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19 **Abstract**

20           Semiarid and arid environments are frequently structured in vegetation patches  
21 that heterogeneously distribute water resources (water runoff and soil moisture). This  
22 redistribution is interrelated with episodes of rainfall triggering pulses of plant growth  
23 according to the Trigger-Transfer-Reserve-Pulse (TTRP) model. Spatial heterogeneity  
24 in the hydrological behaviour of surface patches has been described in Mediterranean  
25 mining restored hillslopes. Nevertheless studies describing the interactions of this  
26 hydrological heterogeneity with ecological processes on restored environments are  
27 lacking. This study investigates the relationships between overland flow running at  
28 hillslope scale and ecosystem processes at patch scale in restored hillslopes. We  
29 selected three approximately 20 year old restored hillslopes along a gradient of overland  
30 flow (hillslope runoff coefficients are 15.9%, 2.2% and 0.3% for the three experimental  
31 hillslopes). We studied environmental conditions describing the ecohydrological  
32 interactions under the TTRP approach for arid and semiarid environments. Our results  
33 indicate that in restored hillslopes: 1) soil moisture content was associated to the type of  
34 vegetation patches; 2) higher soil water content enhanced vegetation diversity and soil  
35 properties, improving vegetation performance and colonization opportunities; 3) there  
36 was an inverse relationship between the volume of overland flow and soil moisture at  
37 the hillslope scale, influencing, in turn, ecohydrological processes at the patch scale.  
38 Overall our results highlight the importance of overland flow modifying soil moisture  
39 distribution at patch scale and hence, influencing vegetation dynamics and ecological  
40 succession in these novel ecosystems.

41 **Keywords:** ecohydrology, mining, restoration, runoff, germination, facilitation.

42

## 43 1. Introduction

44 In semiarid environments, where water is the main limiting factor, a strong  
45 interrelation between vegetation and hydrology has been widely described (2005;  
46 Tongway et al., 2001). Frequently, these ecosystems are structured in different  
47 vegetation patches that distribute water resources heterogeneously (Cammeraat and  
48 Imeson, 1999; Cerdà, 1997a; Ludwig et al., 2000). Particularly, Mediterranean  
49 hillslopes behave as a patchwork of runoff-generating (sources) and run-on-capturing  
50 (sink) areas, where the size of the runoff and run-on patches highly depends on climatic  
51 conditions (Calvo-Cases et al., 2003; Lavee et al., 1998).

52 The heterogeneity of runoff generation and routing processes in restored  
53 hillslopes from opencast coal mining has also been described in Mediterranean-  
54 continental environments (Nicolau, 2002). Overland flow has been identified as a  
55 significant driving force for vegetation dynamics in these restored hillslopes, where the  
56 existence of steep berms generating runoff at the top of the slope is frequent (Hancock  
57 and Willgoose, 2004; Moreno-de las Heras et al., 2008). When the magnitude of  
58 overland flow exceeds a threshold, vegetation recovery is dramatically constrained  
59 (Espigares et al., 2011) and accelerated soil erosion processes arise, being rill erosion  
60 the most characteristic phenomenon (Moreno-de las Heras et al., 2010). Rills efficiently  
61 drain runoff away from hillslopes, reducing rainfall infiltration, and/thus increasing  
62 water deficit (Moreno-de las Heras et al., 2010). As a consequence, vegetation dynamics  
63 become severely affected. It has been shown how seedling emergence, plant  
64 establishment and seed production are limited along a gradient of rill erosion (Espigares  
65 et al., 2011). Moreover, soil moisture content is spatially redistributed, being higher  
66 near rills, and lower on inter-rills. Moreno de las Heras *et al.* (2011) showed the link  
67 between the spatial pattern of the dominant species (*Medicago sativa*), and soil moisture

68 distribution in rills and interrills. When the amount of runoff routing downslope is low,  
69 overland flow is not directed by rills, running mostly as sheet flow. In these situations,  
70 the vegetation is able to establish on hillslopes forming a patchy mosaic structure.  
71 Merino-Martín et al. (2011) described the development of ecohydrological units  
72 (classified as runoff sources or sinks) where vegetation and hydrology are strongly  
73 associated in natural and restored hillslopes.

74 Feedback interactions between vegetation and hydrology in semiarid areas can  
75 be explained by the Trigger Transfer Reserve Pulse conceptual model (hereafter TTRP,  
76 Fig. 1) proposed by Ludwig et al. (1997). This framework states that densely covered  
77 vegetation patches obstruct runoff fluxes and store run-on, which promotes plant growth  
78 pulses. In turn, vegetation patches enhance soil infiltration capacity, which is considered  
79 a feedback mechanism. This model has been applied for the study of ecosystem  
80 functioning in both banded and patchy landscapes (Ludwig et al., 2005), and some  
81 evidences of the functioning of this model have been recently observed in an  
82 experiment in mine reclaimed areas in Mediterranean-continental environments  
83 (Espigares et al., 2012).

84 In this study, we explored the interactions between vegetation and hydrological  
85 processes both at the patch and the hillslope scale, along an overland flow gradient (i.e.  
86 three scenarios subjected to the routing of different amounts of overland flow). We used  
87 as a framework the TTRP approach to study the ecohydrological interactions. First, we  
88 compared soil moisture content in vegetation patches. Second, we analysed differences  
89 in specific ecological attributes between vegetation patches. Finally, we characterized  
90 the effects of vegetation patches on soil infiltration capacity and other soil properties in  
91 order to reveal potential feedback mechanisms. Our main hypotheses were: 1) Soil  
92 moisture content is associated to the type of vegetation patch (source or sink); 2) higher

93 soil water contents are associated to a better development of vegetation and soil  
94 properties. Specifically, we expected that higher soil water content in sink patches will  
95 enhance germination opportunities for plant species; 3) there is an inverse relationship  
96 between overland flow and soil moisture content at the hillslope scale that affects plant  
97 germination and colonization; thus the amount of overland flow routing along the  
98 hillslope influences hydrological processes at the patch scale.

99

## 100 2. Methods

### 101 2.1. Study area

102 This study was carried out in three reclaimed mining hillslopes located at *El*  
103 *Moral* spoil bank (40°47'50"N, 0°50'26"W, Fig. 1a). The spoil bank is located in the  
104 *Utrillas* coalfield (~1100 m above sea level) in the Iberian Mountain Chain (Teruel,  
105 Spain). The climate is Mediterranean-Continental with a mean annual temperature of 14  
106 °C (ranging from a minimum mean daily temperature of 6.7 °C in December and a  
107 maximum mean daily temperature of 23.1 °C in July), with air frost period between  
108 October and April. Mean annual precipitation is 466 mm (mainly concentrated in spring  
109 and autumn) and potential evapotranspiration is 759 mm, yielding a hydrological deficit  
110 of 292 mm running from June to October. The local moisture regime can be classified  
111 as dry Mediterranean (Papadakis, 1966).

112 The three hillslopes were built between 1987 and 1988 by *Minas y Ferrocarril*  
113 *de Utrillas S.A.* mining company. They have a slope gradient of 20° and were covered  
114 with a layer of 80-100 cm of overburden clay-loam substratum. Revegetation of  
115 hillslopes was implemented after cross-slope ploughing by sowing with a mixture of  
116 perennial grasses (*Festuca rubra*, *Festuca arundinacea*, *Poa pratensis* and *Lolium*  
117 *perenne*) and perennial leguminous herbs (*Medicago sativa* and *Onobrychis viciifolia*).  
118 Although the hillslopes were restored using the same general procedures, they diverged  
119 in their subsequent evolution (i.e. rilling processes and vegetation development). The  
120 triggering factor causing these divergent trends is the difference in their  
121 geomorphological design: the different size of a barely covered (<5% cover) steep (40°  
122 slope) berm integrated at the top of the hillslopes that works as a water-contributing area  
123 (Moreno-de las Heras et al., 2009; Moreno-de las Heras et al., 2008). This steep berm

124 (Fig. 2a) generates important amounts of overland flow and has promoted the  
125 development of intense soil erosion processes, causing the formation of rill networks in  
126 one of the experimental slopes (Hillslope 1). Merino-Martín and others (2012)  
127 measured runoff in the experimental hillslopes for the hydrological year 2007-2008,  
128 showing an overland flow gradient from hillslope 1 to hillslope 3, with runoff  
129 coefficients of 15.9%, 2.2% and 0.3% respectively (see Appendix A). A detailed  
130 description of soil, cover, plant and erosion features of the hillslopes is presented in  
131 Appendix A.

132 In the aforementioned hydrological study, the authors identified seven types of  
133 vegetation patches or microsites (Merino-Martin et al., 2012) with different vegetation  
134 cover and composition that were characterized by a different hydrological behaviour.  
135 Vegetation composition in these hillslopes is the result of the combination of introduced  
136 species during restoration practices and colonization from surrounding areas along  
137 vegetation succession. Scattered clumps of (1) legumes (*Medicago sativa*) and (2)  
138 grasses (*Dactylis glomerata*) in a matrix of bare soil, and scattered dwarf shrubs of (3)  
139 *Santolina chamaecyparissus* and (4) *Thymus vulgaris* in a matrix of bare soil were  
140 identified as runoff sources. Patches densely covered by perennial grasses of (5) *Lolium*  
141 *perenne* and (6) *Brachypodium retusum* and by (7) shrubs (*Genista scorpius*) were  
142 identified as runoff sink patches. Since *Santolina* patches (3) were the only ones present  
143 at both ends of the overland flow gradient (hillslopes 1 and 3; Fig. 2b) soil moisture and  
144 seed bank traits in these patches were sampled twice (once in hillslope 1 and once in  
145 hillslope 3) in order to explore the consequences of overland flow volume routing along  
146 the hillslopes in the same patch. The remaining variables were only recorded once at  
147 *Santolina*, in hillslope 1, where the relative abundance of this vegetation patch was  
148 higher.

149 2.2. *Field measurements*

150 2.2.1. *Vegetation and soil seed bank*

151 In each type of vegetation patch, visual surveys of the presence of plant species  
152 were carried out in 15 randomly selected 50x50 cm quadrats to provide a fine  
153 description of vegetation features (floristic composition and richness). Presence of  
154 plant species was considered rather than abundance because in some patches the  
155 existence of two layers of vegetation (canopy and understorey) could influence results.  
156 Total vegetation cover was estimated in other 6 randomly selected 50x50 cm plots in  
157 each patch during the spring 2007.

158 In September 2007, before the arrival of the autumn rains, soil samples (38.5  
159 cm<sup>2</sup> area × 4 cm depth) were collected in order to analyse differences in floristic  
160 composition of the soil seed banks in the different vegetation patches. Ten random  
161 samples were collected from each patch. Each of these samples was subdivided into  
162 four subsamples that were placed in 250 ml plastic containers over a 5 cm vermiculite  
163 layer. The floristic composition of the soil seed bank was determined after germination  
164 under optimal conditions in a greenhouse.

