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RESEARCH ARTICLE

Ecohydrological Source-Sink Interrelationships between Vegetation Patches and Soil Hydrological Properties along a Disturbance Gradient Reveal a Restoration Threshold

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Abstract

Vegetation, soil, and hydrology in drylands often collectively exhibit strong ecohydrological interrelationships in which vegetation both influences and is influenced by runoff, particularly on sites with more gradual slopes. These two-way relationships have important implications for ecological restoration of disturbed sites, such as those being reclaimed following mining, yet studies from both ecological and hydrological perspectives specifically evaluating how the strength of ecohydrological interrelationships varies for a range of natural and restored conditions are still missing. We assessed two-way relationships between vegetation and soil hydrological properties by evaluating patterns of both plant community structure and soil hydrological characteristics related to runoff for natural sites and restored sites following mining. At the plot scale, we identified eight ecohydrological units based on interrelationships between vegetation communities and hydrological properties associated with runoff along a progression from source to sink patch types. Similarly, at the hillslope scale, which included patches of different types, we found a correspondence between the proportions of source and sink patches and both vegetation community and hydrological properties. The relative strength of ecohydrological interrelationships in hillslope mosaics decreased with decreasing disturbance except for rilled hillslopes, likely because parts of the hillslope become isolated from the others. Our results highlight, in general, how ecohydrological interrelationships are related with degree of disturbance, and in particular, how rilling alters ecohydrological interrelationships, thereby precluding effective restoration.

Key words: disturbance, drylands, ecohydrological interrelationships, ecohydrology, hillslope, mining, restoration.

Introduction

Interrelationships between ecology and hydrology are increasingly recognized as central to environmental processes in drylands (Ludwig et al. 1997; Rodriguez-Iturbe & Porporato 2004; Wilcox & Thurow 2006). Most importantly, interactions between ecological and hydrological processes can generate interrelationships that determine patterns and drive ecosystem processes. This is of particular interest for restoration ecology in drylands, where retention of water and soils is a primary focus. For this purpose, one fundamental ecohydrological interrelationship that needs to be understood in drylands is between vegetation and redistribution of runoff (Tongway et al. 2001; Ludwig et al. 2005; McDonald et al. 2009). Restoration of drylands focuses not only on reestablishing patterns of vegetation cover, but also on restarting key ecosystem processes (Aronson et al. 1993; Suding & Hobbs 2009; Tongway & Ludwig 2010). Mining landscapes constitute one of the most extreme challenges for restoration ecology, as mining reclaimed terrains are characterized by a rudimentary structure with undeveloped to poorly developed soils and vegetation (Bradshaw 1983). Restoring key processes in such extremely disturbed sites poses major challenges, especially for the conservation of hydrological resources (Wilcox et al. 2003).

Recent successful mine restoration projects indicate that careful application of technical reclamation procedures and techniques can produce structurally and functionally diverse systems (Koch & Hobbs 2007). However, mining reclamation

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projects have historically failed in the application of comprehensive conceptual frameworks, their general understanding of reference ecosystems, long-term planning, and consideration of contingencies (Nicolau & Moreno-de las Heras 2005). Generally, rehabilitation of ecohydrological function in mining terrains starts with mechanical treatments such as furrowing or creation of micro catchments (Manu et al. 2000), but these treatments are usually ineffective in the long term because of increased erosive potential from the land surface (MacDonald & Melville 1999). Furthermore, these problems have been addressed by the incorporation of keystone species that can be sustained in the long term (Whisenant et al. 1995). Consequently, the application of mechanistic ecohydrological criteria that explicitly considers the interrelationships between vegetation and hydrology is critical to achieve primary management objectives such as optimization of water yields and restoration of degraded areas (Wilcox & Thurow 2006).

How ecohydrological processes and associated interrelationships change following disturbance is directly relevant to challenges associated with restoration of degraded landscapes (Eamus et al. 2006; Wilcox & Thurow 2006). To assess how ecohydrological interrelationships vary with disturbance and their implications for restoration, we evaluated patterns of both plant community structure and soil hydrological characteristics related to runoff in different sites that cover a broad spectrum of disturbance scenarios for restoration (natural areas subjected or not to grazing pressure and restored areas following mining with different levels of success). We specifically considered individual vegetation patches at a plot scale and how they related to patterns and responses at the hillslope scale. Our main objectives were: (1) to evaluate ecohydrological interrelationships at the patch scale, considering the interactions between vegetation communities and hydrological processes in both restored and natural slopes; (2) to explicitly evaluate two-way ecohydrological interrelationships between hydrological processes and vegetation structure at the hillslope scale; and (3) to identify a restoration threshold by comparing the strength of ecohydrological interrelationships among restored and natural hillslopes. We hypothesized (1) that individual patches defined by either vegetation community type or hydrological properties related to runoff would be interrelated; (2) that this interrelationship is evident at larger scales that include a mosaic of individual patches and is based on the relative proportions of source and sink patches; and (3) that the relative strength of ecohydrological interrelationships decreases inversely with disturbance from restored to natural mosaics.

