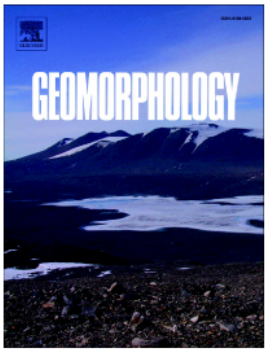

Key factors controlling the post-fire hydrological and erosive response at micro-plot scale in a recently burned Mediterranean forest

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Key factors controlling the post-fire hydrological and erosive response at micro-plot scale in a recently burned Mediterranean forest

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Abstract

The impacts of wildfires on the hydrological and erosive response of forest ecosystems have been extensively studied worldwide. Nevertheless, few studies have measured post-fire runoff and erosion over large time scales in Mediterranean-climate type environments and even fewer studies considered the effects of pre-fire land management practices on post-fire hydrological and erosive processes. In a previous study in the Colmeal study area, Vieira et al. (2016) revealed that post-fire runoff and erosion may not follow the classic window of disturbance model, since the peak of post-fire response occurred in the second and third years after fire. This previous study also showed that pre-fire land management can substantially influence the post-fire response, since annual runoff and erosion were lower in pre-fire unplowed than plowed sites. In this follow-up work, a multiple regression model (MRM) analysis was performed to understand how several key factors influence the hydrological and erosive response of a burned Mediterranean forest, taking into account the wildfire; pre-fire land management practices (unplowed, downslope plowed, and contour plowed) and soil moisture conditions.

Based on the results of the present study, post-fire runoff was largely explained by rainfall amounts and soil water repellency (SWR)-related variables, whereas erosion processes were better explained by rainfall intensity and ground cover variables. Fewer factors were found to control the hydrological response of plowed sites when compared to the unplowed site. Aside from rainfall intensity, which was the major factor controlling sediment losses, bare soil cover also seems to have been important for erosion processes at the unplowed site, whereas at the plowed sites stone cover was the second most relevant factor. Rainfall-related variables (rainfall and maximum 30-min rainfall intensity) were more important for explaining runoff and erosion under dry conditions than under wet conditions. The results of the MRM analysis are an important contribution to understand the dynamics of burned forest areas and should be considered when adapting hydrological and erosion models to post-fire environments.

Key words

Wildfire; runoff; erosion; land management

1. Introduction

Forest fires have been the direct and indirect cause of hydrological and geomorphological changes in forest ecosystems worldwide (Shakesby and Doerr, 2006; Shakesby, 2011; Moody et al., 2013). The magnitude of these changes varies, however, according to the environmental background of the affected area (Vieira et al., 2016; Wittenberg and Inbar, 2009), the burn severity of the wildfire (Keeley, 2009; MacDonald and Larsen, 2009; Vieira et al., 2015), post-fire rainfall dynamics (Moody et al., 2013; Wagenbrener and Robichaud, 2014), and post-fire management practices like logging (Fernández et al., 2007; Malvar et al., 2017), plowing (Shakesby et al., 2002; Martins et al., 2013; Keizer et al., 2015), or mulching (Prats et al., 2012; 2016a, b; Keizer et al., 2018).

In general, an increase in the hydrological and erosive response of forest areas is observed after fire as a consequence of a reduction in rainfall interception and runoff infiltration, together with an increase in soil erodibility (Moody et al., 2013; Shakesby and Doerr, 2006; Shakesby, 2011). Interception decreases has a direct consequence of vegetation consumption, while soil surface heating can change the chemical and physical properties of soils, such as soil water repellency (Doerr et al., 2003; Keizer et al., 2008; Finley and Glenn, 2010) and aggregate stability (Varela et al., 2010; Mataix-Solera et al., 2011), which are often associated to changes in infiltration and soil erosion patterns in burned areas (Shakesby and Doerr, 2006; Shakesby, 2011; Moody et al., 2013).

