Journal of Arid Environments 193 (2021) 104585

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Disentangling the independent effects of vegetation cover and pattern on runoff and sediment yield in dryland systems – Uncovering processes through mimicked plant patches

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A R T I C L E I N F O

Keywords:
Hydrological connectivity
Patch density
Patch size
Plant spatial pattern
Semiarid
Source-sink dynamics

A B S T R A C T

There is strong empirical evidence on the importance of the spatial pattern of vegetation in dryland hydrologic and geomorphologic dynamics. However, changes in vegetation cover and spatial pattern are often linked, making it difficult to disentangle and assess their independent hydro-geomorphologic roles. We used synthetic sponges placed on the soil surface to mimic the aboveground structure of vegetation patches, and manipulated patch cover and pattern as well as the sink capacity of the patches on a set of 24 (2 × 1 m) runoff plots. Combining natural-rainfall and simulated-rainfall experiments, we aimed to test that (1) both vegetation cover and pattern independently control runoff and sediment yield; (2) for any given cover, coarsening the vegetation pattern entails increasing runoff and sediment yield; and (3) pattern effect is mostly exerted by modulating the source-sink dynamics of the system. We found that increasing either patch cover or patch density decreased runoff and sediment yields from natural rainfalls, yet the effect of patch density largely disappeared when the effect of the co-varying patch cover was removed. Simulated-rainfall experiments on plots with equal medium-low patch cover showed however that coarser patterns (lower patch density; higher patch size) increased runoff coefficients and reduced time to runoff as compared with finer patterns. The effect of patch density was particularly clear when the sink function of vegetation patches was also mimicked. Rainfall interception and direct soil protection proved to be critical mechanisms underlying the effects of patch cover, yet they barely contributed to the effects of patch pattern. The control of overland flow by patch pattern was exerted through changes in the level of runoff disruption. However, physical obstructions to runoff hardly reduced runoff unless coupled to mimicked soil sinks. Overall this work demonstrates the independent effects of patch cover and pattern on the hydro-geomorphologic functioning of patchy landscapes, with patch cover being the primary hydrologic control factor and patch pattern exhibiting its full potential for low and medium low patch cover values. Our findings provide useful information for modelling and understanding dryland vegetation dynamics, and for designing management and restoration measures that take into account the critical role played by source-sink dynamics and hydrological connectivity in dryland landscapes.

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1. Introduction

Vegetation exerts a multifaceted control of the hydrologic and geomorphologic dynamics of ecosystems and landscapes. This control relies on mechanisms such as rainfall interception (Love et al., 2010; Li et al., 2017), evapotranspiration (Bosch and Hewlett, 1982), physical obstruction to overland flow (Ludwig and Tongway 1996), soil protection from rain splash (Osborn, 1954; Bochet et al., 1998), and improved soil structure, enhanced infiltration capacity, and increased soil

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https://doi.org/10.1016/j.jaridenv.2021.104585
Received 14 March 2021; Received in revised form 13 June 2021; Accepted 17 June 2021

cohesion (Gyssels et al., 2005; Mayor et al., 2009). Most if not all of these mechanisms are modulated by the multidimensional structure of the vegetation (Liu et al., 2018).

In dryland ecosystems, where water scarcity typically leads to patchy vegetation, vegetation cover is of paramount importance to the hydrologic and geomorphologic dynamics of the landscape (Thornes, 1990). The mosaic of vegetation patches and bare-soil interpatches that characterizes water-limited ecosystems results in an associated mosaic of hydrologic functioning (Pariente 2002), with bare-soil areas exhibiting relatively low infiltration capacity, acting as sources of runoff, sediments, and other resources, and with vegetation patches acting as relative sinks (Tongway and Ludwig 1997; Puigdefábregas et al., 1999; Ludwig et al., 2005). Vegetation cover determines the proportion of the surface that may behave as sink, and the area where the vegetation exerts its multiple control effects on runoff and erosion. Furthermore, the hydro-geomorphologic behavior of drylands is largely dominated by surface processes such as infiltration-excess overland flow, soil crusting, and source-sink dynamics (Martínez-Mena et al., 1998; Ludwig et al., 2005; Cantón et al., 2011), which in turn further reinforces the control role played by vegetation cover.