Methods

Study Area

Our study site was located within the *Utrillas* coalfield (approximately 1100 m above sea level) in the Iberian Mountain Chain in Spain and encompassed a group of hillslopes that spanned a broad range of restoration stages. We selected 25 hillslopes that had been restored and revegetated following construction located in three different reclaimed mine spoil banks (*El Moral at* 40°47′50″N, 0°50′26″W, *Yermegada* at 40°48′38.93″N, 0°52′11.13″W, and *El Umbrión-Sabina* at 40°48′30.70″N, 0°52′55.84″W) and 10 natural slopes unaffected by mining activities (40°48′29.39″N, 0°52′23.18″W; see Fig. S1, Supporting Information). The climate in the area is Mediterranean-Continental type with a mean annual temperature of 14°C (ranging from a minimum mean daily temperature of 6.8°C in December and a maximum mean daily temperature of 23.5°C in July), with an air frost period between October and April. The local moisture regime can be classified as dry Mediterranean (Papadakis 1966) with mean annual precipitation of 480 mm (mainly concentrated in spring and autumn) and potential evapotranspiration of 759 mm, yielding a hydrological deficit of 292 mm running from June to October. The mean number of annual rainfall events in the area is approximately 50, with some convective rainstorms occurring especially in summer, characterized by high rainfall intensities of up to 100 mm in 24 hours (Peña et al. 2002).

The constructed hillslopes were built between 1985 and 1989 by the *Minas y Ferrocarril de Utrillas S.A.* mining company to have slopes between 20 and 30°. Outcropping materials were limestones, clays, marls, silt-sands, and sands from the *Escucha* and *Utrillas* cretacic formations of Albian age. Clay-loam overburden substrata (kaolinitic–illitic mineralogy) with 40–55% rock fragment content were selected to cover the landforms (100–250 cm layer). Revegetation of the slopes was implemented by cross-slope sowing with a mixture of perennial grasses (*Festuca rubra*, *F. arundinacea*, *Poa pratensis*, and *Lolium perenne*) and leguminous herbs (*Medicago sativa* and *Onobrychis viciifolia*). Although the hillslopes were restored using the same general procedures, they differed in their subsequent evolution (i.e. rilling, vegetation development), apparently due to differences in topography and/or some faults in up-slope structures (e.g. berms and channels used to isolate the hillslopes from outside sources of overland flow such as mining tracks and banks; Moreno-de las Heras et al. 2009). This particular feature gives us the opportunity to select two kinds of restored slopes that differ with respect to disturbance level, with 12 slopes that are rilled and 13 that are not.

Soils in natural slopes (unaffected by mining) range from *Typic* or *Lithic Xerorthent* to *Calcic Xerochrept* (*sensu* Soil Survey Staff 1998), and have a low content of organic matter (<3%) and basic pH (Arranz 2004). Most of the natural slopes are covered by sparse shrub communities (dominated by *Genista scorpius* and *Thymus vulgaris*) on abandoned terraces and by cereal crops. Three out of 10 natural slopes were subjected to a sheep grazing regime, thus providing another source of disturbance for the study.

Measurements of Vegetation and Hydrological Properties Related to Runoff

We measured several metrics of vegetation and soil hydrological properties related to runoff for each of the 35 study hillslopes (25 restored and 10 natural) that were selected to span

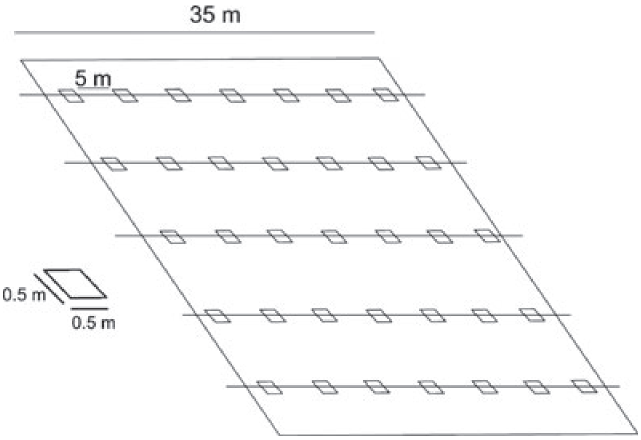


Figure 1. Sampling design: hillslopes ($n = 35$: 25 restored and 10 natural; restored slopes were either rilled or not rilled; natural were either grazed or not grazed), each with five transects perpendicular to the slope, with each transect having seven 0.5×0.5–m plots that were separated from neighboring plots on the same transect by 5 m.