165 2.2.2. *Rainfall simulations*

166 Three rainfall simulations were carried out in each vegetation patch in the  
167 summer of 2008. Experiments were carried out using a single nozzle (HARDI® 1553)  
168 rainfall simulator based on the model described by Cerdà and others (1997b). Rainfall  
169 simulations were performed using a pressure of 2 kg cm<sup>-2</sup> over 0.24 m<sup>2</sup> plots with the  
170 nozzle placed 2 m above the soil surface and protected from wind effects with plastic  
171 sheets. Calibration under these conditions resulted in the following rainfall  
172 characteristics: rainfall intensity was 75.2 mm h<sup>-1</sup>; rainfall uniformity (sensu

173 Christiansen, 1942) was 72.94 %; drop diameter  $D_{50}$  (sensu Anderson, 1948) was 1.7  
174 mm and mean terminal speed was  $4.0 \text{ m s}^{-1}$ , which implies a kinetic energy of  $13.4 \text{ J}$   
175  $\text{mm}^{-1} \text{ m}^{-2}$ . Rainfall intensity was selected in order to achieve a steady infiltration rate in  
176 patches with a dense vegetation cover. Natural rainfall of similar intensity during 30–60  
177 min (range used for rainfall simulations) has a return period of 10–12 years in this area  
178 (Santamaría and Parrilla, 1999). The same intensity was selected in all the patches to  
179 allow following comparisons. Twenty-one steel rings (55cm diameter, 15 cm height)  
180 were installed (by inserting 5 cm into the soil) in the seven vegetation patches (3 in  
181 each; following Moreno-de las Heras et al., 2009). Each of these plots had a 2.5 cm  
182 diameter drainpipe outlet to collect runoff and sediments. Rings were installed in  
183 October 2007 in order to ensure natural consolidation of soil after surface disruptions  
184 caused during ring installation. The duration of each rainfall event was variable (until  
185 runoff rate was stable, lasting a minimum of 30 min). Runoff discharge in each rainfall  
186 experiment was collected manually at 1 min intervals, from the beginning of runoff. The  
187 volume of each 1 min sample was measured and accumulated in a plastic bucket. After  
188 each rainfall experiment, runoff samples stored in the bucket were mixed and a  
189 homogeneous aliquot (0.5 l) was extracted. Sediment concentration ( $\text{g l}^{-1}$ ) was  
190 determined in aliquots by weighing after oven drying ( $105 \text{ }^\circ\text{C}$ ). Time to runoff (min)  
191 was measured and runoff coefficient (%) was calculated. Finally, after each simulation,  
192 a vertical cut in the soil profile was used to measure the depth reached by the wetting  
193 front using a measuring tape (cm). This depth value was divided by the duration of the  
194 rainfall experiment to obtain the soil profile moistening rate ( $\text{cm h}^{-1}$ ). This measure,  
195 although not constant in time, can be used to make comparisons between the different  
196 vegetation patches on the vertical movement of water in the soil profile. To minimize  
197 the influence of water salinity on hydrological soil responses (Agassi et al., 1981) low

198 electrical conductivity and sodium absorption ratio water ( $EC=0.28 \text{ dS m}^{-1}$ ,  $SAR<1$ )  
199 was used.

### 200 2.2.3. *Soil moisture dynamics*

201 To study the soil moisture dynamics in vegetation patches TDR (Time Domain  
202 Reflectometry) sensors were installed horizontally at different depths along the soil  
203 profile: 5, 25 and 50 cm, totalling four replicates in each vegetation patch. Soil moisture  
204 measurements were taken periodically (every 15 days without rain and within 5 days  
205 after each rainfall event) from April to December 2008. A TDR (Tektronix® 1502C)  
206 cable tester was used to collect the data, following the methodology proposed by Cassel  
207 *et al.* (1994), with an accuracy of 94 % in the determination of soil moisture.

### 208 2.2.4. *Soil properties*

209 Three composite soil samples (each sample formed by three homogeneously  
210 mixed subsamples, randomly distributed within each patch) were taken from the first  
211 10 cm of the soil profile in each patch. Stoniness (%) was determined as the content of  
212 soil particles  $> 2 \text{ mm}$ . General physicochemical characteristics were determined using  
213 standardized methods (MAPA, 1994). A standard pressure chamber (Klute, 1986) was  
214 used to determine soil water content (%  $v/v$ ) at four different pressures ranging from  
215 saturation to permanent wilting point ( $\Psi=0$ ; -0.01, -0.03, -1.50 MPa). Parameterization  
216 of the soil water retention characteristic curves was made according to Van Genuchten  
217 (1980) from the samples collected in each vegetation patch. Additionally, soil bulk  
218 density ( $\text{g cm}^{-3}$ ) was determined in the upper part of the soil profile using fifteen  
219 unaltered soil cores (3 cm height x 5 cm diameter) collected in each vegetation patch,  
220 and soil surface strength was measured with a pocket penetrometer (Geotester®) in 15  
221 randomly distributed samples per patch, four times per year (seasonal measurements in

222 summer - July, 30<sup>th</sup>-, autumn - October 27<sup>th</sup> -, winter - February, 15<sup>th</sup>- and spring - April  
223 25<sup>th</sup>).

### 224 2.3.Laboratory measurements

#### 225 2.3.1. Seed germination under different water potentials

226 The hydrological requirements for seed germination in the eight most abundant  
227 species in hillslopes were studied (*G. scorpius*, *B. retusum*, *L. perenne*, *T. vulgaris*, *D.*  
228 *glomerata*, *S. chamaecyparissus*, *M. sativa* and *Aegilops geniculata*). For *M. sativa*,  
229 data obtained from a similar experiment carried out by our research group in the same  
230 study area (Moreno-de las Heras et al., 2011) were used. Seeds of *S. chamaecyparissus*  
231 and *A. geniculata* were collected in the field. As field seed collection of the remaining  
232 species was impractical because of low production, they were obtained from two local  
233 seed suppliers (Semillas Montaraz, S.A. and Zulueta Corporacion Para La Naturaleza,  
234 S.A.). *G. scorpius* seeds were scarified by submerging in sulphuric acid 95–98 % for 10  
235 min following Bochet *et al.* (2007). Seed germination of each species was studied under  
236 eight different water potentials ( $\Psi=0$ ; -0.03; -0.10; -0.20; -0.33; -0.62; -1.10 and -1.50  
237 MPa) representing a gradient of soil moisture between saturation and permanent wilting  
238 point. Water potentials were simulated using polyethylene glycol concentrations (PEG-  
239 6000) following the standard equations of Michel *et al.* (1983). Ten replicates per water  
240 potential were prepared. Replicates consisted of 15 seeds placed in a 9 cm diameter  
241 Petri dish, on a bed composed of a layer of hydrophilic cotton and filter paper.  
242 Replicates were moistened with 35 ml of distilled water (control;  $\Psi=0$ MPa) or PEG  
243 solutions ( $\Psi$  ranging from -0.03 to -1.50 MPa). To avoid water potential variations by  
244 evaporation, Petri dishes were sealed with PVC sheets. Petri dishes were placed in a  
245 phytotron under controlled conditions (day length= 12 h; air temperature= 20 °C;

246 relative air humidity= 75 %). Germination was monitored every three days; considering  
247 a germination when at least 2 mm of radicle emerged. The experiment lasted 46 days  
248 and then germination rate (%) of each species was calculated.

#### 249 2.4. Data analyses

##### 250 2.4.1. Vegetation and seed bank

251 Characteristic species for each vegetation patch were determined by applying  
252 Indicator Species Analysis (Dufrene and Legendre, 1997). We performed ANOVAs and  
253 Tukey *post hoc*s to test significant differences in species richness and Shannon's  
254 diversity (vegetation and seed bank) between vegetation patches. Kruskal Wallis and  
255 Mann Whitney *post hoc* tests were used to analyse differences in soil seed bank density.

##### 256 2.4.2. Rainfall simulations

257 Water infiltration was estimated as the balance between precipitation and  
258 measured runoff on a minute basis, and further fitted to the Horton-type equation  
259 proposed by Borselli *et al.* (1996):

$$260 \quad I_t = I_f + (I_0 - I_f)e^{-\frac{pt}{K}}, \quad (\text{eq. 1})$$

261 where  $I_t$  is the instantaneous infiltration rate ( $\text{mm h}^{-1}$ );  $I_f$  is the final steady infiltration  
262 rate ( $\text{mm h}^{-1}$ );  $I_0$  is the initial infiltration rate ( $\text{mm h}^{-1}$ );  $p$  is the rainfall intensity ( $\text{mm h}^{-1}$ );  
263  $t$  is the time (h) and  $K$  is a coefficient which describes the shape of the apparent  
264 infiltration curve.

265 Differences in response parameters (the final infiltration rate  $I_f$ , the shape  
266 coefficient  $K$ , runoff coefficient, soil profile moistening rate, and sediment  
267 concentration) between vegetation patches were analysed by using ANOVAs and Tukey

268 *post hoc* tests for those cases in which parametric assumptions were satisfied, and  
269 Kruskal-Wallis and Mann-Whitney *post hoc* tests for non-parametric data.

#### 270 2.4.3. *Soil moisture*

271 We performed repeated measures ANOVA with soil water content data from  
272 vegetation patches, vegetation patch and sensor depth being the between-subject factors,  
273 and with time as the within-subject factor.

274 Soil water content was estimated at the hillslope scale (at 5, 25 and 50 cm soil  
275 depth) by considering the abundance (% surface cover) and soil moisture of each  
276 vegetation patch in each hillslope. A Friedman analysis with the Wilcoxon-Nemenyi-  
277 McDonald-Thompson *post-hoc* test was performed to compare the three hillslopes.

#### 278 2.4.4. *Relationships between vegetation traits and soil hydrology.*

279 We performed correlations to study relationships between vegetation  
280 characteristics (species richness, diversity and density of soil seed banks) and  
281 hydrological traits (infiltration parameters and soil water content) in each vegetation  
282 patch.

#### 283 2.4.5. *Soil properties*

284 Differences in soil bulk density between patches were tested by using ANOVA  
285 and Tukey's *post hoc* tests. For soil surface strength, the Friedman and Wilcoxon-  
286 Nemenyi-McDonald-Thompson *post-hoc* tests were used. The remaining soil  
287 physicochemical characteristics were tested using Kruskal-Wallis and Mann-Whitney U  
288 Test *post hoc* tests.

