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Seasonal changes of the soil hydrological and erosive response in contrasted Mediterranean eco-geomorphological conditions at patch scale

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Abstract

Mediterranean areas are characterized by a strong spatial variability that makes highly complex the soil hydrological response. Moreover, Mediterranean climate has a marked seasonal variability that provokes dramatic changes on the soil properties determining the hydrological behavior, such as soil water content, crust formation or soil water repellency (SWR). Thus, soil hydrological and erosive response in Mediterranean areas can be highly time- as well space-dependant. The main goal of this study was to characterize the relations between SWR, aspect and vegetation, determining the soil hydrological and erosive response throughout the rainy period in different microenvironments of opposite hillslopes.

This study was undertaken in a small catchment located in the South of Spain. Erosion plots were installed in the north- and the south-facing hillslope, in areas with different vegetal cover, and runoff and sediments were collected. Moreover, precipitation parameters were recorded and SWR measurements were performed.

SWR proved to have a significant effect on the soil hydrological response, but this influence was modulated by seasonal changes and by the discontinuities on the repellent layer. In general, the influence of SWR was restricted to the first rains after the summer and was greater on the north-facing hillslope due to the more continuous vegetation cover. The more important precipitation parameter influencing runoff generated was maximum rainfall intensity in ten minutes ($I_{\max}$). The relation between $I_{\max}$ and overland flow showed a contrasting seasonal behavior in the north-facing hillslope and, on the contrary, remained homogeneous throughout the year in the south-facing hillslope.

1 Introduction

Traditionally it has been considered that soils infiltrate more when they are dry due to the high matric suction and the action of capillarity forces (Beven, 2001). However, this fact has been revoked under certain circumstances by numerous studies in recent years, arguing that repellent soils can have infiltration rates in several orders of magnitude lower than they are supposed to have in hydrophilic conditions (De Bano, 1971; Doerr et al., 2000). Soil water repellency (SWR) has received an increasing attention from the scientific community in the last decades and has been reported in several climates and soil types (Doerr et al., 2000). This property is favoured by low soil moisture content, although soil drying by itself is not enough to trigger soil water repellency and the addition of fresh hydrophobic compounds is also needed (Doerr and Thomas, 2000).

The necessary conditions for SWR appearance make it a widespread property under Mediterranean climate. On one hand, Mediterranean climate is characterized by the coincidence in summer of the highest temperatures of the year and a three-month-long drought, between June and September. This prolonged dry period reduces soil moisture to the point where water repellency is triggered (Dekker et al., 2001; Verheijen and Cammeraat, 2007; Martínez-Murillo and Ruiz-Sinoga, 2010; Martínez-Murillo et al., 2013). On the other hand, summer drought favours the presence of deciduous and semi-deciduous plant species (Orshan, 1964, 1972), that shed their leaves in summer, providing hydrophobic compounds to the soil surface, since leaves of Mediterranean shrubs are often oil- or wax-rich (Moral García et al., 2005). Moreover, in Mediterranean areas there is also a high recurrence of forest fires (Trabaud, 1981) which are frequently related to SWR appearance.

One of the main effects of SWR is enhancing overland flow and soil erosion due to the low infiltration capacity of repellent soils (Doerr et al., 2000). In addition, SWR can enhance soil erosion since it reduces the aggregation capacity of soil particles making them easily detachable (Shakesby et al., 2000). However, there are several problems that make difficult to establish links between SWR and soil erosion (Shakesby et al., 2000): (i) the effect of SWR on soil erosion is hard to isolate from other factors that also change seasonally, such as soil crust formation and litter production; (ii) the influence of SWR is determined by the scale, changing from plot to catchment measurements due to spaces discontinuities where generated runoff can reinfiltrate; (iii) SWR has a seasonal oddity, being more frequent after the drought season, but it can also appear during dry spells in the middle of the wet season (Crockford et al., 1991). Moreover, in Mediterranean areas, there is a high variability of vegetal cover and soil surface components in short spaces. One of the main factors affecting vegetation is the aspect (Kutiel, 1992), that influences not only the total cover but also the distribution, structure, density and composition of vegetation communities (Klemmedson and Wienhold, 1992; Olivero and Hix, 1998; Kutiel and Lavee, 1999).

Moreover, apart from promoting overland flow triggering SWR, vegetation can enhance infiltration reducing crusting in the soil surface and supplying rests of plants (stems, leaves, and roots) that enrich the soil, and support the microorganisms that transform these remains into soil organic compounds (Puigdefábregas, 2005), favoring the formation of stable aggregates (Imeson and Vis, 1982; Imeson and Verstraten, 1989). Thus, vegetation can influence the soil hydrological response in opposing ways: mostly favoring water infiltration, but also triggering runoff processes when SWR is developed.

This study is developed in a small catchment under Mediterranean climate conditions in the South of Spain. The main goal is to shed light in the relations between SWR, aspect and vegetation, determining the soil hydrological and erosive response throughout the rainy period in different microenvironments. According to this aim, the objectives are: (i) to determine the influence of aspect and vegetal cover on the hydrological and erosive response of soils; (ii) to characterise the seasonality of SWR, runoff and soil loss; (iii) to establish the relations between precipitation and soil erosion parameters; and (iv) to assess the influence of SWR on the soil hydrological and erosive response

2 Field site

The experimental area was a small watershed located in southern Spain (36°50′ N, 4°50′ W) (Fig. 1). In general, the area is characterized by a dry Mediterranean climate (mean annual precipitation 576.1 mm yr^{-1}; mean annual temperature 15.7 °C); the dominance of water erosion processes on steep (> 12.5°) hillslopes with a substratum of metamorphic rocks (phyllites); and land uses including rangelands, evergreen forests, abandoned land, and olive and almond orchards. The De Martonne index (19.7) for the area indicates that the field site is located between semiarid and subhumid climatic conditions. Areas with extensive vegetation cover are characterized by an association of Cambisol and eutric Regosol soils, whereas in the most degraded areas the soils are episkeletic Cambisols associated with haplic epileptic–episkeletic Regosols and eutric Leptosols. Two hillslopes, one north-facing and the other south-facing, were selected for the study.

The north-facing hillslope is characterized by an open woodland of cork oak with typical degraded Mediterranean shrubland (*Smilaci mauritanicae* and *Querceto rotundifoliae querceteso suberis*). The vegetation cover is rather continuous, with a mean tree cover of 40–50 % and shrub cover > 75 %. *Cistus* spp. (*C. monspeliensis* and *C. albidus*) are the dominant shrub species on the hillslope and in adjacent natural areas. The hillslope is steep (15°), with a convex-rectilinear-concave topographic profile, and an aspect of 0° N. The soil surface not covered by shrubs is characterized by the presence of abundant litter from *Cistus* spp. and *Quercus suber*. Soil depths range from 30 to 50 cm, and the rock fragment cover is < 10 %. The soil texture is sandy loam in areas of bare soil, and sandy-clayey loam under shrubs. The organic matter content ranges from 4% in bare soil areas to 5.2 % under shrubs. At hillslope spatial scale, the major soil surface components are patches of *Cistus* spp. (mean size > 2 m^2) and bare soil; in both cases the soil is covered by a thick layer (typically 2–5 cm) of litter.

