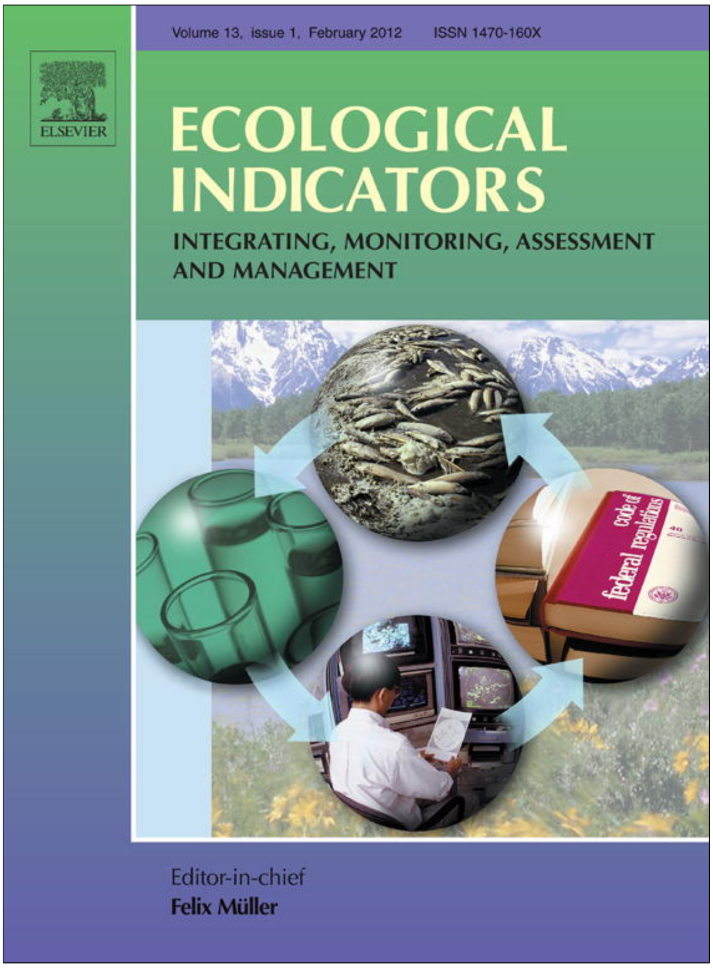
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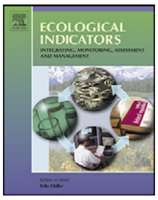

Multi-scale evaluation of soil functional indicators for the assessment of water and soil retention in Mediterranean semiarid landscapes

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ABSTRACT

Ecosystem monitoring and assessment are often based on functional indicators, which provide integrated and yet simple and affordable measures of key ecosystem functions. The landscape function analysis (LFA) assesses ecosystem functioning through three indices that represent basic soil functions: surface stability, infiltration, and nutrient cycling. Given the high scale-dependency of hydrological and erosion processes in semiarid ecosystems, the validation of the stability and infiltration indices requires a multi-scale approach, which has not been applied by previous works. Using records from a four-year monitoring of a semiarid landscape in SE Spain, we evaluated the LFA infiltration and stability indices against quantitative measurements of water and sediment flows at multiple scales. At the finest scale, the indices correctly reflected the higher infiltration and lower sediment production of plant patches as compared with bare-soil interpatches. The infiltration index also captured the spatial variation in the infiltration capacity of bare-soil interpatches. At the hillslope scale, total runoff was inversely related to the average infiltration index for bare-soil interpatches, but it was not related to the global infiltration index, which combines the values from both bare-soil interpatches and plant patches. These results suggest that the hydrological response of semiarid hillslopes depends mainly on the variation in the functioning of bare-soil interpatches. Total sediment yield from the hillslope plots was not related to the stability index. At the catchment scale, both the bare-soil interpatch and the global infiltration indices correctly captured the variability in total runoff produced by three micro-catchments of comparable size. The bare-soil infiltration index predicted bare-soil infiltration rate and hillslope runoff better than common simple indicators of soil functioning such as soil organic carbon, stone cover, crusted bare-soil cover, bulk-density and plant cover, and exhibited a similarly high indicatory potential that a variety of plant spatial-pattern indicators. In contrast to the multi-scale validation of the infiltration index, the indicatory potential of the stability index was only proved for the most contrasting soil conditions in the study site, pointing to a lower sensitivity of this latter index.