289 2.4.6. *Seed germination*

290 A seed-germination sigmoid shape response function (Ahmadi and Ardekani,  
291 2006) was fitted to the germination results obtained for each species:

$$292 \quad G = \frac{G_{max}}{1 + e^{-\frac{P - P_0}{b}}}, \quad (\text{eq.2})$$

293 where  $G$  is the germination rate (%),  $G_{max}$  is the maximum germination rate,  $P$  is the  
294 water potential (MPa),  $P_0$  is the threshold water potential value (MPa) below which the  
295 germination rate drops to zero, and  $b$  is a shape coefficient.

296 Threshold water potential values ( $P_0$ ) were transformed into soil moisture levels  
297 by using the (van Genuchten type) characteristic soil water retention curves that were  
298 parameterized for the different vegetation patch types. The obtained soil moisture  
299 threshold values were used to calculate the number of days suitable for germination in  
300 each vegetation patch throughout the year, or in other words, the days in which soil  
301 moisture at 5 cm depth was above the germination threshold value for each species in  
302 each vegetation patch during the two annual seed germination pulses (spring and  
303 autumn). A general temperature threshold of 10 °C (minimum temperature for seed  
304 germination) was also considered for calculations of the germination potential (Moreno-  
305 de las Heras et al., 2011). A “germination suitability index” (GSI) was determined by  
306 multiplying the number of suitable days for germination and the maximum germination  
307 rate for each species in each vegetation patch. Non-parametric bi-factorial ANOVA was  
308 applied to these data, with species and vegetation patch as factors and the germination  
309 suitability index as the dependent variable. At the hillslope scale, global GSI values  
310 were calculated considering the relative abundance (% cover) of each vegetation patch.  
311 Friedman analysis and *post-hoc* Wilcoxon-Nemenyi-McDonald-Thompson tests were  
312 applied to compare these values between the three hillslopes.

313 Indicator Species Analysis was performed with the PC-ORD package (McCune  
314 and Mefford, 1999). We used the R program (R\_Development\_Core\_Team, 2009) for  
315 the non parametric bi-factorial ANOVA (using the “adonis” function of the “vegan”  
316 package). The *post-hoc* Wilcoxon-Nemenyi-McDonald-Thompson test was performed  
317 with the “coin” and “multcomp” packages using the code of “Tal Galili”, published in r-  
318 statistics.com ([http://www.r-statistics.com/2010/02/post-hoc-analysis-for-friedmans-](http://www.r-statistics.com/2010/02/post-hoc-analysis-for-friedmans-test-r-code)  
319 [test-r-code](http://www.r-statistics.com/2010/02/post-hoc-analysis-for-friedmans-test-r-code)). The remaining statistical analyses were performed using STATISTICA 8.0  
320 (Statsoft, 2001). Data analyzed using ANOVA and Tukey tests fulfilled parametric  
321 assumptions. The scientific names of the species are in accordance with *Flora Europaea*  
322 (Tutin et al., 1964-1980).

323

### 324 3. Results

#### 325 3.1. Vegetation and seed bank

326 A total of 54 species were identified. We found significant differences in species  
327 richness ( $F_{6,98} = 15.54$ ,  $p < 0.01$ ; Fig. 3) and vegetation cover (Kruskal-Wallis test  
328  $H = 34.25$ ,  $p < 0.01$ ; Table 1) between vegetation patches. The “characteristic species” of  
329 each vegetation patch obtained with Indicator Species Analysis are shown in table 1.  
330 Seed density (Kruskal-Wallis test  $H = 36.15$ ;  $p < 0.01$ ), species richness ( $F_{7,72} = 9.85$ ,  
331  $p < 0.01$ ) and Shannon's diversity ( $F_{7,72} = 5.73$ ,  $p < 0.01$ ) of soil seed banks also showed  
332 significant differences between vegetation patches (Fig. 3). Two vegetation patches,  
333 *Medicago* and *Genista*, represent the more extreme cases, with *Genista* patches having  
334 the highest values of vegetation cover, species richness and seed density. *Medicago*  
335 patches, on the contrary, had the lowest values.

#### 336 3.2. Rainfall simulations

337 We found significant differences in final infiltration rates ( $F_{6,14} = 3.70$ ,  $p = 0.02$ ;  
338 Fig. 4a), soil profile moistening rates ( $F_{6,14} = 9.71$ ,  $p < 0.01$ ; Fig. 4c) and sediment  
339 concentrations (Kruskal-Wallis test  $H = 17.01$ ,  $p < 0.01$ ; Fig. 4d) between vegetation  
340 patches. We observed similar differences between patches to those for vegetation traits,  
341 *Genista* and *Medicago* being the most different (Figs. 3 and 4).

#### 342 3.3. Soil moisture measurements

343 The repeated measures ANOVA applied to soil moisture data (see table 2)  
344 showed significant effects of patch, sensor depth and time. *Genista*, *Brachypodium*,  
345 *Lolium* and *Thymus* patches showed higher soil water content (Fig. 5). Regarding sensor  
346 depth, soil moisture generally increased with depth and, with respect to time, it was  
347 higher during spring and autumn. There was a significant interaction between vegetation

348 patch and sensor depth (table 2): soil water content in *Genista* patches increased with  
349 depth while *Brachypodium*, *Santolina* and *Medicago* patches showed constant values  
350 along the soil profile (Fig. 5). There was also a significant interaction between time and  
351 sensor depth, since differences in soil water content with depth became more patent  
352 during spring (Fig. 5). Detailed soil moisture dynamics of patches, interpolated along  
353 the soil profile during the study period, are shown in Appendix B.

354 At hillslope scale we observed significant differences in soil moisture between  
355 hillslopes at the three soil depths (Friedman ANOVA  $p < 0.001$ ). Hillslope 3 showed the  
356 highest soil moisture values while hillslope 1 the lowest (Fig. 5).

#### 357 *3.4. Relationships between vegetation traits and soil hydrology*

358 Regarding plant species richness, we found significant correlations for final  
359 infiltration rate and soil moisture at 25 and 50 cm (Table 3). For vegetation cover, we  
360 found significant positive correlations with final infiltration rate and negative with  
361 runoff coefficient. With respect to soil seed bank species richness and diversity we  
362 found significant positive correlations with final infiltration rate and soil moisture at 25  
363 cm.

#### 364 *3.5. Soil properties*

365 We found significant differences in soil nutrients (N, P) and organic matter  
366 (Table 4), finding the highest and the lowest contents in *Genista* and *Medicago* patches  
367 respectively. There were also significant differences between patches in soil bulk  
368 density and soil surface strength, following the same trend as for soil nutrients.  
369 Maximum and minimum silt content values were found in *Medicago* and *Brachypodium*  
370 patches respectively (Table 4).

371 3.6. Seed germination

372 Germination experiments under controlled conditions highlighted a drastic effect  
373 of water potential on the germination rate of the different species (Appendix C).  
374 Parameters  $P_0$  (threshold water potential level for seed germination),  $G_{max}$  (maximum  
375 germination rate) and the  $R^2$  of the fitted sigmoid equation, together with threshold soil  
376 moisture values are shown in table 5. In general, herbaceous species had lower moisture  
377 requirements (i.e. more negative  $P_0$  water potential values) for germination when  
378 compared to woody species (*G. scorpius*, *T. vulgaris*, *S. chamaecyparissus*), except for  
379 *M. sativa*, which was introduced during revegetation practices. The non parametric  
380 bifactorial ANOVA applied to the germination suitability index showed significant  
381 effects of vegetation patch ( $F_{7,192}=13.64$ ,  $p<0.001$ ) and species ( $F_{7,192}= 6.99$ ,  $p<0.001$ ).  
382 Two species showed fewer suitable days for germination (*Genista scorpius* and  
383 *Brachypodium retusum*). With regards to vegetation patches, *Brachypodium*, *Medicago*  
384 and *Genista* patches appeared to be potentially more suitable microsites for  
385 germination, contrasting with *Santolina* patches, which presents less suitable soil  
386 moisture values for germination (Fig. 6).

387 The germination suitability index was significantly different between hillslopes  
388 (Friedman ANOVA  $p<0.001$ , Fig. 6). Therefore, conditions in hillslope 1 were less  
389 suitable for germination than in the other hillslopes.

390

## 391 4. Discussion

392 Descriptors of the vegetation-hydrology interactions have been explored under  
393 the TTRP framework (Ludwig et al., 2005) described above in four steps: a) soil water  
394 availability for plants in different vegetation patches; b) ecological performance of  
395 vegetation patches related to soil water content; c) feedback effects of vegetation on soil  
396 water availability, specifically by the enhance of soil water infiltration; and d) the  
397 effects of volume of overland flow routing through the hillslope on eco-hydrological  
398 interactions.

### 399 4.1. Soil moisture availability in vegetation patches

400 Measured soil moisture values should be interpreted as a result of the balance  
401 between water inputs through infiltration and water used by plants, which lead to, for  
402 example, higher water stress at the end of the drought period in patches with higher  
403 vegetation cover. Therefore, the interpretation of soil moisture results should be made  
404 together with plant cover values. The three vegetation patches that act as sinks, *Lolium*,  
405 *Brachypodium* and *Genista*, incorporated higher water volumes in depth which were  
406 consumed by vegetation, depleting soil moisture at the end of the growth season (Fig. 5,  
407 Appendix B). Soil water content in these sink patches is the result of higher rainfall  
408 infiltration capacity on site and/or the obstruction of overland flow generated in upslope  
409 source patches. In the case of *Genista* patches, vegetation clumps are especially efficient  
410 at both infiltrating water onsite and obstructing the water flow coming from the upper  
411 part of the hillslope, thus modifying micro-environmental conditions through the  
412 concentration of soil moisture. In general, these results agree with different studies on  
413 the effects of vegetation on soil water content compared to bare open areas (Eldridge  
414 and Freudenberger, 2005; Joffre and Rambal, 1993; Shumway, 2000). Previous studies  
415 showed that the proliferation of *Lolium* and *Brachypodium* patches in these hillslopes

416 was associated to the generation of depositional micro-topographic structures (i.e. rill  
417 fans or splays) that act as geomorphologically-driven "surface sinks" of fine-grained  
418 sediments and nutrients with favourable conditions for the growth of perennial grasses.  
419 These structures are generated by differential erosion in the early stages of succession  
420 after hillslope construction, suggesting a key role of overland flow in structuring  
421 vegetation (Merino-Martin et al., 2012). This spatial arrangement of species and soil  
422 moisture content is also consistent with observations on other ecosystems with banded  
423 vegetation patterns and suggest a coupling between source-patches up-slope and  
424 downslope sinks (Seghieri and Galle, 1999; Seghieri et al., 1997). This coupling has  
425 been further confirmed in an runoff-exclusion experiment study developed on the three  
426 sink patches (Espigares et al., 2012).