According to the window of disturbance model (Prosser and Williams, 1998), this enhanced hydrological and erosive response tends to occur immediately after the wildfire, triggered by the first rainfall storms. Afterwards, this response should decrease to background levels as soon as the vegetation cover is re-established (Shakesby and Doerr, 2006; Wagenbrener and Robichaud, 2014). Several studies, however, have presented variations to this scheme. For instance, Mayor et al. (2007) and Vieira et al. (2016) did not observe this increase in post-fire runoff and erosion during the first year after fire, but rather in the second and third year after the wildfire, attributing these results to the reduced rainfall amounts of the first year and to inter-annual rainfall patterns. As for ecosystem recovery, several researchers observed a full recovery by the end of the second year (e.g., Fernández and Vega, 2014), while others (e.g., Wittenberg and Inbar, 2009; Vieira et al., 2016) could not observe a full recovery even four years after the fire.

Many researchers assert that long-term studies are fundamental to understand soil erosion at the global scale (García-Ruiz et al., 2015). However, most of the research studies on burned areas focus on the short- or medium-term impacts of fire rather than on long-term impacts (Shakesby, 2011). There are three reasons for this situation: (i) there is a notion that wildfire impacts are transient and last less than seven years (Moody et al., 2013); (ii) field data collection is extremely time- and resource-consuming; and (iii) funding limitations. The existing long-term studies typically have a low monitoring frequency, i.e., annual or even longer time-scales (e.g., Moody, 2017; Francos et al., 2018), whereas the most common studies have an intensive monitoring frequency but only during the first two to three years after fire (e.g., Fernández et al., 2011; Malvar et al., 2017).

The present work is a follow up from Vieira et al. (2016), which aimed to understand the effects of wildfires on the annual runoff and sediment losses of three burned eucalypt areas with a different background disturbances. By comparing the annual runoff and erosion figures with two different window of disturbance models, Prosser and Williams (1998) and Wittenberg and Inbar (2009) were able to conclude that pre-fire background disturbances had an effect on the post-fire hydrological and erosive response. Vieira et al. (2016), however, failed to explain which variables were controlling post-fire hydrological and erosive response because the processes were analyzed at an annual time scale. The present study aims to fill this gap by analyzing the post-fire response of the same study sites but at a monthly time scale. To this end a multiple regression model will be used to test the role of several key factors (rainfall amount and intensity, soil water repellency, soil moisture and ground cover) on the hydrological and erosive response of fire-affected hillslopes. More specifically, this analysis will focus on the influence of environmental variables on post-fire hydrological processes at micro-plot scale, taking into account: (1) the wildfire; (2) pre-fire land management practices (unplowed, downslope plowed, and contour plowed) and (3) wet and dry periods. Although micro-plots may not be representative of post-fire processes at the field scale (Prats et al., 2016b; Vieira et al., 2016, 2018), the present study is still an important contribution for a better understanding of the variables controlling the recovery of fire-affected forest ecosystems.

2. Materials and methods

The present study was conducted in a recently burned area near the Colmeal village, Góis municipality, Central Portugal , Fig. 1). Before the wildfire, the area was covered by pine and eucalypt plantations used commercially. On 28 August 2008, a moderate severity fire (according to Hungerford (1996) and DeBano et al. (1998)) burned a total of 68 ha of forest land, including a small catchment of 11 ha where the experimental design of this study was installed (Fig. 1). We selected three eucalypt hillslopes within this catchment due to their distinctive pre-fire land management background (Fig. 1), i.e., no plowing (U), downslope plowing (DP) and contour plowing (CP).

The selected study sites are located over pre-Ordovician schists and greywackes (Ferreira, 1978; Pimentel, 1994). Soils are typically shallow, being generally georeferenced as Humic Cambisols (Cardoso et al., 1971, 1973). In-situ soil profiles, however, revealed that soils vary from Humic Cambisols to Haplic Umbrisols at the DP and CP sites, and from Haplic Umbrisols to Umbric Regosols at the unplowed (U) site (Table 1). The topsoil at all study sites has a coarse texture (sandy loam) with more than 70% of sand and a high stone content (40-46%).

The climate of the catchment is described as humid meso-thermal (Köppen, Csb), with long warm, dry summers. Average annual temperature at the closest (10 km) climate station (Góis; SNIRH, 2016) is 12°C and the average annual rainfall is 1133 mm (Góis; SNIRH, 2016).