The south-facing hillslope was previously cultivated with cereals, but abandoned in the mid-1950s. It is very steep (22.4°), with a convex-rectilinear topographic profile and an aspect of 180° N. It has been reforest and is now covered by a patchy vegetation mosaic of bare soil and Mediterranean plant species (60 % vegetation cover, which is similar to that of natural hillslopes in the surrounding area; mean patch size $< 2\,\mathrm{m}^2$). *Cistus* spp. are the most common plants growing on the hillslope. In winter, the bare soil area is covered by annual plants, the dead structures of which accumulate on the soil surface during summer. The soils are affected by water erosion and, as a result, they are characterized by a rock fragment cover of 20–70 %. The soils depth is shallow (20–30 cm), they have a high gravel content (54.0 % in association with shrubs and 67 % in bare soil areas) and pH of 6.9. The texture is sandy loam in both bare soil and under-shrub areas. The organic matter content ranges from 1.5 % in bare soil areas to 3.5 % under shrubs. The principal soil surface components are *Cistus* spp. patches and bare soil areas. However, the soil surface has less litter cover than the north-facing hillslope. The soil surface beneath shrubs typically comprises annual plants and a 1–2 cm cover of litter.

3 Material and methods

3.1 Precipitation

Precipitation was recorded using a meteorological station installed in the experimental area. The precision of the rain gauge was 0.3 mm. Precipitation was recorded every 10 min and the rainfall intensity was also calculated in a 10 min basis, expressed in $\mathrm{mm\,h^{-1}}$. Precipitation data were grouped into two different categories according to the daily mean rainfall intensity (I), the maximum precipitation intensity (in a 10 min basis) of the day ($I_{\max}$), and number of days between precipitation periods. The mean duration of rainy and dry spells was calculated for each period.

3.2 Soil water repellency

Water repellency was measured using the Water Drop Penetration Time (WDPT) technique (Van't Woudt, 1959), modified by the addition of eight drops of demineralized water rather than three in the sample surface. This test consists on randomly placing eight drops (0.05 mL) on the soil surface using a micropipette and measuring the time until each drop is completely infiltrated. The average of these eight measurements was taken as the respective WDPT (s) of the sample. The test was applied in the two microenvironments analyses on every hillslope (shrub-covered and inter-shrub soils). Undisturbed soil samples from the four microenvironments were collected in 100 cm^3 cylinders and taken to the laboratory. The litter was removed from the surface and then it was smoothed to make it homogeneous. The drops were placed in different places of the soil surface and the time to infiltration noted. The water repellency values obtained with the WDPT were classified according to Doerr et al. (2006) classification (Table 1). All the experiments were conducted under controlled laboratory conditions (22 °C, 60 % relative humidity) to avoid the effects of temperature and humidity in the measurements (Doerr et al., 2002).

3.3 Erosion plots

A total of 8 closed plots were installed in the experimental area distributed as follow: 4 plots in North and South-facing aspect (N and S), and in each slope 2 ot them located in shrub-covered (SC) areas and 2 in inter-shrub areas (IS). These IS areas were often covered by a thick litter layer in the north-facing hillslope and by annual vegetation in the south-facing one. Plots had a surface of 2 m^2 and they were rectangular-shaped and delimited by steel sheets. The steel sheet at the bottom of the plot was performed in a funnel shape in order to enable the conduction runoff to the collector linked to a deposit of 25L. The deposits were emptied manually after every wet spell and the volume collected was noted. The runoff collected was homogenised and a sample of 0.5 L was taken and transported to the laboratory, where it was sieved at a 2 mm mesh and dried in the oven, in order to measure the amount of fine sediments transported by the runoff. The parameters calculated were runoff rate (R_r, mm), runoff coefficient (R_c, %), sediment concentration (S_c, gr L^{-1}) and soil loss (S_l, gr m^{-2}). Although the plots were installed on September 2009, data records were not started until three months later in order to avoid disturbances caused by the soil modifications during the plot installation.

3.4 Statistical procedures

The adjustment of data to normal distribution was tested using the Kolmogorov–Smirnov test, whereas the Barlett test was performed to determine if the data accomplished the homoscedasticity criteria. If these criteria were not satisfied, the logarithmical transformation was attempted. ANOVA test was used if the data were suitable to support parametric statistic and the U Mann-Whitney test was used if they did not. The effects of factors “aspect”, “cover” (vegetal cover) and “season” were tested on SWR, runoff and soil loss data using the above-mentioned analyses. Moreover the relation between precipitation parameters and runoff and soil loss was performed by mean of regression models. The significance level was set at 0.05, and all analyses were performed using R software (R Core Team, 2013).

4 Results

4.1 Precipitation analysis

The period analyzed comprised from 15 November 2009 to 15 December 2010. The daily precipitation during this period is represented in the Fig. 2, as well as the mean and maximum intensity in a 10 min basis.

Precipitation during the study period followed the classic trend of Mediterranean climates of the northern hemisphere, with a three-month-long drought between June and

September, although precipitation from December 2009 to April 2010 (921.2 mm) far exceeded the historical average for the corresponding months (306.5 mm).

In order to facilitate analysis, the rainy period was split into two categories called transition and wet seasons. This was done based on the precipitation characteristics more related with the main objective of this study. Two transition seasons were differentiated lasting from 15 November 2009 to 15 December 2009 and from 1 September 2010 to 15 November 2010, respectively. They comprised the isolated precipitation events typical of autumn in the study area. These seasons had a total rainfall of 107.9 mm, with wet periods of 1 or 2 days (mean 1.3 ± 0.4 days) being usually separated by several days without rain (mean 5.7 ± 4.7 days). The maximum daily rainfall (17 September 2009) was 41.1 mm ($I_{\max}$ 36.6 mm h^{-1}; I 9.1 mm h^{-1}). The wet seasons occurred from 16 December 2009 to 30 April 2010 and from 15 November 2010 to 15 December 2010. Both periods were characterized by series of several rainy days (mean duration 3.5 ± 2.5 days) separated by short periods without rainfall (mean duration 2.5 ± 2.5 days). Rainfall of 30 mm day^{-1} was frequently exceeded (11 times). The maximum $I_{\max}$ occurred on 17 April 2010 (45.6 mm h^{-1}), while the maximum I (6.1 mm h^{-1}) occurred on 25 January 2010. The change of season in 2009 was provoked by a period of 9 days with a total precipitation of 232.1 mm. This change in 2010 was motivated due to a wet spell of 7 consecutive days with a total precipitation of 80.2 mm. The period between 1 May 2010 and 31 August 2010 was not taken into account since only some small events ($P < 2$ m) were registered and runoff was not observed.