#### 427 *4.2. Ecological performance of vegetation patches associated to soil water availability*

428 Sink patches (*Genista*, *Brachypodium*, *Lolium*) showed higher species richness  
429 and diversity compared with other patches located on the same hillslope (Fig. 3). We  
430 didn't find this pattern for soil seed bank density, where *Brachypodium* patches had a  
431 particularly low seed bank density. This could be explained by the resprouting strategy  
432 of *B. retusum*, advantageous over seeding for this rhizomatous perennial grass, that  
433 allows the species to persist continuously after disturbance (Bond and Midgley, 2001).

434 The analysis of the implications of surface soil moisture for germination showed  
435 that the different vegetation patches reached different suitable days for germination,  
436 with two sink patches (*Genista* and *Brachypodium*) and one source patch (*Medicago*)  
437 being the best micro-environments for germination (Fig. 6). However, our findings  
438 highlight final infiltration rate and soil moisture in depth as the variables that best  
439 correlate with vegetation traits, in contrast with soil surface moisture, which was not

440 correlated with the ecological descriptors of patch structure (table 3). Surface soil  
441 moisture (first 5 cm of the soil) is likely to strongly fluctuate with time due to direct  
442 evaporation, and therefore periodical sampling may not record significant changes  
443 among treatments at this soil depth. Our results suggests that soil moisture in depth (at  
444 25 and 50 cm) is ecologically more significant (i.e. it has broader implications on  
445 community richness and diversity) than surface soil moisture. In fact, although surface  
446 soil moisture heterogeneity has implications for colonization (e.g. germination), our  
447 results indicate that soil moisture in depth was more significant for structuring  
448 vegetation patches, probably controlling further vegetation establishment and plant  
449 survival.

450         Plant community composition depends to a large extent on the amount and  
451 spatial distribution of soil moisture available for plants (Breshears and Barnes, 1999).  
452 Our results showed how ecohydrological heterogeneity can influence plant germination  
453 and colonization processes by driving the spatial distribution of soil moisture on  
454 hillslopes. Our study was not designed to measure growth pulses in *Genista* patches (as  
455 would be expected under the TTRP conceptual framework), however we have found a  
456 pulse of floristic and soil seed bank richness in the understorey plant community.  
457 Similar results have been also found in a recent research on coal mine sites (Alday et al.,  
458 2014), where natural shrub encroachment was identified as a key process driving the  
459 generation of spatial heterogeneity in micro-environmental conditions, hence inducing  
460 greater overall plant diversity.

461 4.3. *Feedback effect of vegetation on soil water availability through an increase in water*  
462 *infiltration*

463 A third type of vegetation-hydrology interaction, that drives the performance of  
464 our reclaimed semiarid vegetation communities, deals with the feedback effect of  
465 vegetation on soil water availability. Results from rainfall simulation experiments and  
466 soil properties analyses show that infiltration capacity and soil macroporosity (as  
467 opposed to bulk density) are higher in sink-patches (*Genista*, *Lolium* and  
468 *Brachypodium*) than in source patches (*Thymus*, *Santolina*, *Dactylis* and *Medicago*).  
469 Furthermore, *Genista* patches were the most favourable microsites for water infiltration  
470 and storage. Again, these differences can be attributed to the patch structuring effects of  
471 both differential erosion (i.e. the generation of rill fans or splays) and vegetation in the  
472 case of *Lolium* and *Brachypodium* patches, but only to the effect of vegetation in the  
473 case of *Genista* patches (Merino-Martin et al., 2012).

474 In general, soil enhancement by woody legumes (e.g. *Genista scorpius*) has been  
475 shown to have positive effects on neighbours in nutrient-poor environments (Shumway,  
476 2000), and particularly in Mediterranean systems (Aguilera et al., 1999; Moro et al.,  
477 1997). Gomez Aparicio et al. (2005) in a study about shrub facilitation found that  
478 below-ground, shrubs did not modify soil physical characteristics, organic matter, total  
479 N and P, or soil moisture, but significantly increased available K. Conversely, in our  
480 study we found differences in N, P, organic matter and soil physical properties (i.e. bulk  
481 density and surface crusting) between the different vegetation patches, with sinks  
482 showing a higher content in nutrients and lower bulk density and soil surface strength.  
483 The fact that our system is a restored ecosystem under succession may explain the large  
484 impact of vegetation on enhancing soil properties and conditions. In this regard, the use  
485 of shrubs (Castro et al., 2002; Gomez-Aparicio et al., 2004; Padilla and Pugnaire, 2006)

486 and perennial grasses (*Stipa sp.*, Gasque and García-Fayos, 2004) for restoration has  
487 been widely applied for Mediterranean and semiarid areas.

488 Overall, our results allow us to consider the impact of *Genista* patch as a  
489 vegetation-mediated ecohydrological feedback or “plant nucleation” process  
490 (Puigdefábregas et al., 1999) that enhances microsite ecological and hydrological  
491 attributes for water collection and vegetation establishment. Our findings agree with  
492 those by Maestre et al. (2009), who found that shrubs can reverse land degradation and  
493 desertification in drylands; in our case, promote vegetation recovery along vegetation  
494 succession. They discuss how shrubs with canopies that spread horizontally (as this is  
495 the case for *G. scorpius* in our study) enhance the sink behaviour of the vegetation  
496 patch, contrasting with shrubs that usually colonize other semiarid areas of North  
497 America (e.g. mesquite, creosotebush) and generally are associated with land  
498 degradation and the acceleration of soil erosion processes (Wainwright et al., 2000).  
499 Rango *et al.* (2006) called these sink patches “islands of enhanced hydrologic activity”  
500 in the Chihuahuan Desert. Other authors refer to them as “fertility islands” (Barthes and  
501 Roose, 2002; Cammeraat and Imeson, 1998; Cerdà, 1998; Puigdefábregas et al., 1999) .  
502 The use of shrubs as ecosystem engineers to enhance overall environmental  
503 heterogeneity and different plant communities in restoration has been recently suggested  
504 (Alday et al., 2014). However, these authors emphasize that the effectiveness of these  
505 ecosystem engineers should be tested in future research.

#### 506 *4.4. The modulation of ecohydrological interactions by overland flow volume.*

507 Soil moisture content at the hillslope scale was negatively related to the amount  
508 of overland flow (Fig. 5), showing higher soil moisture contents at the three soil depths  
509 whenever runoff volume decreased. The effects of erosion processes accentuating

510 drought stress and decreasing productivity have been largely described in intensively  
511 eroded arid and semiarid areas (Espigares et al., 2011; Lal, 1998; Pimentel and Harvey,  
512 1999). Our study suggests that in reclaimed hillslopes where erosion rates are not  
513 particularly high (rill erosion rates in the experimental slopes are  $<10 \text{ t ha}^{-1} \text{ yr}^{-1}$ ,  
514 Appendix A), the formation and downslope routing of overland flow is one of the main  
515 factors decreasing soil moisture at the hillslope scale. We also found that hillslope  
516 runoff decreased soil water content at the patch scale, as evidenced by soil moisture  
517 differences in *Santolina* patches between hillslopes 1 and 3, with significantly lower  
518 water contents in the hillslope with the highest runoff volumes. This suggests that if the  
519 sink capacity of a surface patch (i.e. the capacity of the patch to obstruct and infiltrate  
520 water runoff) is exceeded, the spatial connectivity of overland flow increases at larger  
521 scales, leading to the loss of runoff away from the hillslope and therefore decreasing in-  
522 slope soil water content, as observed for the case of hillslope 1. Similarly, other  
523 applications of the TTRP model in natural arid and semiarid environments indicate that  
524 soil-water-vegetation feedbacks driven by coupled reductions (or increases) in sink  
525 capacity of surface patches at small scales with broad-scale amplification (or reduction)  
526 of the spatial connection of overland flow have a critical role for the  
527 activation/promotion of land degradation (or restoration) processes (Moreno-de las  
528 Heras et al., 2012; Okin et al., 2009; Tongway and Ludwig, 1996).

529 Overland flow also influences the germination opportunities for plants at the  
530 hillslope scale, decreasing germination probabilities as hillslope overland flow increases  
531 (Fig. 6). Traditionally, plant colonisation has been considered as limited by the distance  
532 between appropriate seed source areas and target areas in humid reclaimed  
533 environments (Kirmer and Mahn, 2001; Novak and Prach, 2003). Bochet *et al.* (2007)  
534 and Tormo *et al.* (2006), identified water availability as the main factor controlling

535 germination processes in semiarid roadslopes. According to these results, we suggest  
536 that in reclaimed semiarid environments, where water is the main limiting factor for  
537 vegetation growth, overland flow is one of the main factors driving plant colonization  
538 by increasing water deficit in the soil, not only for germination at the surface (5 cm  
539 depth), but also in depth (at 25 and 50 cm) for further plant establishment and plant  
540 community development.

#### 541 *4.5. Practical implications.*

542         Similar ecohydrological interactions have been well described for semiarid  
543 ecosystems spatially structured in mosaics of coupled runoff sources and sinks resulting  
544 from feedbacks in a dynamic equilibrium (Valentin et al., 1999). Imeson and Prinsen  
545 (2004) stated that the spatial differentiation between sources and sinks of surface  
546 resources is a dynamic property of many semiarid ecosystems and it feeds back to plant  
547 growth as well as bare patch development. In our case, we cannot anticipate whether our  
548 system is in a dynamic equilibrium through time or whether we are studying a  
549 temporary stage of succession with a tendency to be fully covered by vegetation.  
550 However, management of spatial heterogeneity (i.e. promotion of patch formation and  
551 manipulation of the spatial coupling or connection between source patches and sinks  
552 with optimum conditions for vegetation establishment) may prove useful for stabilizing  
553 these novel systems, especially at the early stages when vegetation density is low and  
554 soil surface process (e.g. surface crusting, runoff generation, soil erosion and  
555 sedimentation) are particularly active (Hancock and Willgoose, 2004, Tormo et al.  
556 2006, Moreno-de las Heras et al. 2009, Alday et al. 2014).

557         Two patch-forming ecohydrological interrelationships (or feedbacks) were found  
558 in this study: a patch-forming feedback where surface hydrology (i.e. local

559 sedimentation and runoff infiltration in rill fans or splays) is the main driver for  
560 vegetation establishment (in hillslopes 1 and 2, where grasses play a passive role on  
561 patch dynamics), and a biologically-driven feedback where vegetation (*Genista scorpius*  
562 shrubs, in hillslope 3) is the main driver of local surface hydrology and patch dynamics.  
563 This scheme follows the approach by Puigdefábregas et al. (1999), who explained these  
564 two types of mosaic generating process: (1) mosaics driven by differential erosion,  
565 where plant cover plays a passive role on structuring patch dynamics, and (2) mosaics  
566 resulting from “plant nucleation” processes where vegetation plays an active role. As  
567 overland flow and its ecological impacts are determined by hillslope topography design  
568 and topsoil selection, reclamation practices must be appropriately managed in order to  
569 develop a functional ecosystem. Rango et al. (2006) proposed that in order to  
570 rehabilitate degraded landscapes, it may be appropriate to mimic the patchy nature of  
571 fully functional arid and semiarid ecosystems, diverting water to target areas for the  
572 establishment of vegetation. In that respect, the presence of local sedimentation  
573 microsites (e.g. surface depressions, rill discontinuities, surface splays) offer important  
574 advantages for the promotion of patch dynamics and early development of vegetation.  
575 The use of keystone plant species with a high capacity to modify microsite conditions  
576 and obstruct the surface flow of water runoff and sediments (such as *Genista scorpius* in  
577 this study) can also help to enhance the development and dynamics of vegetation and to  
578 control soil erosion processes in these semiarid reclaimed landscapes.