Antecedent conditions related to environmental and human disturbances are important in the study area. Prior to the 2008 wildfire, a fire is known to have ravaged the entire area in 1990. Following this fire, several plowing operations were carried at the three study sites. The CP site was plowed again sometime between 1996 and 2002, as a preparation for a new eucalypt plantation (Vieira et al., 2016).

Several runoff plots were installed in the field before the occurrence of any rainfall event that could lead to an important post-fire response (25 September 2008). At each study site, four bounded micro-plots (0.25 to 0.50 m^2) were randomly installed at the base of each slope, as described by Vieira et al. (2016). This field installation is within the limitations of a plot-based set-up (e.g., Boix-Fayos et al., 2006). The outlets of each micro-plot were connected to 30 or 70 L runoff tanks. From 25 September 2008 until 1 October 2012 (i.e., four years), runoff was measured in each tank at one-week intervals during the first and second monitoring years, while in the third and fourth year, the monitoring frequency decreased, respectively, to two-week and monthly intervals. Sediment concentrations were determined from several 1.5 L runoff samples taken every time the runoff tanks exceeded 250 mL. This field installation is within the limitations of a plot-based set-up (e.g. Boix-Fayos et al., 2006). Additionally, every field trip included the measurement of total rainfall accumulated in five storage gauges, thereby validating in each read out the automatic records of four nearby tipping-bucket rainfall gauges (Pronamic Professional Rain Gauge with 0.2 mm resolution connected to an ONSET Hobo Event Logger Automatic).

Soil moisture sensors (DECAGON EC-5) were installed at two locations within the burned catchment. Four sensors were located at the bottom of the catchment, near the U site, and other four sensors were located at a mid-elevation location, closest to the DP and CP sites. Each DECAGON ECH20 data logger recorded soil moisture at a 5-15 min interval, at a depth of 3-5 cm.

Ground cover (GC, %) and soil water repellency (SWR) measurements were performed in the field every month. Ground cover was described with a square grid (50 x 50 cm; 10 cm grid spacing) laid over the plots by registering the cover category (i.e., stones, bare soil, ash/charred material, litter and vegetation) at each grid intersection. The SWR measurements were made along a five-point transect from the bottom to the top of a slope located at the edge of the catchment, at two soil depths (soil surface and 5 cm depth), using the in agreement to prior SWR studies in the region (e.g., Keizer et al., 2005a,b, 2008). The MED test consisted of the application of three droplets of increasing ethanol concentrations to the soil (0, 1, 3, 5, 8.5, 13, 18, 24, and 36%) until infiltration of the majority of the drops of the same concentration within five seconds. The SWR results were given as relative frequency for each SWR class, where class 0 corresponded to very wettable soils, and class 9 to extremely repellent soils (Santos et al., 2016).

Runoff samples (1663 in total) were analyzed for sediment concentrations in the laboratory. Sediment concentrations were determined by filtration of the entire sample volume (250 to 1500 mL) with a 12-15 µm VWR filter paper (330 mm diameter), which was then dried at 105°C for 24 to 48 h (APHA, 1998). Topsoil samples from each site were air dried and sieved manually (2 mm sieve). Soil texture was determined by mechanical analysis, as defined by Guitián and Carballas (1976), while for bulk density the methodology described by Porta et al. (2003) was used.

A single rainfall data set was used for the entire study area since few differences in rainfall amounts were found between rainfall gauges, as would be expected due to the small size of the studied catchment (11 ha) and small elevation range (100 m). Monthly rainfall erosivity (R, MJ mm ha^{-1} yr^{-1}) was calculated using the Universal Soil Loss Equation (Wischmeier and Smith, 1978) and the rainfall kinetic energy equation of Coutinho and Tomás (1995). Before any erosivity calculation, rainfall events with more than six hours without rain were separated, and for each rainfall event, total rainfall (mm), maximum 30-min rainfall intensity ($I30_{max}$; mm h^{-1}) and rainfall kinetic energy per millimetre of rainfall (E, MJ ha^{-1} mm^{-1}) were calculated to determine rainfall erosivity. All these parameters were converted to monthly values by summing the monthly rainfall (mm), monthly maximum rainfall intensity ($I30_{max}$), and monthly rainfall erosivity (R; Renard et al., 1997).

