger (Simanton *et al*., 1994), revealing the importance of the size scale of a few centimeter geodiversity for hillslope hydrological processes and ecosystem viability.

It is proposed here that geodiversity to a range of between one-decimeter to a few-decimeters scale can be mainly attributed to land-use and management practices (i.e., the anthropogenic factor). This is particularly relevant for rangelands, where type of livestock animals, and moreover, the grazing regimes, including stocking densities (number of animals per unit of land at any one time: Allen *et al*., 2011) and rates (number of animals per unit of land per unit of time: Allen *et al*., 2011), affect the soil and vegetation in a spatially patterned way (Trimble & Mendel, 1995). The effect of features and spatial-patterning of vegetation and soil on the redistribution of water and associated dissolved and suspended resources at the patch-scale and hillslope-scale (Ludwig *et al*., 1999; Tongway & Ludwig, 2003) demonstrate the positive relations between small-scale geodiversity and functioning of rangeland geo-ecosystems. For example, a recent study in the hilly, semi-arid northern Negev region of Israel has proposed that long-term moderate livestock density has transformed the originally two-phase ecosystems into three-phase mosaic shrublands. Across the region, in addition to shrubby patches of *Sarcopoterium spinosum* (L.) Spach and *Corydothymus capitatus* (L.) Rchb.f. and interpatch spaces composed of a range of annual and perennial herbaceous vegetation, the third phase encompasses livestock trampling routes. The routes are easily observable due to their elongated shape of exposed surface, which transect the hillslopes parallel to the contours (Figure 1). It was suggested that the routes – with a mean width of ~20 cm and a cover of ~10% of the hillslopes area – modify the spatial redistribution of resources at the patch scale. This is due to the highly compacted soil of the routes – which act almost as a net source area of water – that flow downslope and accumulate in the shrubby patches and in the remainder of the interpatch spaces. At the same time, the low incline of routes compared with the general slope, composed of ~ 5° and 15°, respectively, sharpens the step-like profile of hillslopes (Stavi *et al*., 2015). Therefore, we propose that the livestock trampling routes have a simultaneous impact on surface hydrological connectivity in two spatial scales. On the one hand, the cleared, compacted, and smooth surface of the routes increases connectivity at the patch scale, augmenting water availability for adjacent shrubby and herbaceous vegetation. On the

Figure 1. A characterizing (north-facing) hillslope in the hilly, semi-arid northern Negev of Israel. Note the livestock trampling routes transecting the hillside. For spatial scale, see the 10 × 10 m plot-frame in the center, and the standing person nearby its right-upper corner. Picture was taken by I. Stavi. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

other hand, the sharper step-like profile imposed by the occurrence of routes decreases connectivity at the hillslope scale, regulating the leakage of water off the hillsides. We assume that under low to normal precipitation regimes, these effects are predominant, encompassing an integral part of the geo-ecosystem structural connectivity (Okin *et al.*, 2015). At the same time, during extremely large rainstorms, an event-specific functional connectivity (Okin *et al.*, 2015) may be developed, overriding the buffer impact of routes (and vegetation), and making the whole hillslope become a consecutive contributor of water and associated resources to the downhill ephemeral stream, with the resultant accelerated soil erosion and land degradation.