## 579 **5. Conclusions**

580 Our results from semiarid reclaimed hillslopes were consistent with the TTRP  
581 conceptual model (Ludwig et al., 2005). Vegetation patches showed diverse  
582 hydrological behaviours and soil moisture contents, acting as runoff sources or sinks.  
583 The hydrological behaviour of three sink vegetation patches (*Lolium*, *Brachypodium*

584 and *Genista*) was due to a higher rainfall infiltration capacity on site and/or the  
585 obstruction of overland flow generated in upslope source patches. Furthermore, there  
586 were important ecological consequences derived from the heterogeneous spatial  
587 distribution of soil moisture. Sink patches showed higher species richness and diversity,  
588 higher infiltration capacity and soil macroporosity. Remarkably, *Genista* sink patch  
589 enhanced microsite ecological and hydrological attributes for water collection and  
590 vegetation establishment. Overall, overland flow influenced germination opportunities  
591 for plants at the patch and hillslope scales, decreasing germination probabilities as  
592 hillslope overland flow increased. Our results highlight the significance of overland  
593 flow as it modifies soil moisture distribution and hence, influences vegetation dynamics  
594 and ecological succession even at moderate runoff rates ( $<10 \text{ t ha}^{-1} \text{ yr}^{-1}$ ).

595           The TTRP general framework was previously applied in natural semiarid  
596 ecosystems in dynamic equilibrium throughout the world. In this study we have also  
597 corroborated this conceptual framework for a highly dynamic and unstable restored  
598 ecosystem subjected to ecological succession.

599

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811 **Figure captions:**

812 **Figure 1.** The Trigger–Transfer–Reserve–Pulse (TTRP) framework linking temporal  
813 (trigger) events, such as rainstorm inputs of water, through spatial transfer (runoff–  
814 runon) and reserve (patch) processes, to pulse events, such as plant growth. These  
815 linkages are denoted with solid arrows. Feedbacks and flows out of the system are  
816 indicated with dashed or dotted arrows (taken from Ludwig *et al.* 2005).

817 **Figure 2.** a) Selected slopes; the red line shows the upslope structure that generates  
818 extra-overland flow. b) abundance and spatial distribution of the different vegetation  
819 patches in the three slopes. G: *Genista*; B: *Brachypodium L: Lolium*; T: *Thymus*; D:  
820 *Dactylis*; S: *Santolina (hillslope 1)*; M: *Medicago*.

821 **Figure 3.** Floristic traits of the different vegetation patches. a) Plant species richness; b)  
822 Seed density of soil seed bank; c) Species richness of soil seed bank; d) Shannon’s  
823 diversity of soil seed bank. G: *Genista*; B: *Brachypodium L: Lolium*; T: *Thymus*; D:  
824 *Dactylis*; S1: *Santolina* in hillslope 1; S3: *Santolina* in hillslope 3; M: *Medicago*.  
825 Different letters indicate significant differences ( $p < 0.01$ )

826 **Figure 4.** Soil hydrological properties of the different vegetation patches. a) Final  
827 infiltration rate ( $\text{mm h}^{-1}$ ); b) runoff coefficient (%); c) soil profile moistening rate ( $\text{cm h}^{-1}$ );  
828 d) sediment concentration ( $\text{g l}^{-1}$ ). G: *Genista*; B: *Brachypodium L: Lolium*; T:  
829 *Thymus*; D: *Dactylis*; S: *Santolina (hillslope 1)*; M: *Medicago*.

830 **Figure 5.** 2007-08 soil moisture dynamics in vegetation patches and hillslopes at three  
831 soil depths. b) 5cm; c) 25cm; d) 50 cm. G: *Genista*; B: *Brachypodium L: Lolium*; T:  
832 *Thymus*; D: *Dactylis*; S1: *Santolina* in hillslope 1; S3: *Santolina* in hillslope 3; M:  
833 *Medicago*. Figure 4a shows meteorological data (daily precipitation and daily mean air  
834 temperature) throughout the monitored period.

835 **Figure 6.** Germination suitability index (a) for each vegetation patch (b) for each  
836 hillslope. G: *Genista*; B: *Brachypodium L: Lolium*; T: *Thymus*; D: *Dactylis*; S1:  
837 *Santolina (hillslope 1)*; M: *Medicago*.

838 **Appendix A.** Descriptive features for the three experimental slopes (mean  $\pm$  SE)  
839 (modified from Merino-Martin *et al.*, 2012)

840 **Appendix B.** 2007-08 soil moisture dynamics in the vegetation patches along depth.

841 **Appendix C.** Seed germination rates of each species under different water potentials.

842

843 **Table 1.** Characteristic species and mean vegetation cover ( $\pm$  SE) of the seven  
 844 vegetation patches.

Vegetation community	Indicator species	Vegetation cover (%)	
<i>Genista</i>	<i>Genista scorpius, Anacyclus clavatus, Bromus rubens, Cerastium pumilum, Eryngium campestre, Plantago lanceolata, Sanguisorba minor, Xeranthemum inapertum</i>	81.3 $\pm$ 12.5	a
<i>Brachypodium</i>	<i>Brachypodium retusum, Avena sterilis, Avenula bromoides, Barkhausia haenseleri, Festuca sp., Koeleria vallesiana</i>	93.7 $\pm$ 3.6	a
<i>Lolium</i>	<i>Lolium perenne</i>	67.3 $\pm$ 11.1	a
<i>Thymus</i>	<i>Thymus vulgaris, Desmazeria rigida</i>	23.3 $\pm$ 3.6	ab
<i>Dactylis</i>	<i>Dactylis glomerata</i>	17.3 $\pm$ 1.7	ab
<i>Santolina</i>	<i>Santolina chamaecyparissus</i>	19.3 $\pm$ 6.1	ab
<i>Medicago</i>	<i>Medicago sativa, Scorzonera laciniata</i>	2.7 $\pm$ 0.4	b

845

846 **Table 2.** Results of the repeated measures ANOVA applied to soil water content in  
 847 vegetation patches.

Effect	Degr. of freedom	F	p
Vegetation patch	7	14.811	<0.000001
Sensor depth	2	13.012	0.000031
Vegetation patch*Sensor depth	14	3.390	0.000795
Time	16	546.762	<0.000001
Time*Vegetation patch	112	6.896	<0.000001
Time*Sensor depth	32	18.608	<0.000001
Time*Vegetation patch*Sensor depth	224	2.482	<0.000001

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857 **Table 3.** Results of pearson correlations between hydrological and vegetation properties  
 858 in vegetation patches. If: final infiltration rate; Qc: Runoff coefficient; Sm: Soil  
 859 moisture. (\*\*:  $p < 0.01$ , \*:  $p < 0.05$ ; n.s.: no significant).

Cover type features		If	Qc	Sm 5cm	Sm 25cm	Sm 50cm
Species richness (vegetation)	p	0.012	0.059	0.316	0.032	0.031
	R	+0.864	-0.752	+0.446	+0.797	+0.802
		*	n.s.	n.s.	*	*
Vegetation cover	p	0.006	0.027	0.450	0.1087	0.052
	R	+0.899	-0.811	+0.339	+0.657	+0.750
		**	*	n.s.	n.s.	n.s.
Species richness (seed bank)	p	0.048	0.132	0.555	0.009	0.088
	R	+0.759	-0.627	+0.272	+0.880	+0.687
		*	n.s.	n.s.	**	n.s.
Shannon's diversity (seed bank)	p	0.032	0.155	0.452	0.003	0.069
	R	+0.796	-0.599	+0.434	+0.919	+0.719
		*	n.s.	n.s.	**	n.s.
Soil seed bank density	p	0.529	0.709	0.669	0.068	0.557
	R	+0.288	-0.173	+0.2	+0.719	+0.270
		n.s.	n.s.	n.s.	n.s.	n.s.

860

861 **Table 4.** Edaphic properties of vegetation patches. Abbreviations: EC: Electrical  
 862 conductivity; w/v: relation weigh (soil)/volume (water):1/2; AWHC: Available water  
 863 holding capacity. <sup>1</sup> Measured in three composite samples (each formed by three  
 864 subsamples) in each vegetation patch or runoff contributing area from the first 10 cm. <sup>2</sup>  
 865 Measured in 15 unaltered soil cores (3cm height by 5 cm diameter); 3 randomly  
 866 distributed soil cores for each 7 vegetation patch. <sup>3</sup> Measured in 15 randomly distributed  
 867 samples in the different vegetation patches during four campaigns (seasonal  
 868 measurements). Values with "\*" differ significantly at  $\alpha=0,05$ . Values with "\*\*\*" differ  
 869 significantly at  $\alpha=0,01$ . <sup>1</sup> Tested using Kruskal-Wallis and Mann-Whitney U tests.  
 870 <sup>2</sup>Tested using ANOVA and Tukey's *post hoc* tests. <sup>3</sup>Tested using Friedman test and  
 871 Wilcoxon-Nemenyi-McDonald-Thompson *post-hoc* tests.