The average (SM, %) and minimum (SM_{min}, %) monthly soil moisture values were calculated, the later to be used as an indicator of SWR. Each month was classified as wet or dry based on its average soil moisture values. According to this classification, a wet and dry month corresponded, respectively, to the months in which soil moisture increased ($SM_{i-1} > SM_i$) or decreased ($SM_{i-1} < SM_i$) relatively to the previous month. This classification is based on the works of Grayson et al. (1997) and Latron et al. (2009). According to Latron et al. (2009), a wet period occurs when precipitation is greater that evapotranspiration and a dry period when precipitation is lower than evapotranspiration. In terms of the monthly water balance, this leads to an increase (wet) and a decrease (dry) in water storage, reflected in the soil moisture content.

The SWR frequency (SWR, %) for each class (0 to 9) was calculated based on the percentage of occurrence of a given class in all the monthly measurements. These frequencies were then summed for the wettable ($SWR_{wettable}$, class 0 to 3) and repellent ($SWR_{repellent}$, class 6 to 9) classes.

Average values of runoff and erosion were used since replicate plots (of both sizes) at each study site presented similar values. Thus, monthly runoff per site corresponded to the average total runoff amounts of the four replicate plots for a given month. Soil erosion was calculated based on the sediment concentrations of each runoff sample, scaled up considering the relative sample volume and the total runoff volume collected in each tank. Monthly erosion rates (Mg ha^{-1}) corresponded to the average total soil losses of the four replicate plots for each month.

All statistical analyses were carried out using the SAS 9.4 software package (SAS Institute, Inc., 2012). Forward stepwise regression analysis (MRM) was used to determine the influence of monthly rainfall amount (Rain, mm); maximum 30-min rainfall intensity ($I30_{max}$, mm h^{-1}), rainfall erosivity (R, MJ ha^{-1} mm^{-1}); minimum soil moisture (SM_{min}, %), soil wettable conditions frequency ($SWR_{wettable}$, %) and ground cover variables (bare soil, ash, stones, and litter + veg.; %) on monthly runoff and erosion measurements. These variables were selected sequentially in a forward selection procedure, in order of decreasing significance by using a minimum p-value of 0.05. These explanatory variables were chosen after testing for collinearity and removing those with a condition index higher than 10 (Belsley et al., 1980). To achieve the normality of model residuals, periods with no runoff were removed from the data set.

Square and fourth root transformations were used, respectively, for runoff and erosion dependent variables meet the normality assumptions. To check the effect of land management and soil moisture seasonality, the regression analysis was conducted individually for these factors. The management effect was tested by splitting the data set according to the study site (U, DP and CP), while the effect of soil moisture seasonality was evaluated by splitting the data between wet and dry periods.

3. Results

In all the studied sites, stone cover was the prevailing ground cover category throughout the four years of monitoring (Fig. 2b). From the ground cover categories defined in this study, only ash and vegetation cover revealed clear temporal patterns. The ash cover decreased markedly between autumn and summer of the first year of study at all sites, but it was already rather low shortly after the fire (10-20%, Fig. 2d). Post-fire vegetation recovery was extremely limited at the U and CP sites, remaining below 10% for most of the monitoring period. At the DP site, by contrast, the vegetation cover increased substantially (from 10 to 30%) between October 2010 and October 2011, remaining almost constant for the rest of the monitoring period (Fig. 2c). Plowed sites present a lower litter cover (19% at DP plots and 14% at CP plots; Fig. 2a) in comparison to the unplowed plots (33%; Fig. 2a). For all the study sites, the litter layer remained practically constant throughout the entire period of study (Fig. 2a). Bare soil cover showed high variability during the first two years after fire at all the study sites. The contour plowed site had a consistently higher bare soil surface than the other two sites, which presented similar values during the entire study period (Fig. 2d).