In addition to the amount of vegetation cover, the spatial pattern of such cover can also be critical for the functioning of dryland ecosystems (Aguiar and Sala, 1999; Svejcar et al., 2014; Berdugo et al., 2017), and for the hydro-geomorphologic functioning in particular (Cammeraat and Imeson, 1999). Using experimental runoff plots that exhibited a variety of vegetation spatial pattern for a very narrow range of variation in vegetation cover, Bautista et al. (2007) illustrated the cover-independent importance of vegetation pattern and bare-soil connectivity to runoff and sediment yield, finding an inverse relationship between patch density and runoff. Similarly, field evidence and simulation studies on spotted patterns suggested that fine-grained patterns are more efficient than coarse-grained patterns in reducing water and soil loss from semiarid slopes, which is mostly attributed to increased resistance to overland flow, and decreased flow concentration and velocity (Abrahams et al., 1995; Puigdefábregas, 2005; Boer and Puigdefábregas, 2005). However, many vegetation pattern properties are not independent of vegetation cover (Gardner et al., 1987), and correlations between vegetation cover and pattern metrics such as bare-soil connectivity (Rodríguez et al., 2018) and patch size (Meloni et al., 2020) have been commonly reported. The dependence of vegetation pattern on vegetation cover makes it difficult to disentangle their independent role and relative importance in shaping the hydro-geomorphic behavior of ecosystems and landscapes.

Furthermore, the particular role of vegetation cover and pattern could vary as a function of the eco-hydrologic and eco-geomorphic mechanisms considered. Thus, it could be expected that interception losses mostly depend on vegetation cover, as evaporation from a wet canopy linearly depends on canopy cover (Gash et al., 1995), whereas water and soil retention by physically obstructing runoff and trapping sediments could largely respond to the spatial arrangement of the vegetation patches, with patterns that minimize the connectivity of the bare soil being the most efficient (Mayor et al., 2008). Overall, reducing runoff and sediment yield by increasing the sink capacity of the dryland system would depend on both vegetation cover and pattern, with the former determining the amount of sink areas, and the latter modulating the potential of those sink areas for capturing and conserving on site the resources redistributed by runoff (Puigdefábregas et al., 1999; Urgeghe et al., 2010). These hypothetical differentiated roles have not been empirically tested and their relative contribution to water and soil conservation is unknown.

In this work, we followed a manipulative experimental approach to assess the independent effect and relative importance of vegetation cover and vegetation pattern as hydro-geomorphologic control factors, and to disentangle how cover and pattern effects are exerted through changes in rainfall interception, obstruction to overland flow, and source-sink processes. On a series of 24 experimental runoff plots, we independently manipulated the amount and spatial arrangement of ground cover and evaluated the effects on runoff and sediment yield. We used synthetic sponges placed on the soil surface to mimic the aboveground structure of vegetation patches, and manipulated their sink capacity with the aid of artificial runoff traps added to the patches. We aimed to test the hypotheses that (1) both vegetation cover and pattern can independently contribute to control runoff and sediment yield; (2) for any given cover, coarsening the vegetation pattern would entail increasing runoff and sediment yield; and (3) pattern effect is mostly exerted by modulating the source-sink dynamics of the system.

2. Methods

2.1. Experimental design and setting

The experimental setting comprised a set of 24 (2 × 1 m) runoff plots, installed in outdoor experimental facilities of the University of Alicante (38° 22′ 03″ N; 0° 31′ 09″ W), Southeast Spain. The climate is semiarid Mediterranean, with an average annual rainfall of 311 mm, which falls mainly in autumn, and an average annual temperature of 18.3 °C (AEMET, Alicante Meteorological Station, 1981–2010 period). The plots were placed contiguous to each other on a homogenous slope (2 m long, 25 m wide, 48% slope angle) built *ad hoc* for experimentation purposes. The experimental slope consisted of a concrete border structure filled with a homogenized and sieved (2 cm sieve) mix of soil material collected from nearby abandoned crop terraces. The soil mix was calcareous, slightly saline, with a loamy texture and a low amount of organic carbon (0.40 ± 0.01%). The plots were separated by 30 cm high steel sheets partially inserted into the soil mix. At the bottom of each plot, we installed a runoff collector (1-m long trough) connected through a pipe to a runoff collection tank. We used synthetic sponges (8 × 12.5 cm in size) placed on the soil surface of the experimental plots to mimic plant patches (Fig. 1). The sponges were fixed to the soil using 13 cm long metal pins, ensuring full adherence of the sponge to the surface. We created different spatial arrangements of mimicked plant patches that varied in total patch cover (from 0% to 30%), patch density (from 10 to 60 sponges/plot), and patch size (from 100 cm^2 to 600 cm^2, which patches made of 1 up to 6 sponge units), yielding 16 cover-pattern combinations. For a given cover (i.e., a given number of sponge units), a decrease in patch density obviously entailed an increase in patch size. In addition, plots for intermediate values of patch cover (40 sponges/plot) and the various spatial arrangements considered (10, 20, 30 and 40 patches of decreasing size), were replicated three times (hereafter, replicated pattern-plots). Table 1 shows the whole set of cover and pattern combinations considered (24 plots in total). We conducted two independent experiments: (1) a natural-rainfall based experiment conducted on the whole set of 24 plots, which focused on testing the effects of patch cover and pattern on runoff and sediment yield through interception and runoff obstruction, and (2) a simulated-rainfall based experiment conducted on the 12 replicated pattern-plots, which focused on testing, for a given patch cover, the effect of patch pattern on the sink capacity of the system.