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	<i>Genista</i>	<i>Braquipodium</i>	<i>Lolium</i>	<i>Thymus</i>	<i>Dactylis</i>	<i>Santolina</i>	<i>Medicago</i>	p
								
<b>pH<sup>1</sup></b>	8.2±0.1 a	8.4±0.1 a	8.2±0.1 a	8.3±0.1 a	8.5±0.1 a	8.5±0.1 a	7.9±0.2 a	n.s.
<b>EC<sup>1</sup> (dSm<sup>-1</sup>)</b>	0.07±0.01 a	0.08±0.02 a	0.04±0.01 a	0.05±0.01 a	0.05±0.01 a	0.05±0.01 a	0.07±0.01 a	n.s.
<b>Carbonates<sup>1</sup> (%)</b>	8.0±0.8 ab	9.4±0.7 ab	10.1±0.4 ab	11.6±0.6 a	9.7±1.1 ab	9.5±1.1 ab	1.9±0.5 b	*
<b>Nitrogen<sup>1</sup> (%)</b>	0.18±0.04 a	0.12±0.01 ab	0.09±0.01 ab	0.09±0.01 ab	0.06±0.01 ab	0.06±0.01 ab	0.03±0.01 b	**
<b>Organic matter<sup>1</sup> (%)</b>	4.4±0.9 a	2.8±0.3 ab	2.1±0.2 ab	2.3±0.5 ab	1.6±0.2 ab	0.5±0.3 ab	0.3±0.1 b	**
<b>C/N<sup>1</sup></b>	13.9±1.7 a	13.8±0.3 a	14.1±0.7 a	15.3±2.9 a	15.8±0.8 a	5.8±2.9 a	6.9±1.8 a	*
<b>Phosphorus<sup>1</sup> (%)</b>	13.7±3.3 a	11.7±1.3 a	5.7±0.3 ab	3.7±0.3 ab	2.7±0.3 b	4.3±0.3 ab	4.3±0.3 ab	**
<b>Clay<sup>1</sup> (%)</b>	19.3±0.3 a	19.7±0.9 a	12.3±0.9 a	18.0±0.6 a	17.3±0.3 a	20.0±1.0 a	15.0±1.2 a	*
<b>Silt<sup>1</sup> (%)</b>	29.0±1.0 ab	25.7±3.2 a	38.3±6.1 ab	38.3±1.8 ab	43.0±2.0 ab	46.3±0.7 ab	52.7±0.9 b	*
<b>Sand<sup>1</sup> (%)</b>	51.7±1.2 a	51.3±3.9 a	49.3±6.6 a	43.7±1.2 a	39.7±2.3 a	33.7±0.3 a	32.3±2.0 a	*
<b>AWC<sup>1</sup> (%)</b>	6.4±0.3 a	8.5±0.3 a	8.1±1.4 a	6.9±0.1 a	9.0±0.4 a	8.8±0.2 a	9.1±0.7 a	n.s.
<b>Bulk density<sup>2</sup> (Mg m<sup>-3</sup>)</b>	1.13±0.04 a	1.30±0.05 b	1.41±0.04 b	1.55±0.02 cd	1.41±0.03 bc	1.42±0.02 bc	1.61±0.01 d	**
<b>Soil surface strength<sup>3</sup> (kg)<sup>3</sup></b>	2.2±2.1 a	4.7±3.8 ab	4.5±4.0 ab	4.7±3.7 ab	4.8±3.9 ab	4.4±3.2 ab	5.4±3.4 b	*

875 **Table 5.** Coefficients of the seed-germination sigmoid function (eq. 2) and  
 876 corresponding water content (%) at threshold  $P_0$  for different species.  $P_0$ : water  
 877 potential threshold value for seed germination;  $G_{max}$ : maximum germination rate.

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Species	$P_0$ (MPa)	$G_{max}$ (%)	$R^2$	Soil moisture (%)
<i>Genista scorpius</i>	-0.611	46.26	0.737	12.36 ± 2.47
<i>Brachypodium retusum</i>	-0.724	49.09	0.745	12.04 ± 2.46
<i>Lolium perenne</i>	-0.766	72.11	0.955	11.94 ± 2.46
<i>Thymus vulgaris</i>	-0.569	78.43	0.928	12.50 ± 2.47
<i>Dactylis glomerata</i>	-0.741	89.19	0.948	11.99 ± 2.46
<i>Santolina chamaecyparissus</i>	-0.620	81.20	0.874	12.34 ± 2.47
<i>Medicago sativa</i> *	-0.416	88.93	0.970	13.13 ± 2.48
<i>Aegilops geniculata</i>	-1.161	79.33	0.796	11.19 ± 2.45

879 \* Data taken from Moreno-de las Heras and collaborators (2011)

880

	N	Hillslope 1	Hillslope 2	Hillslope 3	
Date of reclamation		1988	1988	1987	
<i>Topography</i>					
Hillslope area (m <sup>2</sup> )		497.5	510.6	1474.3	
Hillslope gradient (°)		20	20	20	
Water-Contributing Area (m <sup>2</sup> )		50.4	22.7	0	
Aspect		North	North	North	
<i><sup>1</sup>Soil traits</i>					
Stoniness (%)	9	39.2 ± 4.5	a 40.5 ± 3.2	a 41.9 ± 3.4	a
Sand (%)	9	44.8 ± 2.6	a 45.6 ± 2.7	a 44.0 ± 3.0	a
Silt (%)	9	28.7 ± 0.3	a 25.2 ± 1.1	a 29.8 ± 1.2	a
Clay (%)	9	26.6 ± 2.4	a 29.3 ± 1.6	a 26.3 ± 1.8	a
Texture	9	Clay loam	Clay loam	Clay loam	
pH -H <sub>2</sub> O; w/v: 1/2-	9	8.4 ± 0.3	a 8.3 ± 0.2	a 8.01 ± 0.2	a
EC -w/v: 1/2- (dS m <sup>-1</sup> )	9	0.3 ± 0.1	a 0.3 ± 0.01	a 0.7 ± 0.4	a
Organic matter (%)	9	1.2 ± 0.3	a 1.6 ± 0.34	a 2.0 ± 0.4	a
CaCO <sub>3</sub> (%)	9	7.3 ± 0.4	a 6.2 ± 0.38	a 6.8 ± 0.3	a
<sup>2</sup> Bulk density (Mg m <sup>-3</sup> )	27	1.5 ± 0.1	a 1.5 ± 0.03	a 1.4 ± 0.01	a
<i><sup>3</sup>Cover features</i>					
Bare soil cover (%)	105	44.6 ± 3.1	a 32.3 ± 3.9	b 23.7 ± 2.8	b
Stone cover (%)	105	25.5 ± 3.0	a 22.7 ± 1.6	a 21.1 ± 2.6	a
	105	5.4 ± 1.8	a 1.1 ± 0.4	b 4.0 ± 1.9	a
Litter cover (%)					b
Plant cover (%)	105	24.4 ± 2.8	a 43.9 ± 4.1	b 51.2 ± 4.2	b
<i><sup>3</sup>Plant traits</i>					
Species Richness	105	3.83 ± 0.28	a 6.43 ± 0.44	b 9.26 ± 0.55	c
Shannon's index	105	0.80 ± 0.08	a 1.21 ± 0.08	b 1.30 ± 0.08	b
<i>Erosion features</i>					
<sup>4</sup> Sheet Erosion Index	9	0.70 ± 0.09	a 0.59 ± 0.05	a 0.52 ± 0.06	a
<sup>5</sup> Rill density (m m <sup>-2</sup> )	3	0.58	0.00	0.00	
<sup>6</sup> Rill erosion rate <sup>4</sup> (t ha <sup>-1</sup> yr <sup>-1</sup> )	3	8.41	0.00	0.00	
<sup>7</sup> Runoff coefficient (%)	3	15.9 ± 3.0	a 2.2 ± 0.5	b 0.33 ± 0.17	b
<sup>7</sup> Sediment yield (g/m <sup>2</sup> )	3	107.3 ± 36.0	a 4.8 ± 1.8	b 0.23 ± 0.07	c

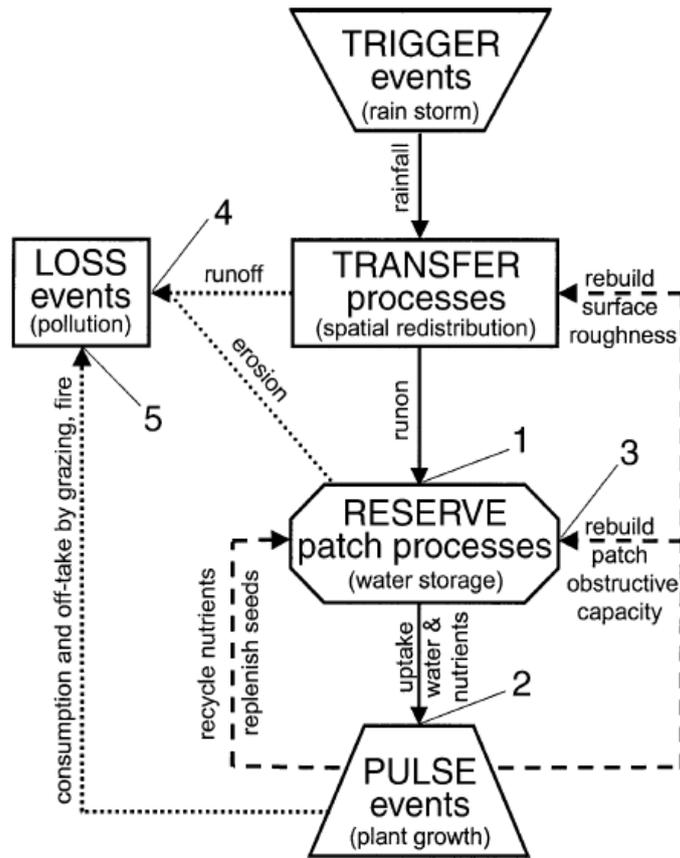
882

883 Abbreviations: N: Number of samples; EC: Electrical conductivity; w/v: relation weight (soil) / volume  
884 (water).885 <sup>1</sup>Measured in three composite samples (each formed by three subsamples) from the first 10 cm in three  
886 transects regularly distributed along the hillslope during winter 2005.887 <sup>2</sup>Measured in nine randomly distributed unaltered soil cores (3cm height by 5 cm diameter).888 <sup>3</sup>Cover, visually estimated in 35 regularly distributed 0,25 m<sup>2</sup> plots per hillslope during spring 2006.889 <sup>4</sup>Measured by the relationship: stone cover/stoniness; following Moreno-del Heras et al. (2008).890 <sup>5</sup>Linear rill length (m) measured per surface area (m<sup>2</sup>).891 <sup>6</sup>Measured from rill network dimensions following Morgan (1997).892 <sup>7</sup>Runoff and sediment yield monitored on the three experimental slopes from October 2007 to December  
893 2008 (Merino-Martín et al., 2012).