a broad range of disturbance conditions. For each hillslope, five equidistant 35-m wide transects were located perpendicular with the slope. Each transect was divided into seven 0.5×0.5–m plots that were separated from each other by 5 m (Fig. 1). For each plot, measurements of cover characteristics related to surface, vegetation, and overland flow potential were obtained during the spring 2006. Surface cover was estimated from measurements of fractional cover of bare soil, stone, litter, and vegetation. Vegetation cover by species was also estimated through visual surveys of the canopy. This sampling procedure for vegetation survey has been successfully tested in reclaimed mining slopes of Mediterranean-dry Spain, encompassing more than 90% of species (Martínez-Ruiz et al. 2007). Characteristics of cover related to potential for overland flow were assessed using methodology similar to that of Barthès and Roose (2002), and included measurements of four overland flow features: sheet flow, rill flow, ponding areas, and infiltration areas. Sheet flow cover was estimated based on cover from surface crusts, stones on the soil surface, small pedestals, and microcliffs; rill flow cover was estimated based on cover of grooves, rills, and gullies; ponding area cover was estimated based on cover of surface microdepressions; and infiltration area cover was based on cover of vegetation and litter.

We estimated rill erosion rates at the slope scale from the rill network dimensions following the methodology of Morgan (1995). Three composite soil samples (each sample formed by three homogeneously mixed subsamples, randomly distributed in each parallel transect) were taken from the first 15 cm of the soil profile in each slope. Stoniness (%) was determined as the content of soil particles greater than 2 mm. Accumulated sheet erosion index (ASEI), which accounts for hydrological processes (i.e. the loss of fine soil particles from the soil surface as a consequence of sheet erosion) spanning the duration of the hillslope lifetime, was estimated using the method of Moreno-de las Heras et al. (2008), calculated as the ratio between mean rock fragment cover of the soil surface (estimated from rock fragment cover measured in 0.25-m^2 plots) and mean soil stoniness.

Data Analysis

We used a variety of approaches for analysis at the plot scale, the hillslope scale, and for hillslope scale analysis as related to ecohydrological interactions and disturbance (Table 1).

Plot Scale Analyses. At the scale of individual vegetation patches, which corresponds to plot measurements, vegetation cover data were analyzed using a divisive hierarchical classification obtained with Two-Way Indicator Species Analysis (TWINSPAN; Hill 1979). The maximum number of indicators

Table 1. Variables and statistical methods.

Variable	*Statistical Analyses*	*References*
Plot scale analyses		
Vegetation cover	TWINSPAN	Hill (1979)
Overland flow features	PCA	Legendre and Legendre (1998)
Vegetation cover and overland flow features	PERMANOVA	Anderson (2001); using the 'adonis' procedure in the vegan package (Oksanen et al. 2010; R package version 2.9.1; R Development Core Team 2009)
Hillslope scale analyses		
Vegetation community cover	Cluster	Tryon (1939)
Overland flow feature covers	Cluster	Tryon (1939)
Total vegetation cover, total species richness and Shannon's diversity	Kruskal–Wallis analysis for hydrological groups	Kruskal and Wallis (1952)
Rill erosion rate and sheet erosion index	Kruskal–Wallis analysis for vegetation groups	Kruskal and Wallis (1952)
Hillslope scale analysis—Ecohydrological interactions and disturbance		
Vegetation cover and overland flow features	Redundancy analysis	Legendre and Legendre (1998); using the vegan package (Oksanen et al. 2010; R package version 2.9.1; R Development Core Team 2009)

per division was five and the classification was followed up to the third division. The ‘characteristic species’ of each group were determined by indicator species analysis (Dufrene & Legendre 1997). In addition, we used nested permutational multivariate analysis of variance (PERMANOVA, Anderson 2001) to identify potential relationships between vegetation communities, as obtained with TWINSPAN, and hydrological properties (overland flow features). The PERMANOVA used the ‘adonis’ procedure in the vegan package (Oksanen et al. 2010; R package version 2.9.1; R Development Core Team 2009). The variables used for the test were the four overland flow features covers (sheet flow, rill flow, ponding areas, and infiltration areas), and the vegetation communities as the factor nested within slopes. For simplicity, we plotted the hydrological properties in a principal component analysis (PCA) (Legendre & Legendre 1998) and we used the first PCA axis to show the trends in overland flow hydrological behavior for the vegetation communities.