4.2 Soil water repellency

Figure 3 shows the SWR values measured in every microenvironment and season. SWR data did not accomplish the normality and homoscedasticity criteria required for ANOVA analysis; hence U Mann–Whitney test was performed to compare pairs of means taking into account independently aspect, season and cover. Factors “aspect” and “season” had significant effect on SWR ($p < 0.001$), whereas “cover” did not ($p > 0.05$). Repellency was higher in the north-facing hillslope and, in general, its values were higher during the transition season, decreasing significantly once the wet season started. This reduction of SWR was not observed in the case of inter-shrub areas of the south-facing hillslopes, given that soils were already wettable during the transition season.

If data are separated by aspect and season, as previous analysis suggests to do, significant differences in SWR between covers in the transition season appeared in both hillsopes ($p < 0.001$); these differences were masked in the general analysis by the data of the wet season, when mean values of SWR remained homogeneous in both hillslopes ($p > 0.05$). This fact is clearly showed in Fig. 3 and was corroborated by a Kruskal–Wallis analysis of SWR with the variable "microenvironment" (conjunction of aspect and cover) on every season (Table 2). In the transition season there were significant differences between microenvironments ($p < 0.001$) and the pairwise U Mann–Whitney test showed differences within every hillslope. In the wet season, the soil remained wettable in all the cases but there were quantitative differences between microenvironments ($p < 0.05$). In this period, there were no differences within every hillslope.

4.3 Hydrological and erosive response

Table 3 shows means and standard deviations of the hydrological and erosive parameters recorded during the study period. The dispersion of data was large, usually with CV values higher than 100 %. In the transition season NIS plots showed the highest mean values for runoff variables ($R_r = 2.99$ mm, $R_p = 12.22$ %) and SSC showed the lowest ones (0.35 mm, 1.27 %). The maximum event values during this season were also measured in the NIS plots (8.51 mm, 19.33 %), after 44 mm of precipitation with $I = 2.7\,\mathrm{mm\,h^{-1}}$ and $I_{max} = 36.6\,\mathrm{mm\,h^{-1}}$. During the wet season, there was a change of trend and the highest mean values were in SIS plots (1.49 mm, 2.59 %), whereas the lowest occurred in the NSC plots (0.15 mm, 0.23 %). The maximum event values in this season were recorded in the SIS plots (6.34 mm,11.77 %) after 53.9 mm of precipitation ($I = 2.9\,\mathrm{mm\,h^{-1}}$ and $I_{max} = 44.4\,\mathrm{mm\,h^{-1}}$).

Regarding the sediment concentration, the highest mean value in the transition season was 0.91 gr L^{-1} and it was found both in NIS and SSC plots.On the other handthe lowest value was 0.25 gr L^{-1} in the SIS plots. In the wet season the maximum mean value was 0.59 gr l^{-1} in the SSC plots and the lowest one was 0.08 gr L^{-1} in the NIS plots. The maximum sediment concentration measured in the transition season was 3.76 gr L^{-1} (NIS plots), recorded after a short event of 2.9 mm ($I = 3.6$ mm h^{-1}, $I_{\max} = 6$ mm h^{-1}). In the wet season it was 2.59 gr L^{-1} (SSH plots), after 14.7 mm of precipitation ($I = 1.9$ mm h^{-1}, $I_{\max} = 4.8$ mm h^{-1}).

Lastly, mean soil loss in the transition season was higher in NIS plots (0.91 gr m^{-2}), as a result of the high runoff rate and sediment concentration, and lower in the SIS plots. Soil loss in the wet season was higher in the SIS plots (0.37 gr m^{-2}) and lower in the NSC plots (0.02 gr m^{-2}). The maximum measurements was recorded in the same event and microenvironment previously described for the maximum values of the runoff variables and they were 2.69 and 2.62 gr m^{-2} in the transition and wet seasons, respectively.

4.3.1 Factors affecting runoff

ANOVA analyses showed that the only individual factor that affected runoff rate was “cover” ($p = 0.009$), whereas “aspect” and “season” did not have any significant effect. Effectively, runoff rate was clearly different in shrub covered (0.47 ± 0.67 mm) and inter-shrub soils (1.54 ± 2.14 mm). This confirmed the expected trend of more amount of runoff generated in bare soils than in shrub-covered ones. Interestingly, the interaction of “aspect” and “season” affected significantly the runoff rate ($p = 0.03$), what means that the changes in runoff rate between seasons were different depending on the hillslope considered. In both microenvironments of the north-facing hillslope runoff rate was lower during the wet season (Fig. 4a), whereas in the south-facing hillslope this was not observed, being the runoff rate lower in the transition season (slightly in the inter-shrub plots). Due to the large dispersion of data, only in bare soils of the north-facing hillslope the difference in runoff rate between seasons was significant.

Regarding the runoff coefficient (Fig. 4b), both "cover" ($p < 0.01$) and "season" ($p < 0.001$) had significant effect on this property, being R_c higher during the transition season and in those patches without shrubs. "Aspect" as a single factor did not have any effect. If the analysis was performed to check the differences between seasons on every microenvironment, it resulted that there were significant differences on both microenvironments of the north-facing hillslope, whereas in the south-facing one they were not found. In spite of having no effect as an individual factor, "aspect" is an important variable to take into account for the runoff analysis, since R_c is homogeneous during the year in the south-facing hillslope but heterogeneous in the north-facing one. As a consequence, R_c was higher in the north-facing hillslope during the transition season and in the south-facing hillslope during the wet season (Fig. 4b).

4.3.2 Precipitation and runoff

Once we analysed the differences in runoff rate and coefficient between aspects, vegetal cover and season, we tried to elucidate the precipitation property that best correlated with the overland flow in our study site.

Among the rainfall parameter analysed, the best correlation with the runoff rate was found for I_{max}. Interestingly, in the north-facing hillslope the hydrological behavior was different during the transition and the wet seasons (Fig. 5a and b). In inter-shrub soils, the relation between I_{max} and runoff rate was significant ($p < 0.01$) for the whole set of events but it improved when data were split between seasons, turning the R^2 coefficient from 0.49 for the complete dataset, to 0.93 and 0.61 for the transition and wet season respectively. Moreover, the I_{max} threshold for runoff generation increased from 4.9 mm in the transition season to 6.4 mm in the wet season, whereas the slope of the relation I_{max}–R_r decreased 2.7 times, from 0.254 to 0.093 (Fig. 5a and Table 4). The relation between P and R_r was weaker and it only was significant in the transition season. Beneath *Cistus* spp. the relation between runoff rate and I_{max} was not significant when we took into account the whole study period ($p > 0.05$, $R^2 = 0.08$). However, interestingly, when we split the data between seasons, this relation became significant only in the transition season ($p < 0.05$, $R^2 = 0.77$), whereas in the wet season it remained not significant ($p > 0.05$, $R^2 = 0.17$). In this case, the relation between P and runoff rate was significant in the wet season ($p < 0.05$, $R^2 = 0.4$), indicating a change in the runoff generation mechanisms.