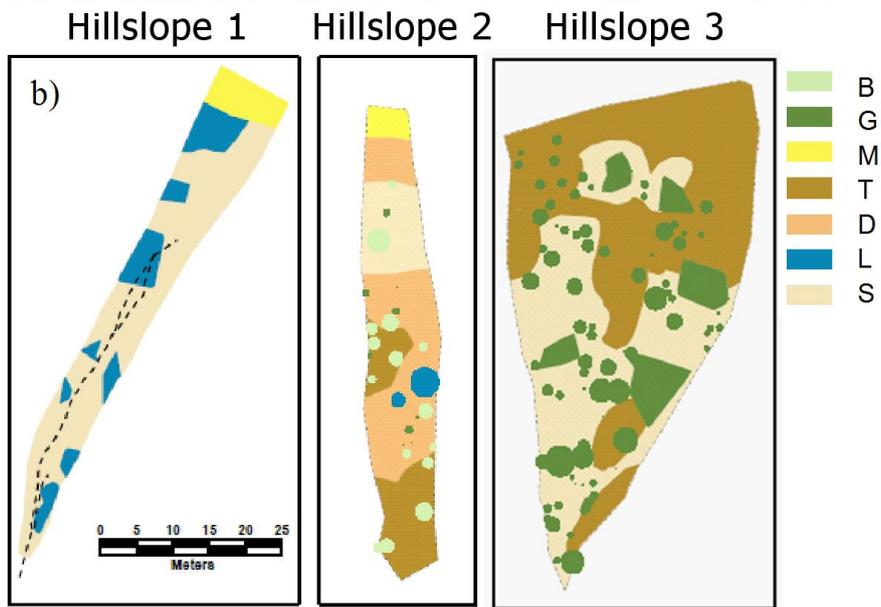
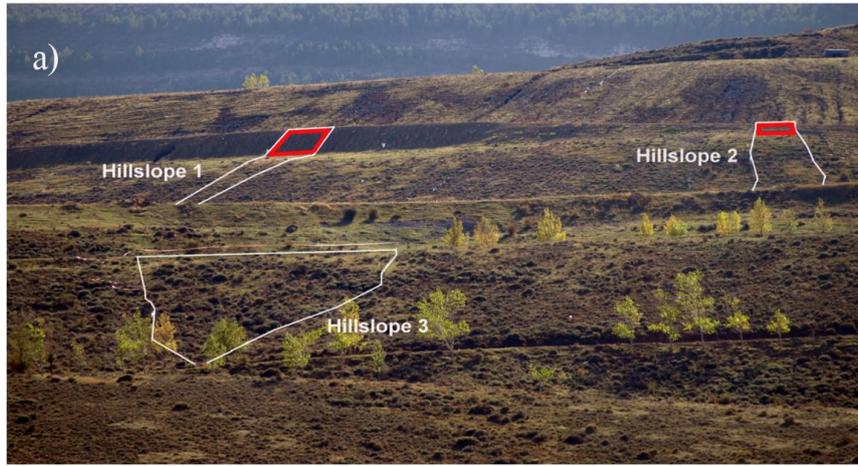
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895 All physico-chemical soil characteristics were analyzed following standardized methods proposed by the  
896 Spanish Ministry of Agriculture (MAPA, 1994). Values with the same letters (a-c) within rows do not  
897 differ significantly at  $\alpha=0,05$ . Tested using Kruskal-Wallis and Mann-Whitney post-hoc tests.