1. Introduction

The retention of water, frequently tied to the retention of soil and nutrients, is the most essential function in semiarid ecosystems (Whitford, 2002), and its assessment is crucial to the management of these ecosystems. However, measuring runoff and other water flows is highly time-consuming and costly, especially at large spatial extent. Instead of using direct measures of the processes of interest, methods based on functional indicators (i.e., indicators of ecosystem functions) are often used. The landscape functional analysis (LFA; Tongway and Hindley, 1995, 2004) assesses the functional status of an ecosystem or landscape by means of easily measured indicators of landscape structure and soil surface condition. These indicators are further integrated into three indices that represent basic soil functions: infiltration, surface stability and nutrient cycling. The LFA approach has been extensively applied in semiarid ecosystems worldwide, such as in Australia (e.g., Tongway and Hindley, 2000; McR. Holm et al., 2002; Ludwig et al., 2004; Bartley et al., 2006), Iran (Ata Rezaei et al., 2006), South Africa (Parker et al., 2009), Tunisia (Derbel et al., 2009), and Spain (Maestre and Cortina, 2004).

Before they can be reliably used, functional indicators require validation against direct measures of the ecosystem processes that they aim to represent (Dale and Beyeler, 2001). The magnitude and rates of many ecosystem processes are highly scale-dependent, which is certainly the case for runoff, erosion, transport and

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Table 1
Assessment scale, type and size of the hydrological monitoring units at El Ventós study site.

Assessment scale	Monitoring units	Unit size
Patch–interpatch	9 bare-soil microplots 15 plant-patch microplots	0.24 m^2
Hillslope	9 closed plots	16 m^2
Catchment	3 microcatchments (MC) 1 catchment (C)	3.0 ha (MC1) 3.7 ha (MC2) 6.0 ha (MC3) 20.2 ha (C12)

deposition of sediments (Mayor et al., 2011). Therefore, indicators aimed to represent the ecosystem potential for soil and water retention require validation at multiple scales. In spite of the broad application of the LFA indices, they have been only validated at very fine scales (e.g., plant patches and/or bare-soil interpatches), often using average estimates for scaling them up (McR. Holm et al., 2002; Tongway and Hindley, 2004; Ata Rezaei et al., 2006; Bartley et al., 2006; Maestre and Puche, 2009). Thus, the full potential of the LFA infiltration and stability indices as surrogates of soil and water retention remains unknown. To fill this gap, we aimed to (1) evaluate the LFA infiltration and stability indices against quantitative measurements of water and sediment flows at the patch–interpatch, hillslope and catchment scales, and (2) compare the predictive capacity of these indices with that of other well-known process-based and structure-based indicators of dryland hydrological functioning.

2. Material and methods

2.1. Study area

The study area is located in El Ventós Experimental Station, SE Spain. The climate is Mediterranean semiarid with average annual precipitation and temperature of 275 mm and 18 °C, respectively. The area represents a common Mediterranean semiarid landscape, characterized by steep slopes covered by a mosaic of alpha-grass (*Stipa tenacissima* L.) steppes and open shrublands, with gradual transitions between them. The vegetation cover, around 45% on average, is arranged in plant patches on a matrix of bare-soil interpatches. The soils, derived mainly from limestone and marls, are very shallow (<15 cm on average) and loamy to silty-loam in texture (Bautista et al., 2007).

2.2. Field sampling and data analysis

The LFA infiltration and stability indices were tested against quantitative direct measures of water and sediment flows at various scales (Table 1). At the finest scale (i.e., patch–interpatch scale), we used steady infiltration rate and sediment concentration records from rainfall simulation experiments performed on nine bare-soil and fifteen plant-patch microplots, for two contrasting soil moisture conditions: wet (antecedent soil moisture > 20%) and dry (antecedent soil moisture < 7%) soils (see further details in Mayor et al., 2009). At the hillslope and catchment scales, we used the records of total runoff and sediments produced from natural rainfall over a four-year monitoring period on nine closed hillslope-plots, three microcatchments, and one catchment (Table 1). During the monitoring period, the sediment production at the catchment scale was negligible (see further details in Mayor et al., 2011).