For the natural-rainfall experiment, we monitored plot runoff and sediment yield over three months in autumn. During that period, we recorded 6 rainfall events that produced runoff, with rainfall amount of the individual events ranging between 6 and 25 mm, totaling 79 mm of cumulated rainfall. After each rainfall event, we measured the runoff in the collection tanks of each plot and calculated the sediment yield as the dry weight of the sediments settled on the base of the plot trough and on the base of the runoff measuring container. For the simulated-rainfall experiment, we conducted high-intensity rainfall simulation runs on the 12 replicated-pattern plots, which were covered by the same number of sponge units (40 sponges; 20% ground cover), yet distributed in either 10, 20, 30 or 40 patches per plot (3 replicates per patch-density level). For these plots, we artificially increased the capacity of the patches for capturing runoff by installing two small metal-sheet arms on the upper

Fig. 1. General view of the experimental setting (top) and details of the upslope side of no-sink (bottom left) and sink-mode (bottom right) patches during simulated-rainfall runs.

Table 1
Patch size (cm^2) for each combination of patch cover and patch density, and total number of plots per each cover value.

Number of sponges (cover)	Number of patches (density)					Total number of plots
	10	20	30	40	60	
0 (0%)						1
10 (5%)	100					1
20 (10%)	200	100				2
30 (15%)	300	150	100			3
40 (20%)	**400**[a]	**200**[a]	**133**[a]	**100**[a]		4 × 3 replicates = 12
60 (30%)	600	300	200	150	100	5

[a] In bold, Patch size in the replicated pattern-plots: 3 replicates for each 20%-cover plot type (having 10, 20, 30 or 40 patches each).

side of each patch (sink mode; Fig. 2), which aimed to temporarily retain rainfall and runoff water upslope the patches, slowing down the water flow and facilitating water infiltration, and thus mimicking the enhanced water infiltration capacity typically exhibited by the soil underneath plant patches as compared with bare-soil interpatches (Mayor et al., 2009). On each replicated-pattern plot, we conducted two rainfall simulation runs: before and after the modification of the water-capturing capacity of the patches (no-sink and sink mode, respectively; Fig. 1), with a minimum period of 5 days between the two runs. The simulated rainfalls were produced using a large rainfall simulator, equipped with two full-cone nozzles set at a height of 2 m that evenly distributed water over the entire surface of each 2 × 1 m plot. Rainfall intensity was high, 65 mmh^{-1}, which guaranteed a short time to generate runoff and minimized the effect of antecedent soil moisture (Castillo et al., 2003). The duration of each simulated rainfall was 20 min, which resulted in stabilized runoff rates for most of the simulation runs. We determined time to runoff visually, and measured runoff every minute. The runoff coefficient was estimated relative to the total amount of rainfall input from the time that runoff started till the end of the simulation run.

2.2. Data analysis

We used regression analyses to study the relationships between patch cover and patch density as explanatory variables and runoff and sediment yield as response variables. Given the expected correlation between patch cover and patch pattern, we additionally used partial correlation analysis to test the independent effect of each explanatory variable. We analyzed the data on runoff coefficients and time-to-runoff from the rainfall simulation experiments using Repeated-measures