In the south-facing hillslope (Fig. 5c–d, and Table 4), there was a good and significant relation between runoff rate and $I_{\max}$ ($p < 0.001$) in inter-shrub patches, as well beneath shrubs. This relation was consistent along the entire study period and the points corresponding to the transition season are straightened to the points of the wet season. In bare soil the R^2 was 0.86 and beneath shrubs was 0.70. As it occurred in the bare soil environment of the north-facing hillslope, the relation of runoff rate with P was weaker than the relation with $I_{\max}$, so the later was the main controlling rainfall factor affecting the runoff generation. In both microenvironments of the south-facing hillslope, the $I_{\max}$ threshold for runoff generation and the slope of the relation $I_{\max}$–R_r only registered slight variations. It is important to highlight that the relation $I_{\max}$–R_r in inter-shrub soils of the south-facing hillslope was not significant during the transition season, in spite of the high R^2 of 0.91. This was due to some missing data caused by the effect of grazing on the erosion plots. Nevertheless, since the relation was apparently good, we took into account the parameters of the regression models, although with all due caution.

No significant relation was found between runoff coefficient and precipitation parameters, but interestingly, when it was plotted against P and $I_{\max}$, two clearly different groups of points according to the season could be observed in the north-facing hillslope, whereas in the south-facing hillslope this different response did not exist (Figs. 6 and 7).

4.3.3 Sediment concentration and soil loss

Sediment concentration and soil loss had a similar behavior in this study. According to the ANOVA test, the only factor that had a statistically significant effect on the erosion variables was “season”. In spite of the lacking of statically significant differences, it is noteworthy the contrasting behavior of the sediment concentration and soil loss in the two hillslope depending on the season considered (Fig. 8a and b). The decrease observed in both parameters was much higher in the north-facing hillslope than in the south facing one.

It can be observed that in three out of four microenvironments (SIS was the exception) there was a large decrease of sediment concentration and soil loss when the transition to the wet season were compared (Fig. 8a and b). Sediment concentration and soil loss did not show any significant relation with any of the precipitation parameters studied.

5 Discussion

5.1 Soil water repellency

SWR results highlighted the seasonal character of this property, reported widely in the literature in temperate humid areas as well in semiarid environments (Witter et al., 1991; Doerr et al., 2000; Kaiser et al., 2001; Benito et al., 2003; Whal, 2008; Zavala et al., 2009). SWR is commonly associated to dry soils and it is supposed to disappear when soil water content increase to a critical soil moisture threshold (Crockford et al., 1991; Imeson et al., 1992; Ritsema and Dekker, 1994; Doerr at al., 2000). SWR results were consistent with this statement and after the summer drought, three out of four microenvironments showed hydrophobicity and only one of them remained wettable, whereas during the wet season all the microenvironments were wettable. The SWR measurements corresponding to the transition season was done just after the

2009 dry season and in consequence soil moisture was clearly below the wilting point at that time. However, according to Doerr and Thomas (2000), soil drying by itself is not enough to restore soil water repellency and the addition of fresh hydrophobic compounds is also needed. In the study area the dominant species are *Cistus albidus* and *Cistus monspeliensis*. They are seasonal dimorphic species (Aronne and De Micco, 2001), an adaptation to the Mediterranean summer drought (Orshan, 1964, 1972) that involves the cessation of dolichoblast growth at the end of spring, flower formation, and leaf abscission in order to avoid transpiration water loss. Hence, abundant litter accumulates on the topsoil beneath the shrubs and in surrounding areas during summer (Gabarrón-Galeote et al., 2013). Moreover, this litter is rich in wax and oil compounds, frequently associated to SWR appearance (Verheijen and Cammeraat, 2007).

The differences in litter input would explain the contrasts between and within hillslopes. On one hand, in the north-facing hillslopes shrubs covered a.c. 75 % of the hillslope, consequently there were no true bare soil areas because the great amount of litter produced covered the patches between shrubs (Gabarron-Galeote et al., 2012). Thus, there was a high input of hydrophobic compounds, more abundant in the shrub covered areas, that triggered SWR when soils became dry. On the other hand, in the south-facing hillslope shrub-cover was rather discontinuous and there were large patches where the litter layer was absent. These areas are covered by annual vegetation during the wet season. We expected to find SWR also due to the annual vegetation growth, as it was reported by Martinez-Murillo and Ruiz-Sinoga (2007) in the same study site, but the values obtained in the present study are lower. This might be caused by an extremely rainy previous year to their measurements (1081 mm) that caused an extraordinary vegetation growth and a higher than average litter production during that summer. In contrast, precipitation during the year previous to our study was 528 mm.

The values of SWR in the wet season are consistent to the seasonal behavior of SWR. Crockford et al. (1991) reported that only 9 days without rain during the wet season were enough to provoke repellent conditions in the soil. The wet season in our study was rainier than usual and the mean duration of dry spells was 2.5 days, so we can expect permanent wettable conditions along this season. Thus, there was a heterogeneous pattern of soil water repellency related to vegetation cover and litter input (Doerr et al., 1998) during the transition season that turned into homogeneous and wettable during the wet season.

5.2 Runoff generation

During the transition season, the maximum values of runoff rate took place in the north-facing hillslope in both environments, whereas in the wet season the maximum values took place in the vegetated areas, independently of aspect. This suggests a change in the factor controlling runoff generation. As it happened with SWR, hydrological behavior was different between hillslopes. Soil water repellency has been proven to have significant effects on the soil hydrological response, on the runoff generation as well as on soil erosion (Doerr et al., 2003; Shakesby et al., 2000). However, these effects are not always of the same magnitude and they are strongly dependent on the continuity of the repellent layer and the cracks and pores on the soil surface.

In the north-facing hillslope, overland flow was higher in the bare patches than beneath shrubs, and two clearly contrasting soil responses were observed along the hydrological year. At a plot scale, all the hydrological variables (R_r, R_p, S_c and S_l) were significantly higher in the transition season. The change of conditions was observed not only in the mean values of rate and runoff coefficient, but in the correlation of these properties with precipitation. On one hand, the slope of the relation between runoff rate and I_max was clearly different between seasons in both microenvironments. On the other hand, the events with higher R_c occurred in the transition season, being independent of precipitation. This seasonal behavior of overland flow in Mediterranean conditions could be related to soil crust formation (Nunes et al., 2010), but soil surface layer in the north-facing hillslope had more than 5 % of organic matter, so surface crusting was not the reason of the enhanced overland flow (Hillel, 1998; Beven, 2001), this suggests SWR as the more probable cause (Doerr et al., 2003). The strong influence of SWR on runoff generation during the transition season was studied in the same hillslope by Gabarron-Galeote et al. (2012) by mean of rainfall simulations. They obtained runoff in the 100 and 60 % of the experiments developed in bare soil and beneath shrubs respectively. When runoff is a consequence of SWR, it is generated by Hortonian mechanisms, since the wettability of the soil surface decreases dramatically (De Bano, 1971). Indeed, the significant relation between I_{max} of the event and the runoff rate suggests that runoff is mainly generated by Hortonian mechanisms in the north-facing hillslope during the transition season. The fact that the R_{c} was higher in NIS (12.22 %) than in NSC environments (5.26 %), whereas SWR was moderate and severe respectively, was probably caused by the presence of more macropores due to root development of shrubs in NSC patches. These macropores caused discontinuities in the repellent layer and allowed the runoff generated to reinfiltrate within the plot and reach the hydrophilic layer beneath the repellent one. This kind of discontinuities, due to macropores as well as to a patchy pattern of SWR, is the cause of the low response to runoff generated in repellent conditions at the catchment level (Doerr et al., 2003). In the study mentioned above, Gabarron-Galeote et al. (2012) found that macropores were the main infiltration way during rainfall simulations when soil surface is repellent. The I_{max} threshold for runoff generation was higher in the bare patches, a result consistent with the lower SWR.