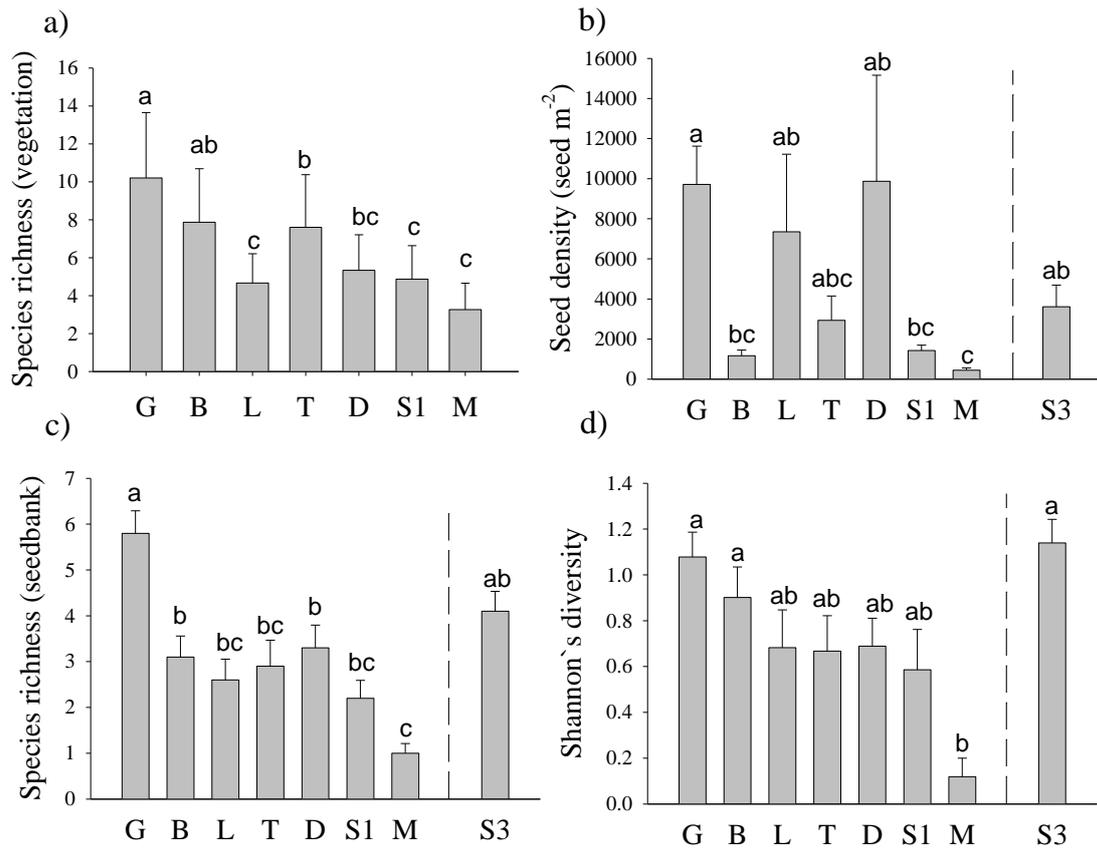
898



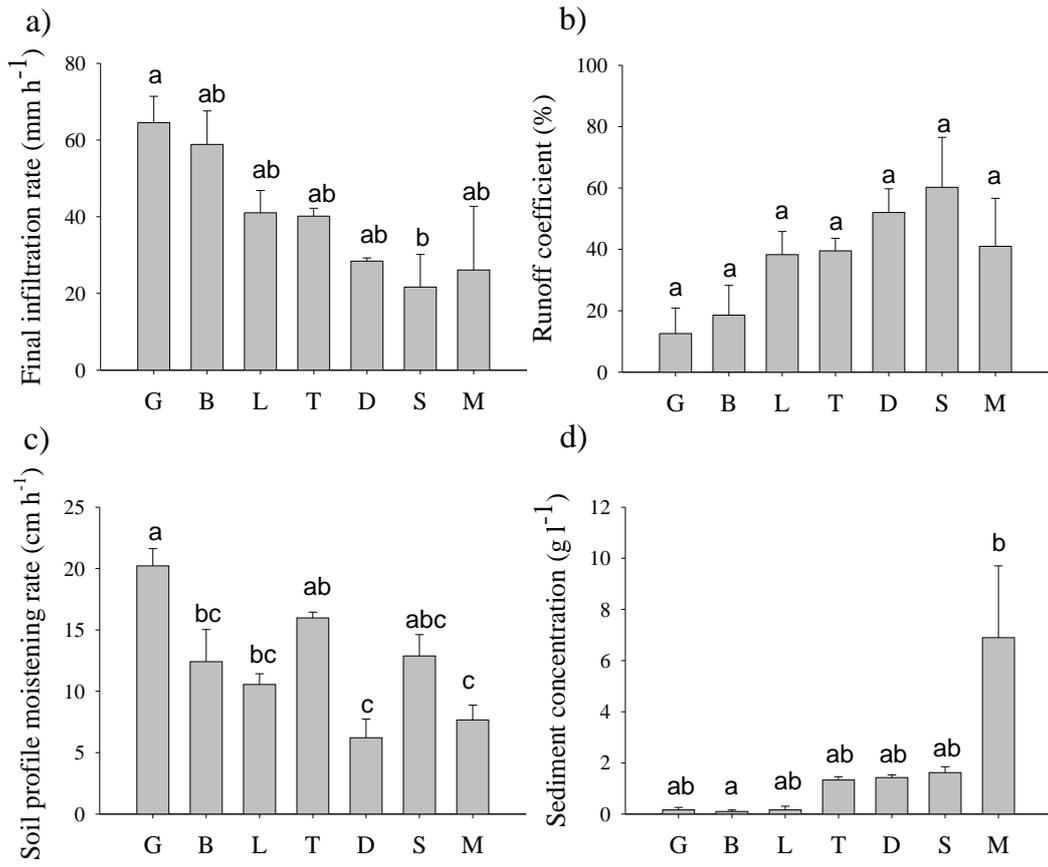
**Figure 1**



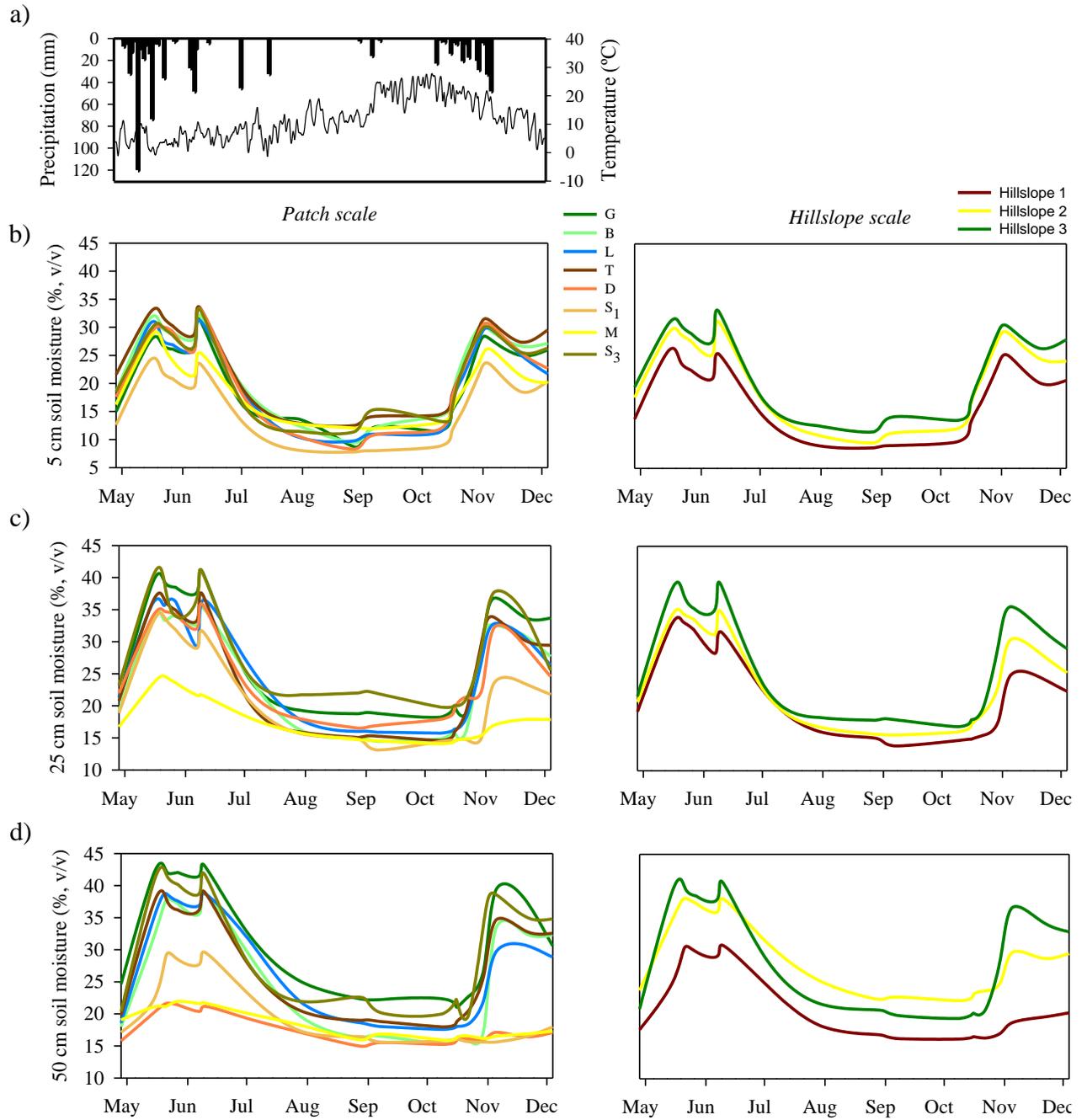
**Figure 2**



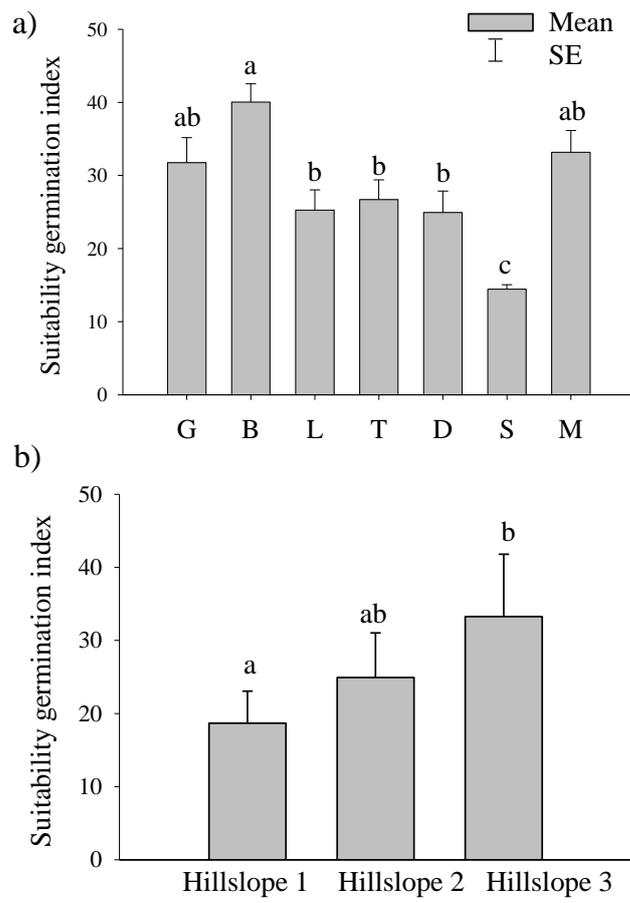
**Figure 3**



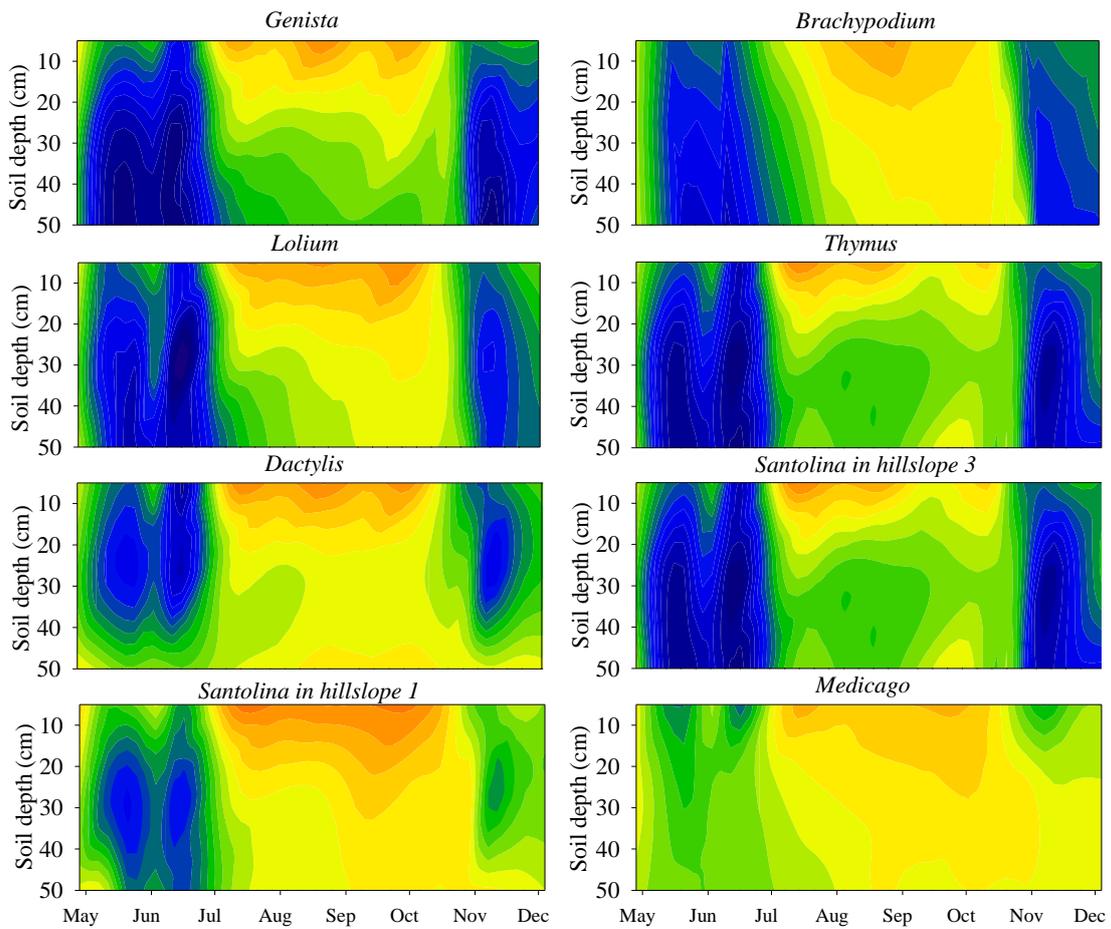
**Figure 4**



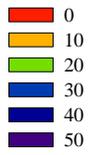
**Figure 5**



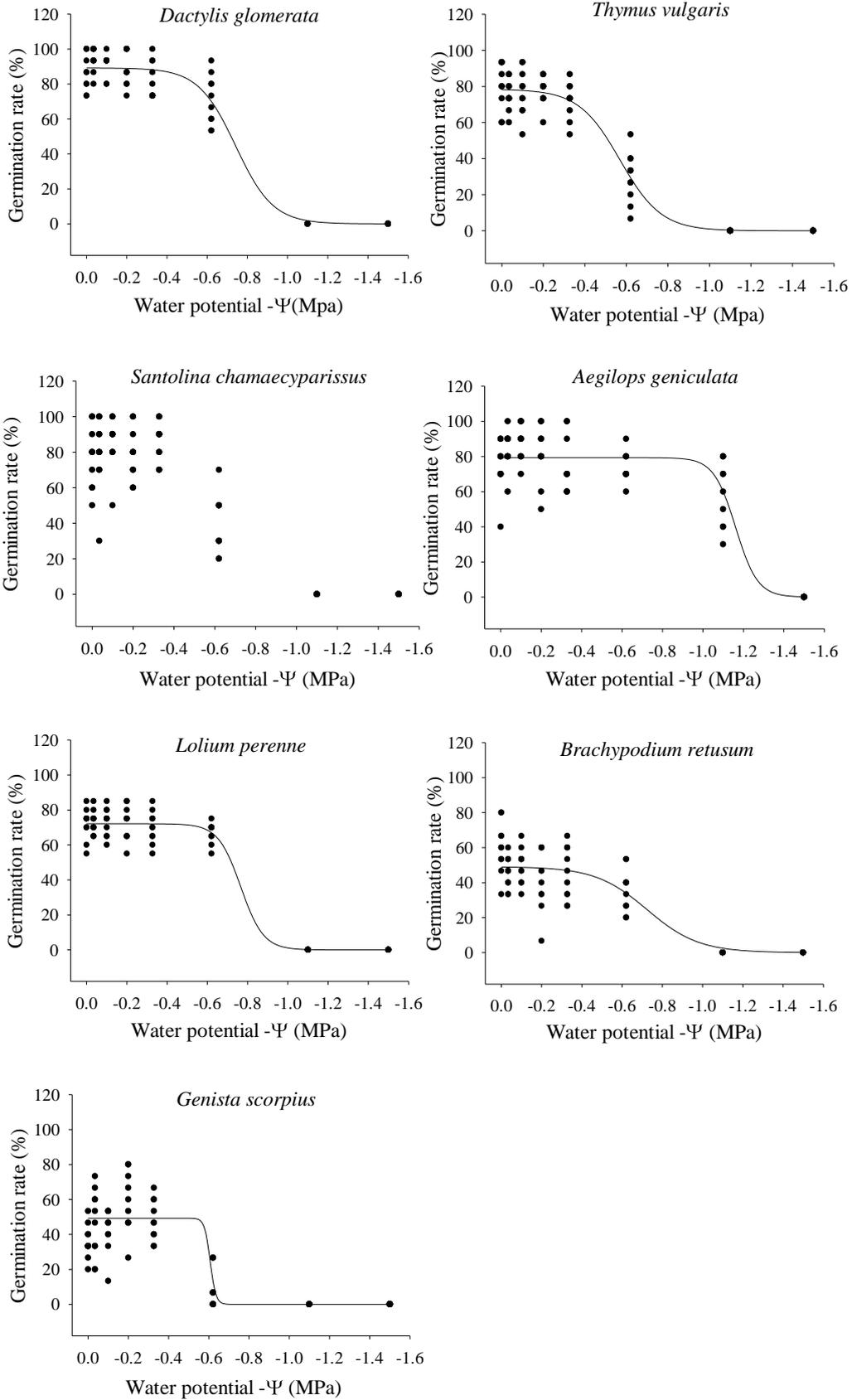
**Figure 6**



Soil water content (%)



## Appendix B



Appendix C