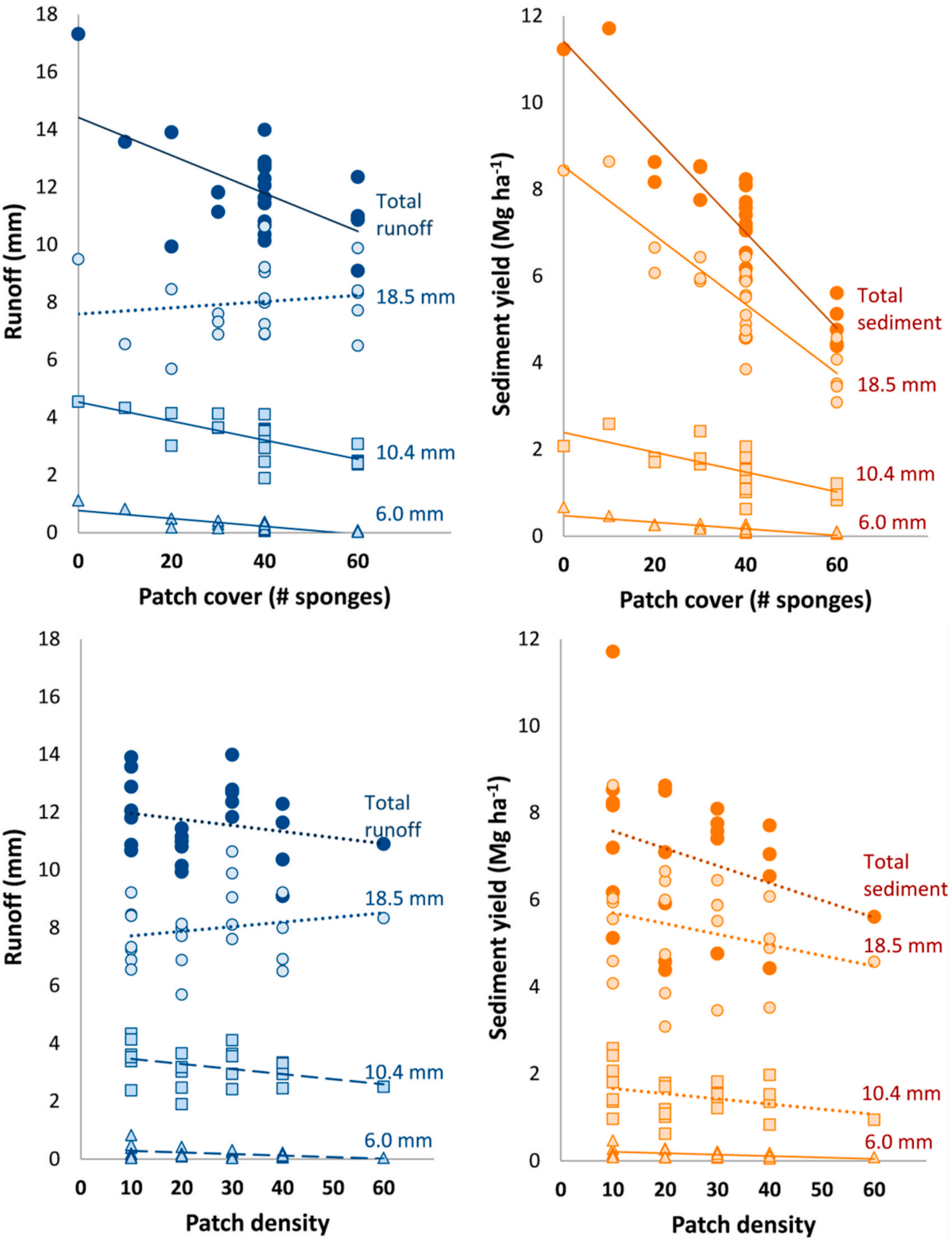

Fig. 2. Relationships between either patch cover (top) or patch density (bottom) and runoff and sediment yields. Data represent relationships for total runoff and sediment yielded by 79 mm of accumulated runoff-productive rainfall over the whole study period, and event-based yields for three contrasting natural rainfall events of 6.0, 10.4, and 18.5 mm. Solid, dashed, and dotted lines represent significant, marginally significant, and no significant linear regressions, respectively.

ANOVA, with sink function (no-sink versus sink mode) as within-subject factor and patch density as between-subject factor, followed by Tukey test for pair-wise comparisons between the patch-density levels. To further explore potential differences between sink function levels, we performed rank-based Jonckheere-Terpstra tests for ordered differences between groups to determine if there was a statistically significant trend in runoff coefficient (decreasing order) and time to runoff (increasing order) in response to increasing patch density for each sink function level separately. All the analyses were conducted using IBM SPSS Statistics version 25.0.

3. Results

The total accumulated runoff yielded by the six rainfall events that produced runoff during the study period ranged between 9.1 and 17.3 mm, produced on plots with 30% and 0% ground cover, respectively. The averaged accumulated runoff across the experimental plots was 11.9 mm, which represents 15.1% of runoff coefficient relative to the 79 mm of accumulated rainfall for those six events. Only three out of the six rainfall events produced runoff in all the plots, with rainfall amounts of 6 mm, 10.4 mm, and 18.5 mm, which led to small, medium, and large runoff events, respectively. Total sediment yield ranged between 4.4 and 11.7 Mg ha^{-1}, with an average value of 7.2 Mg ha^{-1}.