Preliminary observations across the study region – revealing the three-phase mosaic hillslopes to be considerably more verdant than two-phase dominated hillslopes – have raised the idea that the susceptibility of the more complex type of ecosystem to droughts is lower than that of hillslopes from which the routes have been absent. Particularly, this was revealed by the preliminary study of the effects of trampling routes, by using numerical simulations of a well-known mathematical model of vegetation patterns in drylands (Kéfi *et al.*, 2010). In this model, the pattern-forming feedback is based on the infiltration contrast between vegetated and bare-soil domains, which is dictated by the parameter α that stands for maximum soil-water infiltration (Kéfi *et al.*, 2010; Yizhaq *et al.*, 2014; Stavi *et al.*, 2015). We used the same set of parameters as in Kéfi *et al.* (2010), including cumulative annual precipitation rates (although with a lower biomass diffusion coefficient value), in order to illustrate the ecosystem response to prolonged drought and to simulate the vegetation patterns in a specific site. The trampling routes were defined with lower values than the background, wherein the larger the value of α, the larger the effect of trampling routes. Figure 2 shows the response of vegetation biomass to a sharp decrease in precipitation – from 533 to 438 mm y^{-1} – for domains (50 × 50 m) with no trampling routes, with five trampling routes, and with seven trampling routes (39 cm width each) and for a 30-year duration. In the domains with no trampling routes, the vegetation did not survive the prolonged drought, whereas in the two domains with trampling routes, some of the vegetation patches survived. Figure 3 shows the vegetation total biomass along a gradual precipitation downshift in the same domains as in Figure 2 (with no trampling routes, with five routes, and with seven routes). The total biomass in the two domains with the trampling routes was found to be larger than that in the domain without trampling roots, and of which their vegetation survives under a lower precipitation rate. This leads us to conclude that the livestock-modified (three-phase) ecosystems have a higher tolerance for prolonged droughts, as well as for the widely accepted forecasts of worsening water availability following climatic change scenarios. Yet, it should be emphasized that this mathematical modeling approach is of a simple nature and has to be elaborated in order to more precisely describe the role of trampling routes in vegetation pattern formation.

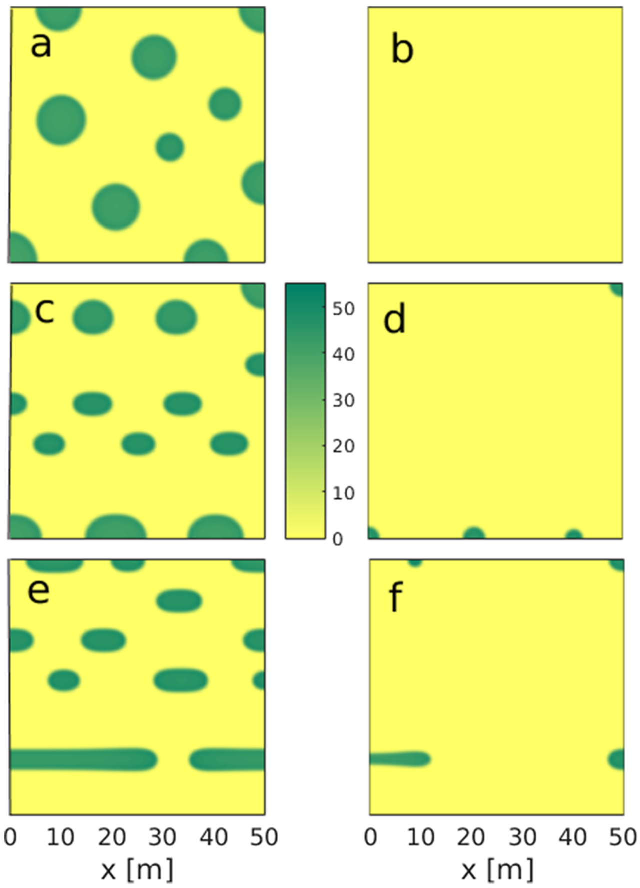

Figure 2. Numerical simulations of the model of Kéfi *et al.* (2010), showing the vegetation response to sharp decrease in precipitation from 533 (left panels) to 438 mm y^{-1} (right panels) for 30-year duration, and for different domains (50 × 50 m) in the presence of zero (panels a and b), three (panels c and d), and five (panels e and f) trampling routes. The parameters values are given by:

$c = 10, g_{max} = 0.05\ mm^{-1}m^{-2}, k_1 = 5\ mm, d = 0.25\ d^{-1}, k_2 = 5\ gr\ m^{-2}, W_0 = 0.2, r_w = 0.2\ d^{-1}, i_0 = 0.06\ d^{-1}, D_p = 0.005\ m^2d^{-1}, D_w = 0.1\ m^2d^{-1}, D_s = 100m^2d^{-1}$
and $\alpha = 0.2d^{-1}$ in the background, $\alpha = 0.04d^{-1}$ for the five trampling routes domain, and $\alpha = 0.001d^{-1}$ for the seven trampling routes domain. For more details on the model see: Kéfi *et al.*, 2010 and Yizhaq *et al.*, 2014. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Currently, additional studies are in the pipeline, aimed at empirically assessing and thoroughly modeling the impact of the prolonged droughts scenarios in two-phase mosaics versus three-phase mosaics. Regardless, it is important to stress that once livestock density becomes too high (overstocking), it can result in the complete clearing of vegetation cover (Gamoun *et al.*, 2010), or in the expansion of unpalatable woody vegetation (Schlesinger *et al.*, 1990). One way or another, under each of these scenarios, herbaceous vegetation cover becomes extinct, pastoral productivity gets lost, and the three-phase pattern vanishes (Stavi *et al.*, 2015). Regardless, unlike the widely common perception, this short report shows the overall positive impact of moderate livestock grazing on rangeland functioning and productivity. To some extent, a similar observation was indicated for

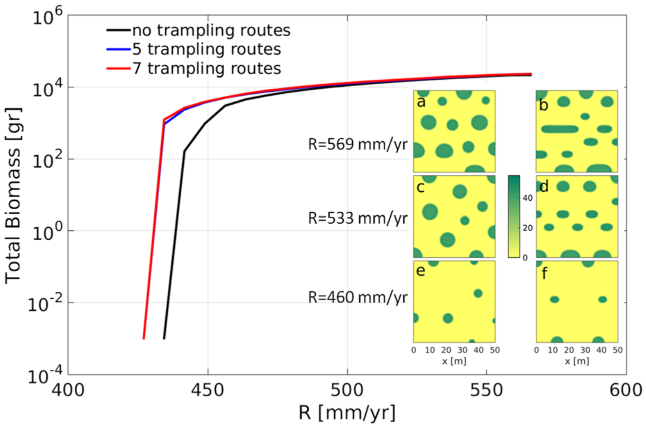

Figure 3. Numerical simulations of the model of Kéfi *et al.* (2010), showing the effect of decreasing precipitation (in $7 \cdot 3\ \mathrm{mm\,y^{-1}}$ steps) on the transition to the bare soil state for different number of trampling routes. The inset shows snapshot of the vegetation patterns for no trampling routes (a, c, and e) and for five trampling routes (b, d, and f). The parameter values are the same as in Figure 2. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

the Argentinean Patagonia, where livestock-induced greater spatial heterogeneity of soil and vegetation was proposed to accelerate the recovery of degraded semi-arid shrublands (Kropfl *et al.*, 2013). Also, somewhat similar to our study, in degraded Mediterranean shrublands in northern Greece, it was reported that compared with either heavy grazing or livestock exclusion, the implementation of moderate grazing has improved the overall provision of ecosystem services, with a particular increase in forage productivity (Papanastasis *et al.*, in press).

Overall, we propose that small-scale geodiversity should be considered as a relevant indicator or measure for assessing the functioning of semi-arid rangelands and their vulnerability to prolonged droughts or other abrupt conditions (known as catastrophic shifts or regime shifts. Rietkerk *et al.*, 2004). As such, it bears practical implications for land managers, pastoral and environmental planners, and policy makers. Also, it is proposed that the rate or degree of existing small-scale geodiversity can help in assessing land degradation, as well as the suitability of degraded lands for restoration projects, and for monitoring the success and performance of such activities. Moreover, it is stressed that sustaining small-scale geodiversity should be defined as a specific target to be achieved in land restoration projects. Also, specific efforts should be directed at developing an index for small-scale geodiversity, enabling the formation of an important unit-less means of quality control and comparisons among different geo-ecosystems.

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