The first year after fire was a regular rainfall year (1095 mm) with 4% less rain than the long-term (1917-1997) annual average at the nearest climate station (Góis, 1133 mm; SNIRH, 2016). Years 2 and 3 were wet years (1295 and 1534 mm, respectively), with 13 to 15% more rain than the annual average, and year 4 was a markedly dry year (833 mm), with 34% less rainfall (Fig. 3).

In terms of seasonal patterns, rainfall amounts in year 1 were lower than the long-term average for most of autumn and occasionally during spring (October and November, March and May, Fig. 3). In years 2 and 3, the rainfall amounts during the autumn and winter seasons (November, December, and January) were substantially higher than the long term-mean (26 to 46% more, Fig. 3). The fourth year presented a very dry period from December to March (only 89 mm of rain in total), corresponding to 86% less rainfall than the average for that same period. During year 4, substantially higher rainfall (60%, Fig. 3) was observed during spring (April and May) in comparison to the long-term average for that location.

In general, the average soil moisture varied according to rainfall patterns, with the highest annual values (19-32%) recorded in winter and the lowest values (7-10%) in summer (Fig. 4). The fourth year, however, was an exception since the annual maximum record was observed during spring (21%, Fig. 4). During the first post-fire year, soil moisture was slightly lower (8-19%), than in the second (10 -25 %), 3rd (8-32 %), and fourth years (10-21%).

Repellent conditions ($SWR_{6\text{-}9}$) were more frequent during the first year of monitoring than in the remaining years (Fig. 4). With the exception of January and February, the first post-fire year was dominated by repellent conditions (on average 53%). Afterwards, there was a shift into wettable conditions around the January 2010 (second year of monitoring), followed by a reestablishment of repellency in the third (33%) and fourth years (35%, Fig. 4).

In the first year after the wildfire, the runoff coefficients varied between 8 and 17% (Fig. 5). During this period, the contour-plowed site (CP) was more productive in terms of runoff (191 mm) than the unplowed (U 53% less) and downslope plowed site (DP 31% less). Runoff generation increased in the second and third year at all the study sites. As in the first year after fire, the CP site presented a higher runoff response (550 and 671 mm) than the unplowed and the downslope plowed sites in the second (U 55%; DP 55%) and third year after fire (U 54%; DP 39%). In the fourth year, the relative difference between sites was still observed (CP>DP>U) and despite this being a dry year, runoff amounts were approximately three times higher (U - 218mm, DP 459 mm, CP - 503 mm) than in the first year (U 90 mm, DP 131 mm, CP - 191 mm) at all the study sites (Fig. 5).

In terms of monthly patterns, wet periods were responsible for most of runoff generation (77% runoff), however in several dry periods (February and October 2011, September 2012) runoff amounts were still substantial (Fig. 5). In all the monitoring years, runoff coefficients were on average higher in autumn (September to November; U - 27%, DP - 37%, CP - 50%) than in winter (December to February; U - 9%, DP - 15%, CP - 30%), despite rainfall amounts being higher in winter than in autumn (first year: + 145 mm, second year: + 126 mm and third year: + 41 mm). In the fourth year, the hydrological response was substantially different from the previous years, since it recorded the highest runoff coefficients. During this year, most of runoff was generated in autumn (U - 40%, DP - 71%, CP 69%) and spring (U - 26%, DP - 54%, CP 56%).

During the first year after the wildfire, few differences in sediment losses were found among the three study sites (Fig. 6). During this year, sediment losses at the CP site (0.55 Mg ha^{-1} yr^{-1}) were slightly higher than at the DP (0.45 Mg ha^{-1} yr^{-1}) and U site (0.25 Mg ha^{-1} yr^{-1}). Soil erosion increased in the second year at the U (+ 36%) and CP (+ 149%) sites. In the third year, an increase in sediment losses was observed at the U (+ 61%) and DP (+ 85%) sites as a result of the rainfall increase, while at CP site the sediment losses were slightly decreased (- 4%). Conversely, in the fourth year, a decrease in erosion was observed at all sites (- 74% at U, - 54% at DP, and -46% at CP) due to 46% less rainfall.