Both total runoff and total sediment yield significantly decreased with increasing patch cover, yet they did not vary with increasing patch density (Fig. 2; Table 2). On an event basis, small and medium runoff events exhibited a decreasing pattern in response to increasing patch cover, and a marginally significant decrease with increasing patch density. However, the largest runoff event did not show any relationship with patch cover or patch density. Sediment yield from individual events significantly decreased with increasing patch cover in all cases, with the largest event and total sediment yield showing the strongest dependence on patch cover. We only found a significant relationship between sediment yield and patch density for the smallest event considered, which produced more sediment the lower the patch density. Partial correlation analyses showed that the negative dependence of runoff and sediment yield on patch cover was still significant once the effect of patch density was removed. Conversely, there was no significant correlation between patch density and either runoff or sediment yield once the effect of patch cover was removed (Table 2).

For moderately low patch cover (40 sponge units; 20% ground cover), the rainfall simulation experiments showed lower runoff coefficients and higher time to runoff for finer patch patterns (i.e., higher patch density) and for the sink-mode patch (Fig. 3; Table 3). Increasing patch density decreased runoff coefficient by both reducing steady runoff rates and increasing the time required to achieve steady runoff rates (Fig. S1; Fig. S2; Table S1; Supplementary information). The most relevant changes occurred between patch densities of 30 and 40 patches (for runoff coefficient) and between densities of 30 and 20 patches (for time to runoff) (Fig. 3). There were no differences, however, in the hydrological response of the two plots with the lowest densities (10 and 20 patches). Although there were no interaction effects between sink-function and patch-density factors (Table 3), the effect of patch density on runoff coefficient and time to runoff was more evident for the plots under the sink mode that under the no-sink mode (Fig. 3). The Jonckheere-Terpstra tests for ordered differences between groups showed significant trends of lower runoff coefficient ($T_{JT} = 10.0$, $z = -2.4$, $P = 0.016$) and higher time to runoff ($T_{JT} = 44.5$, $z = 2.5$, $P = 0.013$) in response to increasing patch density for the sink mode, while the same trends were barely significant ($T_{JT} = 13.0$, $z = -2.0$, $P = 0.047$, for runoff coefficient) and marginally significant ($T_{JT} = 39.5$, $z = 1.8$, $P = 0.075$, for time to runoff) for the no-sink mode.

Table 2

Results from linear regression (F statistics; P-values; R^2) and partial correlation (ρ coefficients; P-values) analyses showing pair-wise relationships between either patch cover or patch density as explanatory variables and the response variables: total runoff, total sediment yield, and event-based runoff and sediment yield for three contrasting natural rainfall events (Significant and marginally significant results are depicted in bold and bold-and-italics, respectively; n = 24).

Response variable	Linear regression		Partial correlation	
	Explanatory variable			
	Patch cover	Patch density	Patch cover (density-effect removed)	Patch density (cover-effect removed)
Total runoff[b]	**$F = 12.32$; $P = 0.002$**; $R^2 = 0.36$	$F = 1.07$; $P = 0.312$; $R^2 = 0.05$	$\rho = -0.333$; $P = 0.130$	$\rho = 0.066$; $P = 0.852$
Large runoff event (18.5 mm rainfall)	$F = 0.45$; $P = 0.508$; $R^2 = 0.02$	$F = 0.73$; $P = 0.402$; $R^2 = 0.03$	$\rho = 0.301$; $P = 0.173$	$\rho = 0.042$; $P = 0.771$
Medium runoff event (10.4 mm rainfall)	**$F = 25.51$; $P < 0.001$**; $R^2 = 0.54$	***$F = 3.13$; $P = 0.092$***; $R^2 = 0.13$	**$\rho = -0.616$; $P = 0.002$**	$\rho = -0.138$; $P = 0.631$
Small runoff event (6.0 mm rainfall)	**$F = 46.39$; $P < 0.001$**; $R^2 = 0.68$	***$F = 3.67$; $P = 0.069$***; $R^2 = 0.15$	**$\rho = -0.705$; $P < 0.001$**	ρ -0.138; $P = 0.633$
Total sediment yield[b]	**$F = 89.04$; $P < 0.001$**; $R^2 = 0.80$	$F = 2.16$; $P = 0.156$; $R^2 = 0.09$	**$\rho = -0.856$; $P < 0.001$**	$\rho = 0.144$; $P = 0.523$
Large sediment event (18.5 mm rainfall)	**$F = 79.84$; $P < 0.001$**; $R^2 = 0.78$	$F = 1.51$; $P = 0.233$; $R^2 = 0.07$	**$\rho = -0.851$; $P < 0.001$**	$\rho = 0.224$; $P = 0.317$
Medium sediment event (10.4 mm rainfall)	**$F = 22.34$; $P < 0.001$**; $R^2 = 0.50$	$F = 2.45$; $P = 0.133$; $R^2 = 0.10$	**$\rho = -0.666$; $P = 0.001$**	$\rho = -0.033$; $P = 0.885$
Small sediment event (6.0 mm rainfall)	**$F = 52.55$; $P < 0.001$**; $R^2 = 0.71$	**$F = 5.14$; $P = 0.034$**; $R^2 = 0.20$	**$\rho = -0.736$; $P < 0.001$**	$\rho = 0.193$; $P = 0.389$

[b] Total yields resulting from 79 mm of accumulated rainfall.