SWR disappeared in the wet season and the hydrological response also changed clearly. Relations between runoff rate and I_{max} were weaker, what suggested that under hydrophilic conditions the formation of Hortonian overland flow was prevented, and the lower runoff of this season was produced by saturation of the shallow soil (Shakesby et al., 2000), favored by the extremely wet season of the year 2009–2010. In fact, in the NSC patches the relation of runoff with I_{max} disappeared, whereas the relation with P became significant. In a study of Doerr et al. (2003), developed in an area with similar topographical and geological characteristics, but significantly more rainy, the hydrological response at plot scale during the wet season was similar to the reported here in the north-facing hillslope. They detected only 1 out of 60 events with more than 3 % of runoff during the wet season, whereas our maximum value was 2.26 %. Doerr at al. (2003) also pointed out that only in very wet conditions could be developed saturation overland flow, due to the saturation of the relatively shallow soil. This statement is also applicable to the north-facing hillslope of our experimental area.

In the south-facing hillslope there were no significant differences in rate and % of runoff between seasons, neither in the relation between $I_{\max}$ and runoff rate. However, there were some remarkable differences between microenvironments that are important to highlight. In the transition season the runoff was 3.06 and 1.27 % in inter-shrub and vegetated patches, respectively. These values are both lower than the corresponding ones in the north-facing hillslope. In the bare patches this fact seems reasonable since soils are wettable even in the transition season. So although in absence of SWR soil conditions of this layer are less favorable to promote infiltration as they are in the north-facing hillslope (soils less developed, with low organic matter content and hydraulic conductivity; Martinez-Murillo et al., 2007), a lower overland flow was detected. In addition, annual vegetation created paths that favor infiltration of the generated runoff. Regarding the shrub covered areas, they showed moderated SWR during the transition season but, surprisingly, the lower overland flow was measured here. This can be explained by the vegetation allocation on the south-facing hillslope. The non-uniform distribution of vegetated areas promotes the spatial concentration of soil moisture, nutrients and biological activity beneath shrubs (Mou et al., 1995; Pan et al., 1998; Anderson et al., 2004; Puigdefábregas, 2005). At the same time soil fertility is reduced in inter-shrub areas because of erosion and gas emission processes. The availability of nutrients and water resources favor the growth and survival of vegetation, which is a feedback process (Pugnaire et al., 1996; Cerdá, 1997; Holmgren et al., 1997) that continuously improves the soil properties of so-called fertility islands (Schlesinger et al., 1990). This process is reinforced because of the more frequent hydrological response of inter-shrub soil areas under Mediterranean conditions: source of runoff, sediments and nutrients. When these sediments are transported down-slope they are usually retained in adjacent vegetated areas, where they contribute to the improvement of soil properties, and therefore vegetation growth (Cammeraat, 2004;

Ludwig et al., 2005; Puigdefábregas, 2005). Due to the good soil conditions and the biological activity, Hortonian overland flow generated due to repellent conditions was rapidly reinfiltrated through animal burrows (Garkaklis et al., 1998), root channels and macropores (Sevink et al., 1989; Doerr et al., 2003) and there was no connectivity between the small patches source of runoff even at a plot scale.

During the wet season no SWR was detected and runoff was of 2.59 % in bare patches and 0.96 % in vegetated areas. These values are consistent with fertility island theory formerly explained and are a direct consequence of the infiltration capacity and the quality of soils.

It is difficult to elucidate the runoff generation mechanism in south-facing hillslopes of the study area. In similar conditions, Martinez-Murillo and Ruiz-Sinoga (2007) found differences in runoff rate generated as well as in the mechanisms between seasons in south-facing exposures. The differences in runoff generated were justified because they found water repellency in the transition season in both microenvironments. They pointed out that during the wet season runoff was produced by saturation mechanisms. In our case, the consistent relation between $I_{\max}$ and runoff rate could suggest Hortonian runoff generation, but in absence of soil water repellency overland flow by saturation of the shallow soil cannot be discarded (Shakesby et al., 2000).

To sum up, during the transition season SWR was the main factor controlling overland flow generation, especially in the north-facing hillslope, whereas in the wet season runoff generation depended mainly on the soil properties that favor infiltration (e.g. organic matter, aggregate stability), determined by the vegetal cover.

5.3 Sediments and soil loss

Sediment transport was higher during the transition season in the three microenvironments where soil water repellency was detected. Actually, the factor “season” was the only one that affected the erosion variables measured. The cause of this increase of soil erosion in repellent soils is the enhanced splash erosion (Terry and Shakesby, 1993; Ahn et al., 2013). According to Ahn et al. (2013), soil water repellency increases the distance of ejection of particles after a drop impact, what in hillslopes with a certain degree of inclination involves greater net downslope movement and hence net erosion of particles. Shakesby et al. (2000) reported that in hydrophilic soils the wetting provoked an increase in the particles cohesion and a compact surface seal, that limited the amounts of splashed sediments, was developed. On the contrary, in hydrophobic soils, particles remained dry and easily detachable.

During the transition season a larger sediment transport in the repellent microenvironments was observed, but it did not follow the same order than SWR or overland flow. In fact, sediment transport does not have to be necessarily proportional to these factors (Shakesby et al., 2000), since it also depends on the availability of sediments and the capacity of water to move them. For example, overland flow in vegetated areas was larger in the north-facing hillslope, meanwhile soil loss was higher in the south-facing one. This is a consequence of the high availability of sediments in the later areas, that receive sediments from the adjacent bare areas in the wet season. Moreover, the thick layer of litter in the north-facing hillslope also prevented the sediment movement, since the energy of raindrops decreases before impacting soil particles (Casermeiro et al., 2004). Under Mediterranean climate, Nunes et al. (2010) also detected more erosion in the dry period in herbaceous, shrubland and oak-tree areas, although they attributed this fact to crust formation instead of soil water repellency.