Hillslope Scale Analyses. At the larger scale of the hillslopes, each of which encompasses a mosaic of vegetation patches, measurements were classified using two cluster analyses (Tryon 1939): one for vegetation, and one for hydrological properties related to runoff. Variables of both cluster

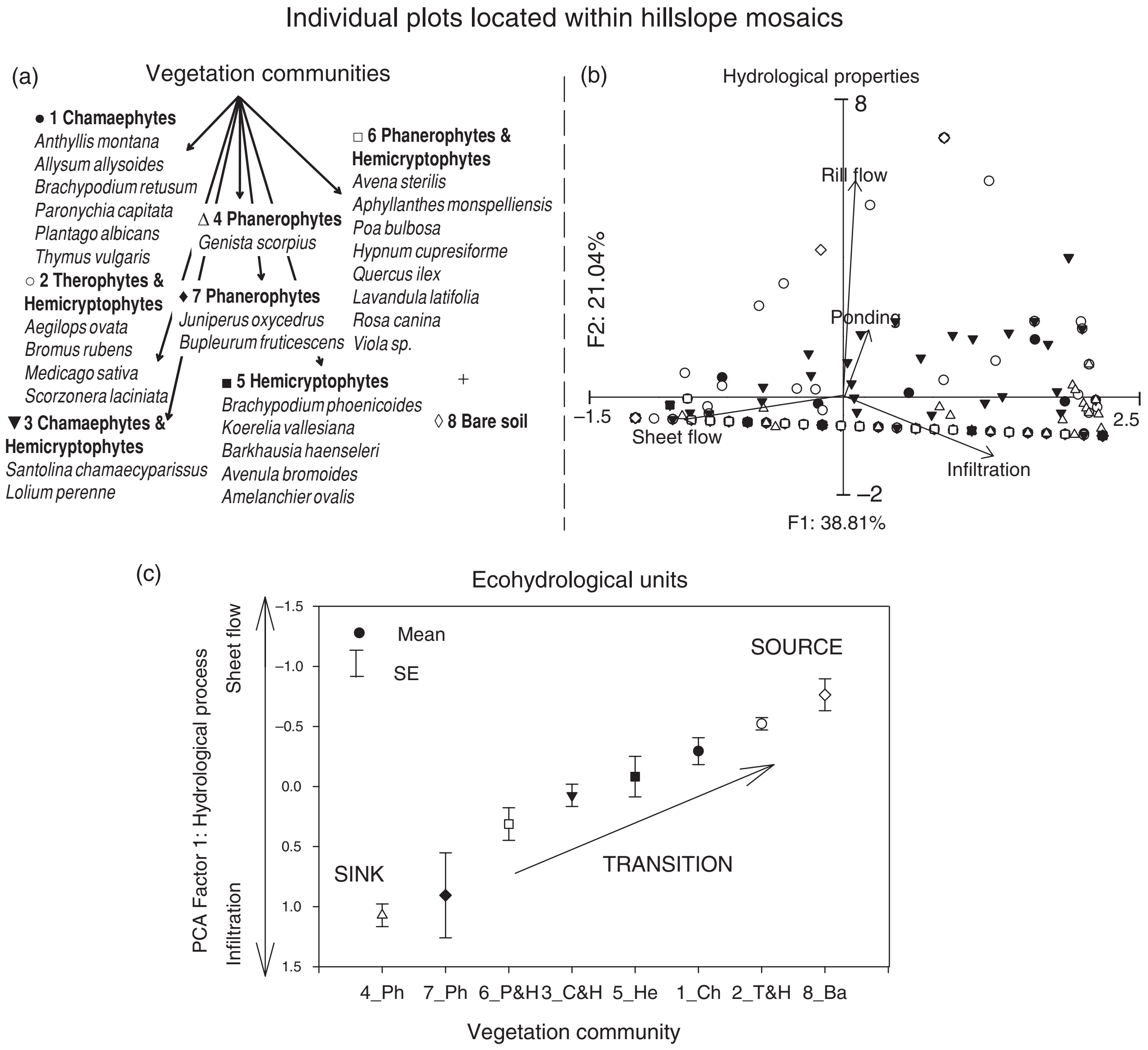


Figure 2. Identification of ecohydrological units linking vegetation communities and hydrological properties. (a) Vegetation communities identified using TWINSPAN and the characteristic species of each; bare soil was designated as an additional vegetation cover category. (b) Hydrological properties identified by PCA ordination, with symbols indicating vegetation community. (c) Ecohydrological units identified by PERMANOVA analysis between vegetation communities and hydrological properties (PCA 1): source, sink, and transition; for vegetation community in (c), labels are community numbers connected with an underscore to an abbreviation for the community name.

classifications were independent from the variables selected for the characterization of the obtained groups. For each slope, the variables used to identify vegetation groups were vegetation community covers per slope, and the variables used to identify hydrological groups were the four overland flow features covers (sheet flow, rill flow, ponding areas, and infiltration areas). Setup parameters were Euclidean distance measure and Ward's group linkage method (Ward 1963).