4. Discussion

Supporting our first hypothesis, the results from the manipulative experiments conducted are conclusive about the relevance of both patch cover and patch pattern as hydrological control factors in patchy drylands. However, the relationships found between patch cover and runoff were always stronger than those between patch density and runoff, and the effect of patch density largely disappeared when the effect of the co-varying patch cover was removed. Only for plots with equal medium-low patch cover values, the effect of patch density emerged clearly. Regarding sediment yield, we found full dominance of patch cover over patch density as control factor. Overall, our findings point to a subsidiary role of patch pattern in modulating dryland hydro-geomorphologic behavior as compared with patch cover, and suggest that both factors interact in their control of runoff and sediment yield.

Both vegetation cover and spatial pattern can independently control the connectivity of bare soil (Rodríguez et al., 2018) and thus control the potential for physical disruption and slowing down of overland flow, which in turn promote opportunities for water infiltration and sediment retention (Ludwig and Tongway,1996; Mayor et al., 2008). However, vegetation cover controls an additional set of processes, with multiplicative effects on runoff and sediment yield, for which the influence of vegetation spatial pattern is less relevant. These processes include rainfall interception by the canopies and enhanced infiltration capacity and hydraulic conductivity in the soil underneath vegetation patches (Nicolau et al., 1996; Mayor et al., 2009; Love et al., 2010). Although the patch size can modulate the potential of the vegetation for rainfall interception, soil protection and microsite amelioration (Ludwig et al., 2000; Hao et al., 2016; Magliano et al., 2019), total patch cover exerts a major effect on these processes through the control of the extent of the area where they can take place (Tongway and Hindley, 2004). Furthermore, vegetation cover modulates the amount of bare soil available for detachment by raindrop impact, which is critical for soil conservation in systems where rainfall-driven erosion is the dominant erosion process (Kinnell, 2005). Only for systems where overland flow has sufficient power to detach soil in addition to transporting the soil particles detached by raindrops, it could be expected that the vegetation spatial pattern played a critical geomorphologic role (Polyakov et al., 2020). Taking the above into account, it is not surprising that patch pattern effects are somehow subsidiary of patch cover effects on dryland hydro-geomorphologic processes. However, according to our results and several previous works (Moreno-de las Heras et al., 2012; Berdugo et al., 2017), the effects of the spatial pattern of vegetation patches on dryland functioning would be most evident for medium-low cover values. This can be explained by the inverse non-linear dependence on plant cover of bare-soil connectivity (Rodríguez et al., 2018), so that small changes in low cover values would result in sharp changes in bare-soil connectivity, which has been proved to be a major control factor of dryland hydrologic functioning (Bracken and Croke, 2007; Mayor et al., 2008). It is worth noting that moderately low vegetation cover values, around

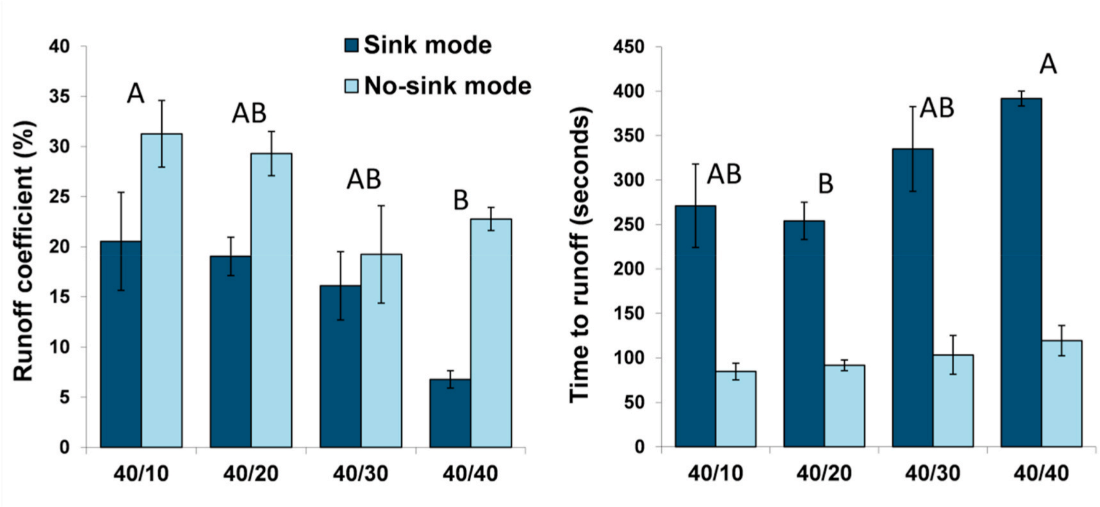

Fig. 3. Variation in runoff coefficient (left) and time to runoff (right) from simulated-rainfall experiments as a function of patch density (10–40) for plots with equal patch cover (40 sponge units) and patches under either sink or no-sink modes. Data are mean values ± 1 SE. Different letters represent significant differences between patch-density classes (Tukey test for pair-wise comparisons).