During the wet season, with wettable soil conditions, the same scheme was repeated in both hillslope: runoff generated beneath shrubs had more sediment concentration due to the higher sediment availability but, given that overland flow was larger in bare areas, soil losses were also larger in these microenvironments. The causes for the high availability of sediments in shrub covered plots are (Martínez-Murillo and Ruiz-Sinoga, 2007): (i) the inter-shrub areas are more frequently washed by runoff, (ii) the washed sediments are deposited beneath shrubs and they are only transported when the precipitation event is strong or intense enough. Similar spatial relationships between sediment yield, vegetation and bare soil were found by Puigdefábregas and Sánchez (1996a) and Puigdefábregas (1998, 1999).

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6 Conclusions

Aspect was a key factor determining the hydrological and erosive response throughout the year in the experimental area. This influence was exerted through the vegetation pattern, that in turn depended strongly on the hillslope exposure.

The north-facing hillslope was characterized by a rather continuous vegetation pattern and a greater litter input in the soil, that triggered soil water repellency after the summer drought, in shrub covered as well as in inter-shrub patches. Consequently, the soil hydrological response was homogeneous during the transition season and high runoff coefficients and soil losses were measured in both microenvironments. However, SWR had a marked seasonal behavior and when it disappeared the switch from repellent to wettable conditions provoked a strong decrease of overland flow and erosion, and even a change in the runoff generation mechanism, turning from Hortonian mechanisms in the transition season to soil saturation mechanisms in the wet season.

In the south-facing hillslope there was a clearly patchy vegetation pattern. The areas covered by shrub also showed soil water repellency after the summer drought but in this case its influence on the hydrological response was mitigated by the soil conditions favouring reinfiltration. The patchy vegetation pattern triggered a transfer of runoff and sediments from the inter-shrubs to the shrub covered areas, developing fertility islands and improving soil conditions on the later ones (e.g. more organic matter, aggregate stability, biological activity). In the present study, the south facing inter-shrub patches did not show SWR even in the transition season As a consequence, in the south-facing hillslope no important seasonal changes were detected on the hydrological and erosive soil response.

In conclusion, our results support that SWR has a significant influence on the soil hydrological response, but at the same time this influence is dependent and modulated by factors as antecedent precipitation, presence of macropores and other areas of re-infiltration, and soil structure. In the present study SWR effects are important after the summer drought in the north-facing hillslope, where the hydrological response was homogeneous in space and heterogeneous in time. In contrast the south-facing hillslope hydrological behavior was heterogeneous in space and homogeneous in time.

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Table 1. WDPT classes and class increments used in the present study (after Doerr et al., 2006).

WDPT class	0	1	2	3	4	5	6	7	8	9	10
WDPT intervals (s)	≤ 5	6–10	11–30	31–60	61–180	181–300	301–600	601–900	901–3600	3601–18 000	$> 18\,000$
Persistence rating	Wettable	Slight			Moderate			Severe		Extreme	

Table 2. Quantitative and qualitative values of SWR. WDPT: Water drop penetration time; NIS: North-facing inter-shrub; NSC: North-facing shrub-covered; SIS: South-facing inter-shrub; SSC: South-facing shrub-covered. Different letters denote significant differences between microenvironments in every season.

Micro environment	Transition season			Wet season		
	WDPT (sg)	Category		WDPT (sg)	Category	
NIS	130.6 ± 96.2 b	4	Moderate	5.5 ± 3.2 a	0	Wettable
NSC	797.0 ± 627.1 a	7	Severe	3.8 ± 1.5 ab	0	Wettable
SIS	4.3 ± 1.7 c	0	Wettable	3.6 ± 1.5 ab	0	Wettable
SSC	77 ± 46.7 b	4	Moderate	2.8 ± 0.6 b	0	Wettable

Table 3. Summary of precipitation and soil hydrological and erosive response. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered; P: precipitation; I: mean rainfall intensity; I_{max}: maximum rainfall intensity; R_r: runoff rate; R_c: runoff coefficient; S_c: sediment concentration; S_l: soil loss.

Total	P(mm)	921.2			
	I(mm)	3.1 ± 1.2			
	I_{max}(mm)	18.7 ± 13.5			
	Microenv	NIS	NSC	SIS	SSC
	R_r(mm)	1.74 ± 2.26	0.47 ± 0.76	1.31 ± 1.88	0.47 ± 0.51
	R_c(%)	4.83 ± 5.72	1.71 ± 2.63	2.69 ± 3.32	1.06 ± 0.87
	S_c(gr L^{-1})	0.32 ± 0.86	0.23 ± 0.29	0.30 ± 0.18	0.66 ± 0.66
	S_l(gr m^{-2})	0.32 ± 0.63	0.15 ± 0.31	0.32 ± 0.66	0.28 ± 0.29
Transition season	P(mm)	107.9			
	I(mm)	3.2 ± 0.3			
	I_{max}(mm)	16.7 ± 10.9			
	Microenv	NIS	NSC	SIS	SSC
	R_r(mm)	2.99 ± 2.86	1.24 ± 1.04	0.66 ± 0.49	0.35 ± 0.32
	R_c(%)	12.22 ± 4.95	5.26 ± 2.33	3.06 ± 1.84	1.27 ± 1.06
	S_c(gr L^{-1})	0.91 ± 1.42	0.49 ± 0.38	0.25 ± 0.05	0.91 ± 0.37
	S_l(gr m^{-2})	0.91 ± 0.91	0.43 ± 0.45	0.14 ± 0.09	0.58 ± 0.39
Wet season	P(mm)	813.3			
	I(mm)	3.1 ± 1.4			
	I_{max}(mm)	19.6 ± 14.4			
	Microenv	NIS	NSC	SIS	SSC
	R_r(mm)	1.22 ± 1.71	0.15 ± 0.17	1.49 ± 2.07	0.53 ± 0.57
	R_c(%)	1.75 ± 1.95	0.23 ± 0.30	2.59 ± 3.61	0.96 ± 0.73
	S_c(gr L^{-1})	0.08 ± 0.04	0.12 ± 0.10	0.31 ± 0.20	0.59 ± 0.71
	S_l(gr m^{-2})	0.07 ± 0.08	0.02 ± 0.03	0.37 ± 0.73	0.19 ± 0.39

Table 4. Relevant parameters of the regression models performing the relation between I_{max} and R_r. I_{max} threshold is the I_{max} necessary to generate runoff.

Micro environment	Transition season			Wet season		
	I_{max} threshold	slope	R^2	I_{max} threshold	slope	R^2
NIS	4.88	0.254	0.93*	6.45	0.093	0.61*
NSC	1.86	0.083	0.77*	–	–	0.17
SIS	7.62	0.110	0.91	8.21	0.128	0.86*
SSC	3.74	0.027	0.85*	2.47	0.036	0.71*

* denotes significance ($p < 0.05$).