Following the LFA methodology (Tongway and Hindley, 2004), we estimated the LFA infiltration and stability indices by combining field measurements of eleven soil surface features: ground cover, canopy cover, litter cover and degree of decomposition, crust cover, crust fragmentation, erosion type and severity, amount of deposited materials, soil surface roughness, surface resistance to disturbance, crust stability, and soil texture. Using 50 cm × 50 cm sampling quadrats, and following a rating scale (Tongway and Hindley, 2004), these soil features were measured for bare-soil interpatches and the main types of plant patches in the area (*S. tenacissima* tussocks, shrubs, subshrubs, and perennial short grasses). The rainfall-simulation microplots were assessed using one LFA sampling-quadrat per microplot. Six, randomly selected bare-soil interpatches and twelve plant patches (three per patch type) were sampled per each catchment, and two additional bare-soil inter-patches were sampled per each hillslope plot. The plant patches within these plots were assumed to be well represented by the patches sampled at their respective, or nearby, catchments. For each catchment and plot, the percentage of the soil surface covered by bare-soil interpatches and by each type of plant patch was estimated from available high resolution vegetation maps (80 cm and 8 cm pixel size for catchment and plots, respectively). Two types of infiltration and stability indices were calculated for each plot and catchment: (1) average indices for bare-soil interpatches and (2) global indices, estimated by averaging patch and interpatch values, weighted by the relative cover of each type of surface.

At the patch–interpatch and hillslope scales, we also assessed the following soil surface properties: stone cover, crusted bare-soil cover, bulk density, and soil organic carbon (at 0–5 cm depth) (see methodological details in Bautista et al., 2007, and Mayor et al., 2009). In addition, using high-resolution vegetation maps of each hillslope plot, we estimated total plant cover and two plant-pattern indices, Flowlength index (Mayor et al., 2008) and directional leakiness index (DLI, Ludwig et al., 2002), which are conceptually related to the efficiency of the landscape to conserving resources, and have been successfully tested in semiarid lands.

3. Results and discussion

At the finest scale, the infiltration and stability indices correctly captured the contrasting hydrology of bare-soil interpatches and plant patches for wet soils (Fig. 1). However, the indices did not captured the hydrological variation within each type of surface, probably because the relatively rapid saturation of the very shallow soils of study could have masked the small variation in soil surface features that occurred within each type of surface (Mayor et al., 2009). For dry soils, we found a strong correlation between the infiltration index and the final infiltration rate of the bare-soil interpatches, but not between the stability index and the sediment concentration in runoff (Fig. 1; Table 2). These results are in agreement with previous works that have proved the indicatory potential of the LFA indices for small areas with highly contrasting vegetation cover (Tongway and Hindley, 2000; Roth, 2004; Bartley et al., 2006; Maestre and Puche, 2009). In addition, our results prove the high sensitivity of the LFA infiltration index to capturing very small variations in the water retention potential of bare soils, and a much lower sensitivity of the stability index.

At the hillslope scale, total plot runoff showed a significant negative relationship with the infiltration index for bare-soil interpatches (Fig. 2, left), but not with the global infiltration index, which considers the relative cover and the soil surface condition of both bare-soil interpatches and plant patches (Table 2). These results suggest that hillslope runoff highly depends on the soil surface condition of the bare-soil interpatches, which are the main runoff sources in semiarid lands. The stability index was not a good predictor variable of hillslope sediment yield (Table 2). The coefficient of variation of the bare-soil infiltration index (11.2%) was much higher than that of the stability index (5.8%), which points to a lower sensitivity of the latter index. Likewise the results at

Table 2
Spearman correlation coefficients between water and soil retention variables, measured at the patch–interpatch and hillslope scales and several water and soil retention indicators, including the infiltration and stability indices given by the LFA (landscape functional analysis) methodology. $N = 9$ in all cases.

	fc (mm h^{-1})[a,b]	Sediment concentration (g l^{-1})[b]	Total runoff (mm)	Sediment yield (g m^{-2})
Stone cover (%)	0.15	−0.65[‡]	−0.47	−0.50
Crusted bare-soil cover (%)	−0.19	0.66[*]	0.68[*]	0.71[*]
Soil organic C (%)	0.18	−0.07	−0.58[‡]	−0.50
Bulk density (g cm^{-3})	−0.55	−0.29	n.a.	n.a.
Plant cover (%)			0.07	−0.45
Flowlength index			0.72[*]	0.70[*]
Directional leakiness index			0.72[*]	0.88[*]
Bare-soil infiltration index	0.79[*]		−0.78[*]	
Bare-soil stability index		−0.04		−0.25
Global infiltration index			0.40	
Global stability index				0.17

Abreviations: n.a. = not available; DLI = directional leakiness index.