Monthly erosion patterns revealed that wet periods generated 76% of the erosion in the entire study period. During these periods, peaks in sediment losses were more noticeable at the plowed sites than at the unplowed site (Fig. 6). When comparing the two plowed sites, the CP site presented a higher erosive response than the DP site (Fig. 6).

The greatest monthly sediment losses were verified in four occasions at the CP site, (i) October 2009 (0.41 Mg ha^{-1}); (ii) October 2010 (0.47 Mg ha^{-1}); (iii) May 2011 (0.30 Mg ha^{-1}); and (iv) November 2012 (0.40 Mg ha^{-1}). The unplowed (U) site also presented its maximum sediment losses during one of those periods (May 2011, 0.13 Mg ha^{-1}), while at the DP site the greatest sediment losses were only observed by November 2011 (0.26 Mg ha^{-1}).

The multiple regression model revealed that independent variables explained 57% of the variability in monthly runoff data (Table 2). Rainfall amount was the most important factor explaining 34% of runoff variability. Soil water repellency explained around 13%, as shown by the combination of $SWR_{wettable}$ and the negative parameter estimate of soil moisture SM_{min}. The ash cover variable (Ash) seem to indicate a water retention capacity by its negative parameter estimate and explaining 7% of the variation.

The erosion model only explained 44% of the variability of monthly erosion data. Rainfall intensity ($I30_{max}$) accounted for 18% of data variability, followed by bare soil cover with 13%. The relationship between runoff generation and erosion was reflected by the presence of runoff-related variables like soil water repellency and soil moisture in the erosion model (Table 2).

The site-specific models (unplowed vs. downslope plowed and contour plowed) showed a reduction of factors explaining runoff generation from unplowed to plowed sites (Table 3). In addition, the correlations were lower for the unplowed than the plowed sites. Rainfall, ash cover and soil water repellency were common to all sites, explaining 42% of runoff variability at the unplowed site and about 60% at the plowed sites (Table 3). Rainfall amount was the most important explanatory variable, being more relevant to the plowed than the unplowed site (Fig. 7a).

In the erosion model, 46% of the variability was explained by $I30_{max}$ and ground cover-related variables in the unplowed sites, and around 30% in the plowed sites (Table 2). The correlation between $I30_{max}$ and sediment losses was similar among plowed and unplowed sites (Fig. 7b; Table 3). Cover-related variables explained about 23% of sediment losses at the unplowed site (bare soil and ash), while at the downslope plowed site stone cover was one of the major controlling factors (11%). At the contour plowed site, stone as well as ash cover seem to have been determinant for sediment losses (8%).

Individual regression analyses for wet ($SM_{i-1} < SM_i$) and dry ($SM_{i-1} > SM_i$) months detected differences in runoff and erosion controlling factors for each of these conditions. In the wet period, rainfall explained

20% of runoff variability, whereas in the dry period it accounted for 44% (Fig. 7c, Table 3). The variables associated to infiltration (SM_{min}, $SWR_{wettable}$) explained the runoff patterns under dry (15%) slightly better than wet conditions (13%). Similar results were found for erosion, since $I30_{max}$ explained 13% of sediment loss variability during wet periods and 36% during the dry periods (Fig. 7d, Table 3). In the erosion model, bare soil is of greater importance compared to the runoff model, whereas infiltration decreases its relevance.

4. Discussion

The hydrological and erosive response in the Colmeal study area during the four years after the wildfire showed few signs of recovery, as reported by Vieira et al. (2016). These results differ from other studies with the same duration (Lavabre and Martin, 1997; Butorac et al., 2009; Wittenberg and Inbar, 2009; Noske et al., 2016) since in previous studies sediment losses returned to background levels two to three years after the fire. According to the window of disturbance model (Prosser and Williams, 1998), this decrease in sediment losses to background levels can be attributed to vegetation recovery and an increase of the litter layer and the occurrence of a surface stone cover. In the present study, however, vegetation recovery was very limited (maximum = 30%), the litter cover was constant and the stone cover was very high (60-80%) during the entire monitoring period, which might explain the deviation from the standard window of disturbance model. Vieira et al. (2016) justified the Colmeal extended recovery period with the occurrence of past disturbances (wildfire and plowing) that led to highly degraded soils.