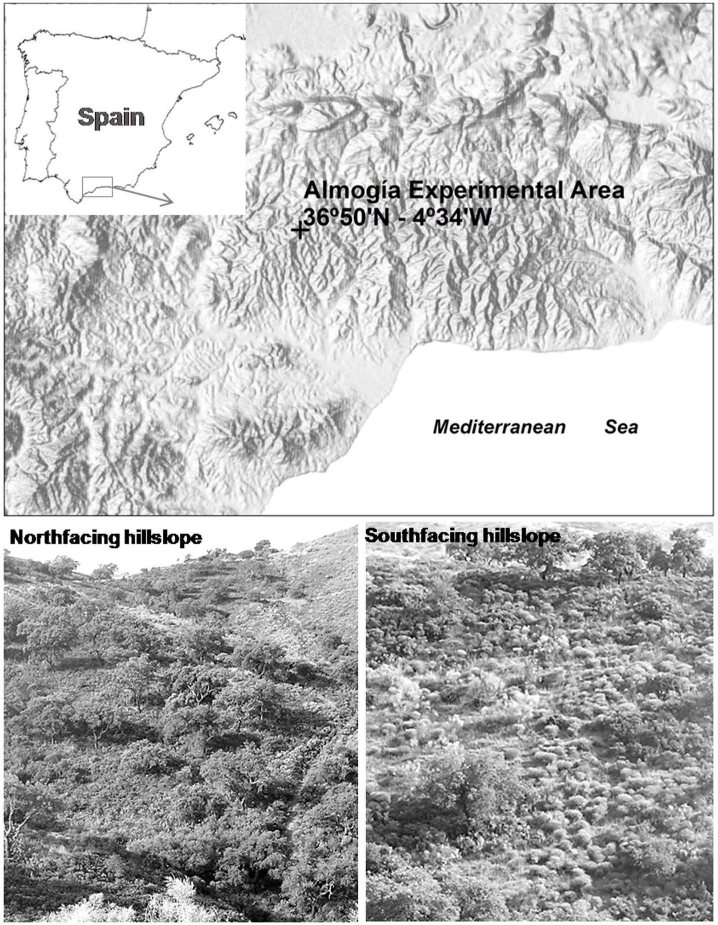

Fig. 1. Location of the experimental area and general view of both north and south-facing hillslopes.

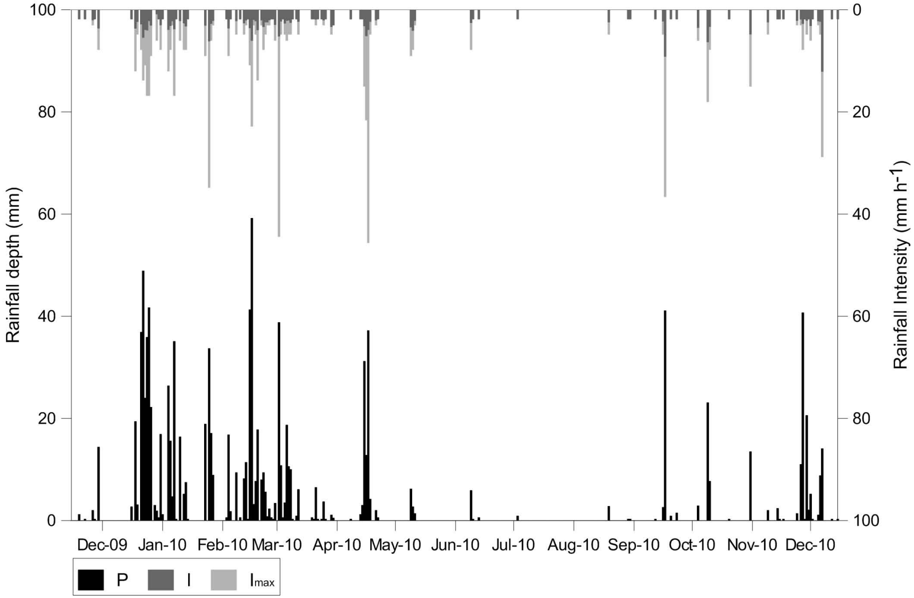

Fig. 2. Daily precipitation (*P*), mean intensity (*I*) and maximum intensity (I_{max}) during the study period.

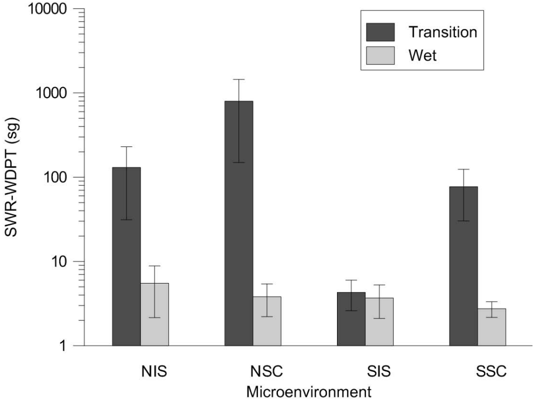

Fig. 3. SWR measured on every microenvironment and season. Note the logarithmic scale in the *y* axis. Error bars represent standard deviation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

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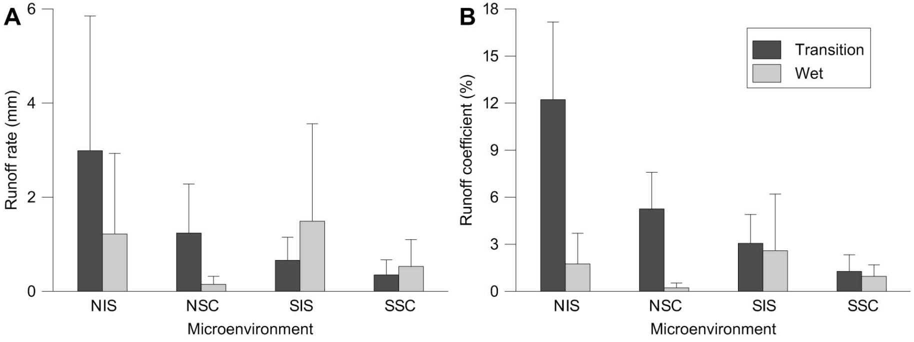

Fig. 4. Mean values of runoff rate and coefficient in every microenvironment and season. Error bars represent standard deviation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