To evaluate potential associations between vegetation and hydrological properties, hydrological groups were evaluated for differences in vegetation properties different from those used in determining the vegetation groups (total vegetation cover, total species richness, and Shannon's diversity at slope scale). Similarly, vegetation groups were evaluated for differences in hydrological properties different from those used in determining the hydrological groups (rill erosion rate and sheet erosion index, both measured at slope scale). Significant differences (considered at $\alpha = 0.05$) among groups for a given property were determined by Kruskal–Wallis analysis.

To evaluate the strength of the two-way interrelationships we used a redundancy analysis (RDA; Legendre & Legendre 1998; R package version 2.9.1; R Development Core Team 2009) which quantifies the percent of variance in vegetation explained by hydrological properties related to runoff. For this, we classified the slopes in four disturbance categories: Restored rilled (12 slopes), restored not rilled (13 slopes), natural grazed (3 slopes), and natural ungrazed (7 slopes) and we performed the RDA for each disturbance group. The variables used in the analysis were the species vegetation matrix for vegetation and overland flow features for hydrological properties. Other statistical analyses were performed using STATISTICA (Statsoft 2001).

Results

Plot Scale Analyses of Vegetation, Hydrological Properties Related to Runoff, and Ecohydrological Units

For vegetation at the plot scale, the TWINSPAN analysis identified seven different vegetation communities based on floristic composition of 110 species appearing in more than 5% of the plots (Fig. 2a). For its use in subsequent analyses, we designated bare soil as an additional community, resulting in a total of eight community types. Community composition was significantly related with soil hydrological properties (PERMANOVA, $F_{[1,1224]} = 38.78$, $R^2 = 0.18$, $p < 0.001$). For hydrological properties related to runoff at the plot scale, the PCA analysis indicated two main gradients (Fig. 2b). The first component of the PCA explained 38.81% of the variance and roughly corresponded to gradients of infiltration and sheet flow; the second component of the PCA explained an additional 21.04% and roughly corresponded to

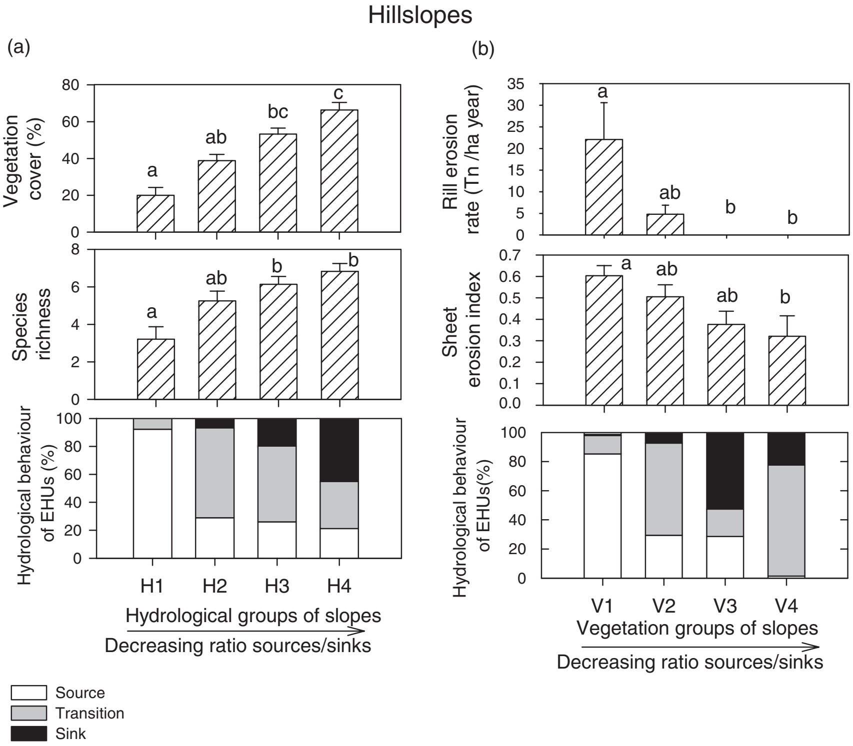


Figure 3. Classification of hillslopes based on hydrological properties (a) and vegetation properties (b) using cluster, resulting in four groups in either case. Hydrological groups were evaluated for differences in vegetation properties other than those used in determining the vegetation groups (cover and richness); similarly, vegetation groups were evaluated for differences in hydrological properties other than those used in determining the hydrological groups (rill erosion and sheet erosion). Significant differences among groups for a given property are indicated by different letters (Kruskal–Wallis).

rill flow. Numerous plots are lined up at the bottom of the second axis because of the way the variance-covariance based PCA method orders plots with extreme variance along an axis. Nevertheless, we only used axis one, for which this was not an issue, for subsequent analysis.