Table 3
Results from repeated measures ANOVA on runoff coefficient and time to runoff from rainfall simulation experiments, with sink function (no-sink and sink-mode) as within-subject factor and patch density (10, 20, 30, and 40) as between-subject factor (Significant results are depicted in bold).

	Runoff coefficient	Time to runoff
Within Subject		
Sink type	**$F = 23.80$; $P = 0.001$**	**$F = 105.13$; $P < 0.001$**
Sink type × Patch density	$F = 1.65$; $P = 0.254$	$F = 1.38$; $P = 0.318$
Between subject		
Patch density	**$F = 4.74$; $P = 0.035$**	**$F = 4.96$; $P = 0.031$**

30–40% ground cover, are very common in semiarid lands (e.g., Safriel and Adeel, 2005), and that dryland ecosystems can exhibit contrasting vegetation patterns for very similar vegetation cover values (e.g., Abrahams et al., 1995; Bartley et al., 2006; Bautista et al., 2007). Both facts could jointly explain that for many drylands worldwide changes in ecosystem functionality can be better captured by the pattern of vegetation patches than by the total vegetation cover (Berdugo et al., 2017).

Supporting our second hypothesis, we found that, for a moderately low patch cover, coarser patterns (lower patch density; higher patch size) produce more runoff than finer patterns, with a three-fold increase in runoff coefficient for a four-fold decrease in patch density (from 40 small patches to 10 big patches). A similar result was found for natural conditions in a nearby area, where plots with very similar plant cover showed a five-fold decrease in runoff coefficient for a six-fold decrease in patch density (Bautista et al., 2007). The coarsening of a given patch cover entail both an increase in bare-soil connectivity and, assuming no changes in patch shape, the decrease in the ratio between the patch width and the patch area, (i.e., the ratio between the runoff-trapping capacity and the sink capacity of the patch). Both changes imply a reduction in the overall resource-conserving capacity of the system (Wilcox et al., 2003). This problem exacerbates when the coarsening of the spatial pattern comes together with changes in the vegetation composition towards functional types with lower capacity for trapping runoff-redistributed resources. This may be the case for shrubland encroachment, a common process in dryland rangelands worldwide that has been related to desertification (MEA, 2005), for which the traits of the encroaching shrub species significantly influence the functional outcome of the encroachment (Eldridge et al., 2011). Although finer patch patterns have proved to be more effective for resource conservation than coarse patterns, very small patches may lack enough capacity to efficiently trap runoff, support high levels of soil biological activity, and provide substantial input of organic carbon to the patch soil (McClaran et al., 2008; Meloni et al., 2020). So that any given plant species or functional type requires certain minimum threshold patch size for the patches to efficiently improve soil structure and hydraulic properties, and behave as fully functional sink units (Tongway and Hindley, 2004).