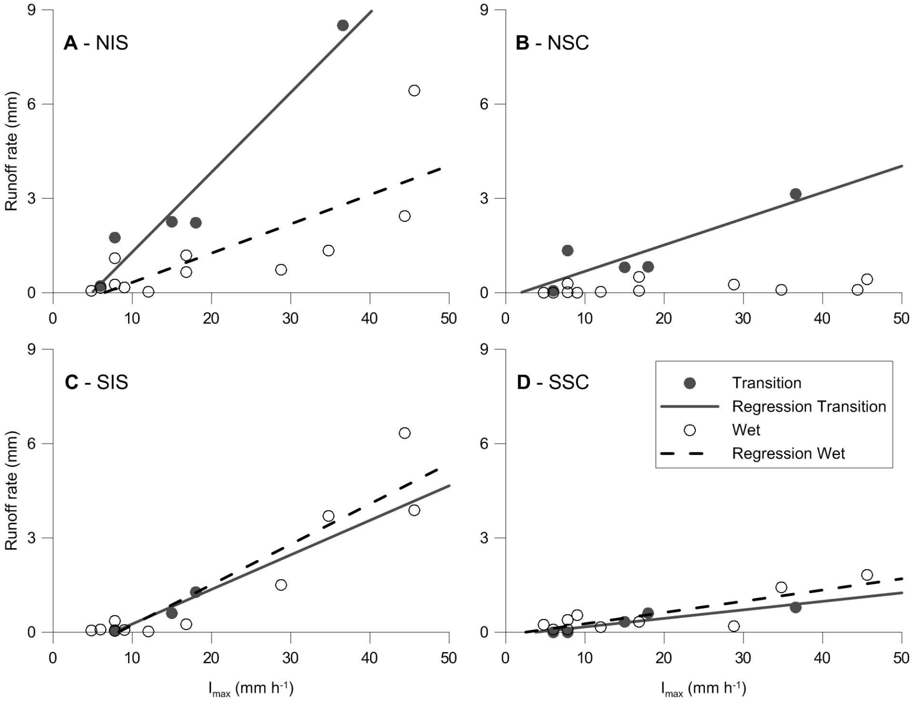

Fig. 5. Relation between I_{max} and runoff in every microenvironment. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

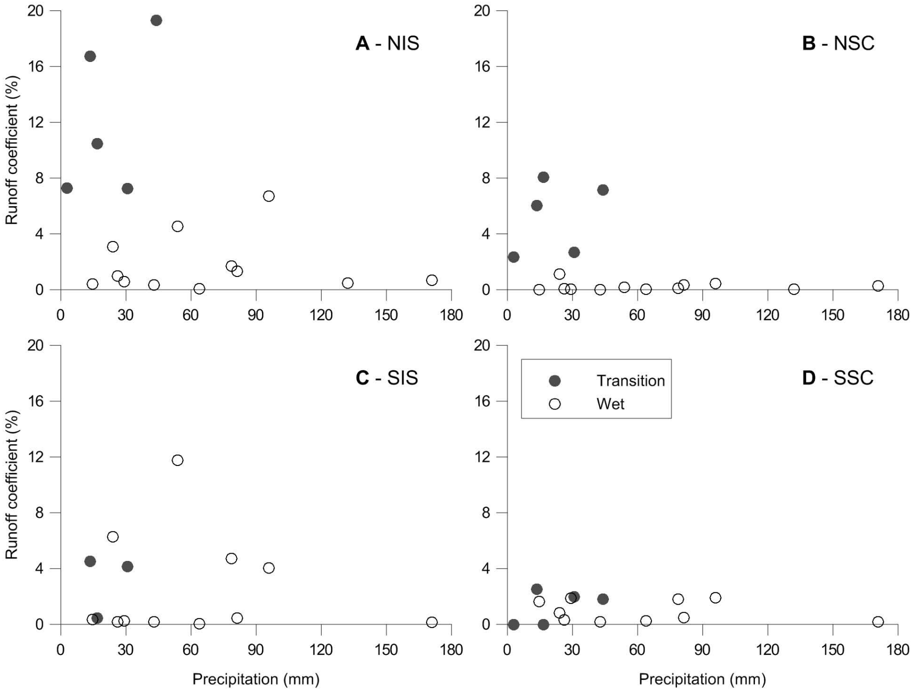

Fig. 6. Relation between runoff coefficient and precipitation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

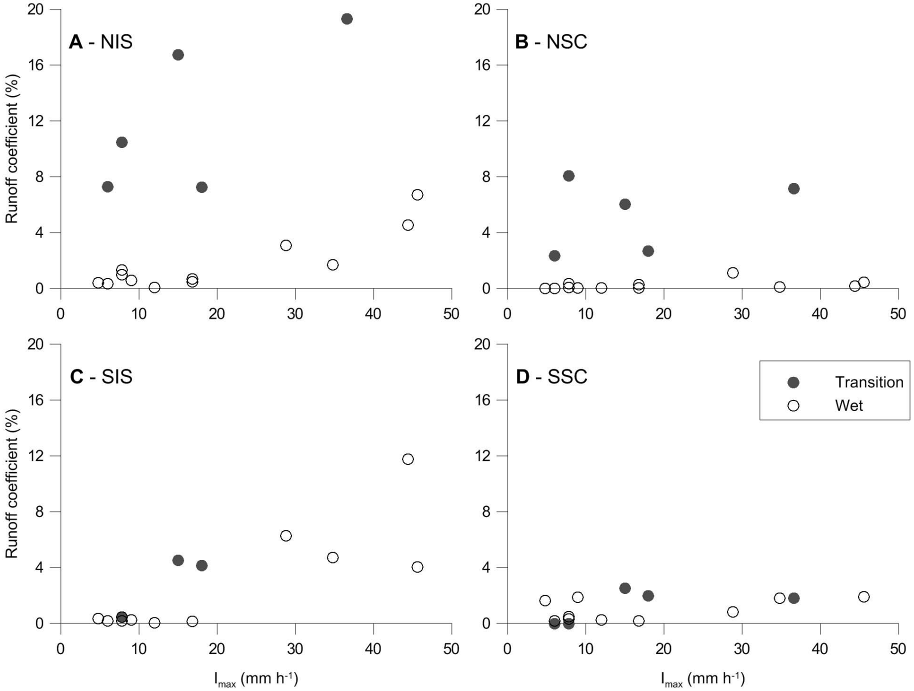

Fig. 7. Relation between runoff coefficient and I_{max}. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

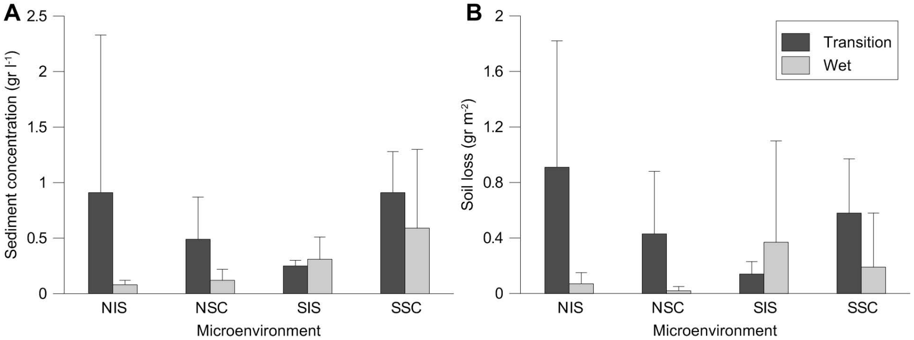

Fig. 8. Mean values of sediment concentration and soil loss in every microenvironment and season. Error bars represent standard deviation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.