We designated ‘ecohydrological units’ based on the eight vegetation community categories and their associated hydrological properties along the main environmental gradient (PCA 1). These ecohydrological units were differentiated into three main hydrological behaviors: sources of runoff, sinks of runoff, and a transition state between these two (Fig. 2c). In general, the *sink* group is composed of two vegetation communities (4 and 7) that include mainly phanerophytes and are characterized by high vegetation cover (Fig. 2a) and domination of infiltration processes (Fig. 2c). One of these sink communities (7) is dominated by *Juniperus oxycedrus* and *Bupleurum fruticescens*, which occurs only on natural hillslopes, and the other (4) is dominated by *Genista scorpius* and occurs mainly on restored hillslopes. The *source* group is composed of two vegetation communities (2 and 8) that occur primarily on restored hillslopes: one dominated by bare soil (8) and the other characterized by terophytes and hemicryptophytes and having low vegetation covers (2); both communities are characterized by sheet flow hydrological processes. The third group of ecohydrological units is the *transition* between sources and sinks of runoff, represented by four ecohydrological units (1, 3, 5, and 6) that are characterized by the presence of chamaephytes, hemicryptophytes and phanerophytes, and scarcely terophytes, which occur on both natural and restored slopes (Table S1, Supporting Information).

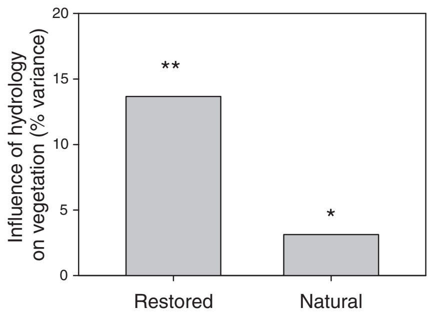
Hillslope Scale Analyses of Vegetation and Hydrological Properties Related to Runoff

At the larger scale of the hillslopes, each of which encompasses a mosaic of vegetation patches, measurements were classified using two Cluster analyses: one for vegetation and one for hydrological properties related to runoff. Classification of hillslopes using cluster resulted in four groups based on either hydrological properties (Fig. 3a) or vegetation properties (Fig. 3b). Resulting hydrological groups differed in vegetation cover and species richness, which largely reflected the changes in the proportions of source and sink areas (Fig. 3a; see also Table S2, Supporting Information). Similarly, resulting vegetation groups showed significant differences for both rill erosion and ASEI (Fig. 3b; see also Table S3, Supporting Information). These differences are also largely reflected in the changes in the proportions of source to sink areas (Fig. 3b).

Ecohydrological Interrelationships Strength Assessed as Vegetation Variation Explained by Hydrological Processes

Ecohydrological interrelationships strength estimated by RDA indicated how much of the variation in vegetation properties was explained by hydrologic properties (Fig. 4). Vegetation variability is better explained by hydrology in restored slopes (13.7%) than in natural slopes (3.1%; Fig. 4a). Additionally, the variation in vegetation explained by hydrological processes also varies in response to disturbance type (Fig. 4b), with the higher amount of vegetation being explained by hydrological processes occurring in restored not rilled slopes (16.7%) and the lowest amount explained for natural ungrazed slopes (3.0%).

(a) Ecohydrological interrelationship and restoration



(b) Ecohydrological interrelationship and disturbance

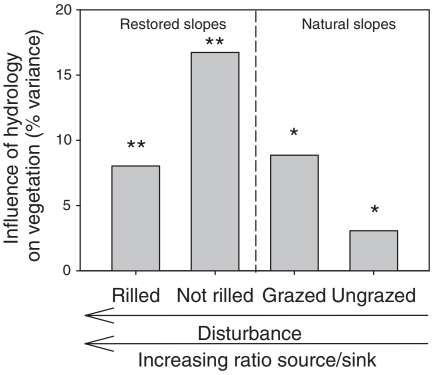


Figure 4. Ecohydrological interrelationship strength estimated by RDA in each disturbance group to determine how much of the variation in vegetation properties is explained by hydrologic properties along a gradient of disturbance and with respect to the ratio of source to sink area, (a) for hillslopes when aggregated to restored or natural, and (b) for hillslopes that were restored rilled, restored not rilled, natural grazed, and natural ungrazed. Statistical significance codes: ‘**’ = 0.01; ‘*’ = 0.05.