[a] Steady infiltration rate.

[b] Measured from rainfall simulations on dry bare-soil interpatches.

[*] Significant correlation at the $P \leq 0.05$ level.

[‡] Marginally significant correlation at the $P \leq 0.10$.

the patch–interpatch scale, this difference in sensitivity might fade when more contrasting areas are compared.

At the catchment scale, the infiltration index correctly described the variation in total runoff measured from the three catchments of comparable size (MC1, MC2 and MC3). However, the largest catchment (C12) produced less runoff than what could be expected according to its infiltration index value (Fig. 2, right), probably due to the effect of increasing transmission losses (water that infiltrates trough the channel bed) in response to increasing catchment size (Goodrich et al., 1997). These results stress the importance of being scale-consistent when using functional indices for comparative ecosystem assessment. Conversely to the hillslope scale,

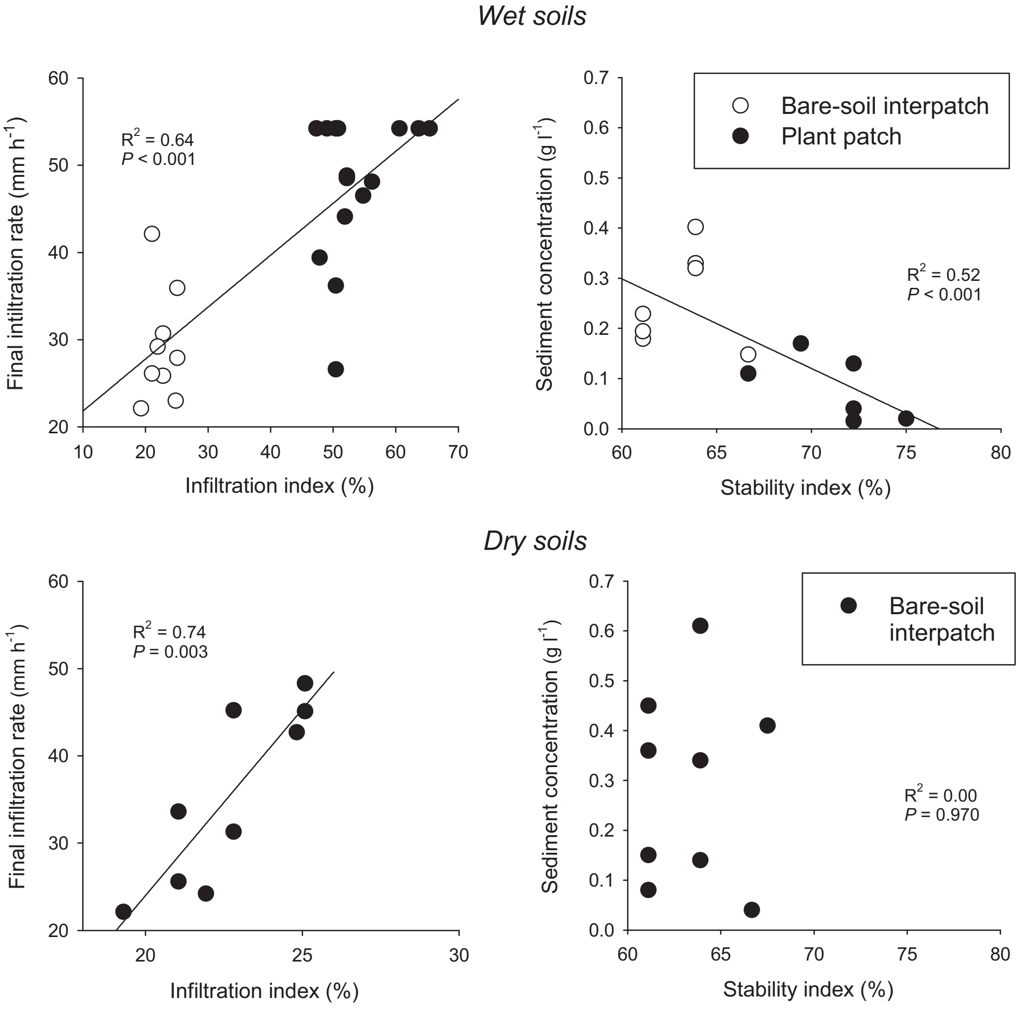

Fig. 1. Relationships between LFA infiltration and stability indices, and final infiltration rate and sediment concentration estimated from rainfall simulation experiments on bare-soil interpatches and plant patches for wet and dry initial soil conditions (plant patches did not produce runoff for dry soil conditions). Results from regression analyses and significant regression lines are shown.