Mimicking vegetation patches by placing sponges on the soil surface can effectively mimic the role of vegetation patches as physical obstacles to overland flow, rainfall-interception structures, and protective covers of the soil, but mimicking also the enhanced water infiltration underneath the vegetation patches, and hence their sink capacity, required an additional structure that temporarily trapped runoff water, thus facilitating water infiltration. Mimicking only rainfall interception, soil protection, and flow disruption (i.e., the natural-rainfall experiment and the simulated-rainfall experiment on plots under no-sink patch mode) resulted in little effect of patch pattern on runoff and sediment yield. However, mimicking those processes was sufficient to capture the effect of patch cover, with total yields being reduced by half on plots with 30% cover as compared with bare plots, in agreement with the magnitude of vegetation cover effects typically reported in the literature (e.g., Elwell and Stocking 1976; Francis and Thornes 1990). For the largest rainfall recorded in the natural-rainfall experiment, the effect of patch cover on runoff vanished, probably due to the early steady saturation of the mimicked canopies during the rainfall event (Li et al., 2017). Overall, these results highlight the importance of the rainfall interception and soil protection mechanisms to the overall hydro-geomorphic effect of patch cover. In contrast, the observed weak effect of patch density on runoff and sediment yield questions the importance of the patch role as physical obstacle to runoff. The addition to the sponges of a structure that captured runoff water, which allowed mimicking the sink capacity of the patch soils for the simulated-rainfall experiment, clearly revealed the hydrologic effects of patch density, with increasing density leading to decreasing runoff. Any obstacle to runoff has the potential to reduce the velocity of the water flow, facilitating water infiltration and the temporary deposition of sediments transported by runoff (Ludwig and Tongway, 1996). However, according to our results, only when the obstacles to runoff combine with functional sinks, it is possible to effectively disrupt the hydrological connectivity (Bracken and Croke, 2007) and control the runoff-driven water loss. Otherwise, most of the runoff water can easily route around the obstacle without compromising the overall connectivity of the water flow (Rossi and Ares, 2017; Liu et al., 2021). This is often the case in degraded drylands where strong differential erosion (Rostagno and Del Valle, 1988) between vegetated patches and bare interpatches contribute to the relative isolation of the vegetation mounds from water fluxes, with the actual amount of runoff-water captured by the vegetation patches depending on mound elevation (Rossi et al., 2018). The influence of patch density on the water-conserving capacity of the mimicked dryland system was captured by both time to runoff and runoff coefficient once plot runoff started (as both were tested separately). Given the high intensity of the simulated rainfalls, the mimicked sinks were saturated early during the simulations (Fig. 1). Even so, the water temporarily accumulated in the runoff traps probably promoted the infiltration of water into the soil, which explains that the patch-density effect was clear not only for the total runoff coefficient but also for steady runoff rates, and indicates that the sink capacity of the whole mimicked ecosystem was not saturated despite the high intensity of the simulated rainfalls.

To our knowledge, this work is the first attempt to experimentally demonstrate the independent effects of patch cover and patch pattern, and the respective mechanisms involved, on the hydro-geomorphic behavior of dryland ecosystems. Our approach falls between a field experiment and a modelling experiment, and can confidently demonstrate the relative effects of the treatments of interest. In fully natural landscapes, a number of soil and topographic properties, such as slope angle and length, soil surface compaction and stoniness, etc., are expected to modulate the magnitude of both patch cover and patch pattern effects. However, since the input conditions of the experiment (range of rainfalls, range of patch cover, soil, and slope angle) are common in natural drylands, and the ratio between plot and patch size allowed the genesis of the intended processes, the outcomes of our experimental approach were realistic, falling within the range of what has been observed in natural systems (Puigdefábregas et al., 1999; Bautista et al., 2007). Our findings provide critical information for modelling and understanding dryland vegetation dynamics (Mayor et al., 2019) and decision-making in dryland management and restoration (Valdecantos et al., 2014; Urgeghe and Bautista, 2015; Liu et al., 2021; Smanis et al., 2021) through the lens of source-sink dynamics and hydrological connectivity.

5. Conclusions

Patch cover and patch pattern independently contribute to control the hydro-geomorphologic functioning of patchy landscapes, yet the importance of each of these two factors is expected to depend on the other factor. Patch cover appears to be a primary control factor, with patch pattern playing a subsidiary role that exhibits its full potential for low and medium low patch cover values. Provided that the amount and/or the intensity of the rainfall result in overland flow and subsequent runoff source-sink dynamics, the coarsening of a given patch cover (i.e., the decrease in patch density and increase in patch size) increases runoff yield. This effect can be explained by the increase in bare-soil connectivity and the decrease in the ratio patch width/patch area that entail the coarsening of the patch pattern. Because drylands worldwide exhibit a myriad of contrasting vegetation patch patterns for medium-low vegetation cover, vegetation cover alone may not be sufficient to predict runoff and sediment yield variation for a wide range of dryland systems, which calls for indicators that capture and integrate the variation in both vegetation cover and vegetation pattern.

Rainfall interception and direct soil protection play most relevant roles as mechanisms underlying the effect of patch cover on dryland hydro-geomorphic functioning, yet they barely mediate the effects of patch pattern. The control of overland flow by patch pattern relies mainly on modulating the overall runoff-sink capacity of the system, with pattern-dependent changes in the physical obstruction to overland flow hardly playing any role unless combined with functional sinks. According to these results, runoff control measures that base only on physical barriers to overland flow placed on the ground could be of little value as compared with measures based on the establishment of vegetation patches, which have the potential for increasing water infiltration under their canopies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Juan Puigdefábregas for inspiring our work. The help of Manuel Ruiz, Nuria Garcia-Forner, Azucena Camacho, Rosario López-Poma, and Luna Morcillo was critical for setting up the experiments and data collection. This work was supported by the Spanish Ministry of Science and Innovation (DRYEX2 project; grant number CGL 2017-89804-R), and the European Union's Seventh Framework Programme (CASCADE project; grant number GA283068).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaridenv.2021.104585.

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