Discussion

Our results at both the patch and hillslope scales, evaluated from both ecological and hydrological perspectives, collectively and using multiple approaches, provide a generally consistent picture of associations between vegetation and hydrological properties leading to runoff, and indicate ecohydrological interrelationships that vary in strength with disturbance. In fact, our results illustrate that species composition at the patch scale corresponds directly with three main types of ecohydrological behavior: runoff sources, runoff sinks, and transitions between sources and sinks. Such differentiation between sources and sinks of runoff has been previously shown to influence plant growth and the development of bare patches (Pugnaire et al. 1996; Ludwig et al. 2005), with runoff from bare source patches being captured as run-on in herbaceous

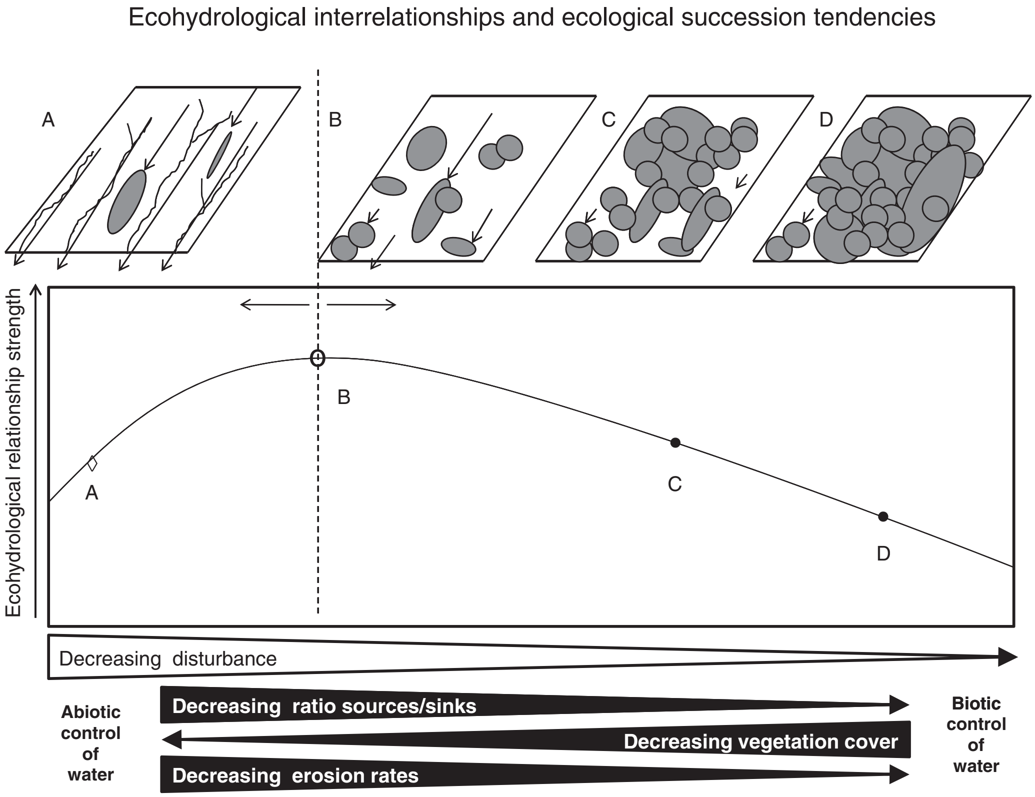


Figure 5. Hypothesized trend in which the strength of the ecohydrological interrelationships between vegetation and hydrology varies along a gradient of disturbance spanning from highly disturbed hillslopes having rills (open diamond) to moderately disturbed hillslopes that are not rilled (open circle) to relatively undisturbed hillslopes with higher amounts of vegetation cover (solid circle). The ratio of source to sink area, the amount of vegetation cover, and erosion rates vary with disturbance along the gradient. The strength of the ecohydrological two-way relationship increases from the relatively undisturbed state to more disturbed states until rilling begins, after which the strength of the feedback decreases because parts of the hillslope become isolated from one another. The effectiveness of restoration hinges on preventing rilling which alters the trajectory of future change by the way in which it affects the ecohydrological feedback.

patches (Seghieri & Galle 1999; Yu et al. 2008; Urgeghe et al. 2010). Other studies have found relationships for runoff and soil erosion with vegetation characteristics of canopy cover (Quinton et al. 1997) and plant morphology (Cerda 1997; Bochet et al. 2006). Our results illustrate how plant functional types, not just vegetation cover, are directly related to hydrological processes. Plant functional types of individual vegetation patches can therefore be used to infer hydrological properties and vice versa. The significant differences in the three types of ecohydrological units identified at the patch scale are apparently substantial enough to drive interrelationships between vegetation patterns and hydrological processes at the hillslope scale. Progressive changes in the proportions of source and sink ecohydrological units are loosely echoed in a variety of vegetation and hydrological characteristics.