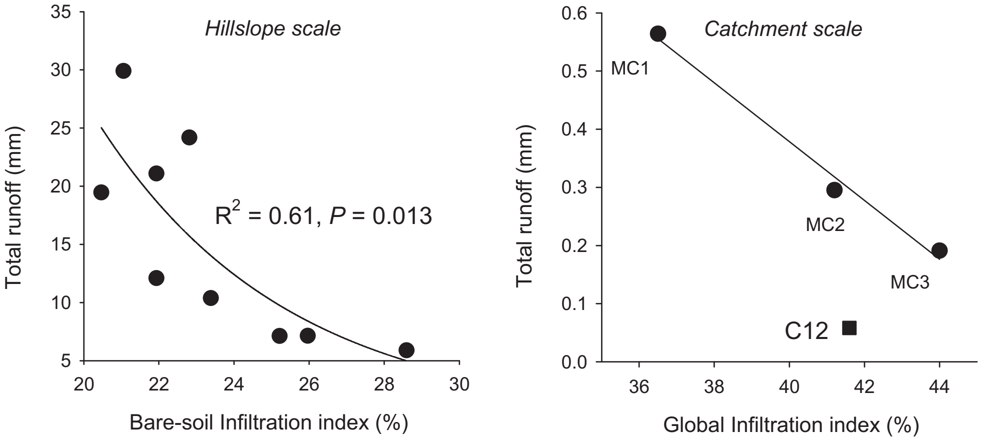

Fig. 2. Covariation between infiltration indices and total runoff produced at the hillslope scale (left), and the catchment scale (right) over a four-year monitoring period. MC1, MC2 and MC3 are micro-catchments 1, 2, and 3, respectively; C12 is catchment 12, which includes MC2 and MC3. Results of a non-linear regression analysis on hillslope-plot data are shown (left). For the three micro-catchments, the negative covariation trend between total runoff and the global infiltration index is illustrated by a linear fitting to the data (right).

the catchment-scale variation in total runoff was better captured by the global infiltration index than by the bare-soil infiltration index, probably because the variation in runoff-sink area among the catchments (coefficient of variation = 20.9%) was higher than the variation among the hillslope-plots assessed (coefficient of variation = 8.0%).

As compared with other common soil indicators and spatial-pattern metrics (Table 2), the bare-soil infiltration index was the best predictor variable for bare-soil infiltration capacity, and it was among the best predictor variables for hillslope runoff, together with the plant-pattern indices assessed (Flowlength index and DLI). Conversely, simple indicators such as stone cover and crusted bare-soil cover were better predictor variables for erosion potential than the LFA stability index.

4. Conclusions

Our results support the use of the LFA infiltration index as a surrogate of the ecosystem potential for water retention at the patch–interpatch, hillslope, and catchment scales. Besides, the infiltration index has proved to be very sensitive to relatively small variations in bare soil condition, capturing well the within-site variation in water infiltration and runoff yield in the study area. The infiltration index for bare-soil interpatches represented the within-site variation in hillslope runoff better than the global infiltration index. However, it would be expected that the global infiltration index might be more informative than the bare-soil index for areas with larger variation in plant cover and/or plant composition. In contrast to the infiltration index, the stability index only proved to be a good predictor variable of soil retention for the most contrasting soil conditions in the study site. In areas where sediment yield is strongly correlated to runoff yield, the infiltration index could be a good indicator for both water and soil retention. The stability index could complement the infiltration index when assessing contrasting areas where the variation in soil retention mostly depends on the variation in soil erodibility, and therefore on the sediment supply.

The information provided by the LFA indices is of great use when (i) comparatively evaluating the functional status resulting from the various land uses and management actions in target drylands, (ii) identifying and prioritizing dryland areas for conservation, sustainable management or restoration programmes, and (iii) exploring the role of a variety of environmental factors as drivers of dryland degradation or recovery.

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