The generally consistent results indicating that vegetation characteristics correspond to hydrologic properties and vice versa suggest a two-way feedback from hydrology to vegetation and from vegetation to hydrology. The redundancy analyses provide more direct support of such feedback, consistent with other studies and models of this process (Ludwig et al. 2005; McDonald et al. 2009). However, our results reveal that the strength of such ecohydrological interrelationships may vary with the degree to which a hillslope is disturbed. Our experimental design, which included hillslopes subject to a range of disturbance regimes, allowed us to evaluate the effect of disturbance in ecohydrological interrelationships.

Our results illustrate how the relative strength of ecohydrological interactions in hillslope mosaics decreased with decreasing disturbance, from unrilled restored to ungrazed natural ones (Fig. 5). Notably, however, rilled restored hillslopes—the most disturbed type—had weaker ecohydrological interrelationships than unrilled restored ones. Our results from a progression of disturbance regimes (the '*soil erosion disturbance transect*') highlight a major threshold between rilled (with a clear abiotic control of water) and unrilled slopes. Such behavior is consistent with previous research describing patterns of overland flow generation and continuity in association with different climatic conditions (the '*climatic transect*'), where the controls over soil erosion exhibited a sharp threshold-type behavior between abiotic-controlled (arid) and biotic-controlled (humid) systems (Lavee et al. 1998). This threshold-like transition in both the soil erosion disturbance and climatic transects is ultimately associated with connectivity features that influence plant water availability in the hillslope. In short, the relative strength of ecohydrological interactions in hillslope mosaics decreased with decreasing disturbance except for rilled hillslopes, likely because rilling isolates different parts of the hillslope (Espigares et al. 2011; Moreno-de las Heras et al. 2010; Moreno-de las Heras et al. 2011). Not surprisingly, our results show a low amount of variance explained in all cases, which is a common finding given that the study was not developed under controlled conditions. Our results highlight, in general, how ecohydrological feedbacks are interrelated with degree of disturbance, and have useful implications for restoration; managers should pay special attention in trying to avoid the rilling process, where vegetation–runoff interrelationships are minimized.

Our results highlight that ecohydrological interrelationships underlie the progression of a restored hillslope toward a less disturbed one, with the interrelationships becoming less strong as more vegetation establishes and the ratio of source/sink area decreases. Indeed, there is an optimum ratio of bare to herbaceous cover that maximizes the total amount of water that herbaceous patches can capture (Yu et al. 2008; Urgeghe et al. 2010). In fact, when rilling occurs, this trajectory is altered because the connectivity from source patches to sink patches is circumvented by the rills. Consequently, a different type of ecohydrological interrelationship proceeds in rilled hillsopes. Particularly in the case of constructed slopes, land managers should strive to avoid reaching the rilling threshold (open circle in Fig. 5). Therefore, caution must be applied when ecohydrological interrelationships are strong because the system can bifurcate toward a weaker feedback either in a desired progression toward a more vegetated and less disturbed state or toward an undesired highly rilled state—an insight not generally appreciated from a more traditional focus on simply the presence or absence or rilling.

Implications for Practice

- Ecohydrological interrelationships stem from ecohydrological units, where functional types of vegetation, not just vegetation cover, are directly related to hydrological processes and vice versa. These ecohydrological interrelationships can be easily derived from metrics of vegetation and hydrological processes.
- The strength of the ecohydrological interrelationships is higher in restored slopes than in natural slopes.
- Recognizing where ecohydrological interrelationships are minimal is fundamental to achieving the objectives of restoration.
- Restoration activities in semiarid landscapes need to successfully repair key ecohydrological processes. Managing to minimize initial rill establishment is central to long-term success of restored hillslopes, such as mine spoils and other disturbed landscapes.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Slopes selected for study [orthophotos obtained from Plan Nacional de Ortofotografía Aérea de España (PNOA), Instituto Geográfico Nacional].

Table S1. Comparison of hydrological, cover and plant traits associated to the ecohydrological units (mean ± SE).

Table S2. Basic characteristic (mean ± SE) of the four slope's groups obtained from cluster analysis of hydrological data.

Table S3. Basic characteristic (mean ± SE) of the four slope's groups obtained from cluster analysis of vegetation data.