A delay of the post-fire response has also been reported by Mayor et al. (2007) in a small Mediterranean catchment in the Alicante province (Spain). As in the present study, these authors observed an increase in runoff and erosion during the second and the third year after fire, arguing that rainfall amounts were not sufficient to produce a hydrological response during the first year after fire (Mayor et al., 2007). Shakesby (2011) also found that a rainfall threshold must be overcome to trigger an enhanced hydrological and erosive response, this process being independent from whether runoff generation is driven by infiltration-excess (Hortonian) overland flow, by saturation overland flow, or a combination of both. Similarly to Mayor et al. (2007), the discrete response that was observed in Colmeal during the first year can be explained by the low rainfall amounts observed in autumn 2008, especially during November (11 mm). During autumn the soil is likely to generate more runoff and erosion, caused by the re-establishment of SWR after the dry summer months, in this case fire-induced SWR (Fig. 4), and by the s typically intense rainfall (Figs. 5 and 6). The hydrological response in this season is generally characterized by elevated runoff coefficients (27-50%), which concerned a substantial portion of the annual runoff (34-56 %) and erosion (42-74 %) of the second, third, and fourth years. But instead, due to the absence of rainfall, this particular season contributed with less than 20% to the annual runoff and erosion amounts. According to the MRM analysis, the runoff response in Colmeal can be explained by the rainfall and SWR patterns, similarly to what was found by Prats et al. (2012) and Malvar et al. (2016) in burned eucalypt sites (unplowed and pre-fire plowed). This analysis also suggests that the ash cover behaved as a runoff sink, as hypothesised by several authors (Cerdà, 1998; Martin and Moody, 2001; Gimeno-García et al., 2007; Bodí et al., 2012, 2014), because it presents an inverse relationship with runoff. However, this might not be true because the runoff model relates the low runoff response in the first year to the presence of ash and the increase in runoff in the second and third years with the absence of ash. Several reasons can be pointed out to justify why the ash cover cannot be a sink for runoff: (i) the ash cover was extremely limited (around 10% in the first winter); (ii) the ash was dispersed; and (iii) the ash layer was too thin (<1 mm) to be able to act as a sink. Regarding the erosive response, rainfall intensity ($I15_{max}$, $I30_{max}$) explained most of sediment losses, as reported by Prats et al. (2012) and Malvar et al. (2016). In the study of Prats et al. (2012), however, the protective litter cover was found to be more relevant for sediment losses than bare soil as found in the Colmeal study sites. A potential explanation for these findings might be the limited variation in vegetation, litter and stone cover that was observed in Colmeal during the entire monitoring period.

Pre-fire land management practices seem to influence post-fire runoff and erosion patterns, since runoff and erosion models differed between unplowed and plowed sites (Table 3). Plowing is known to promote infiltration through the increase of surface roughness that limits runoff generation (Morgan, 2005). The

MRM results, however, contradict this notion since a better relationship was found between runoff and rainfall for the plowed than the unplowed site (Table 3). These results might be explained by the higher litter cover in the unplowed plots (U=33% vs. DP=19% and CP=14%; Fig. 2a), which greatly contributed to rainfall interception, thereby reducing runoff generation. Because of the constant percentage of litter cover during the study period, however, the MRM was unable to associate the litter cover to a runoff reduction, unlike what was found by other authors (Prats et al., 2012, 2016a).

The variable that most influenced soil erosion was rainfall intensity ($I30_{max}$), showing a similar influence at the unplowed (23%) and plowed sites (DP=19%, CP=20%). The main difference between the unplowed and plowed erosion models was the influence of bare soil, which only appeared at the unplowed site (19%), possibility because it was much higher than in plowed sites (Fig. 2e). At the latter sites, stone cover was a major factor (DP=11%, CP=4%), suggesting that it acts as a protective soil cover, as highlighted by several authors (Morgan and Duzant, 2008; Shakesby, 2011). Its presence, however, can also mean that the fine sediments were already eroded as a result of past disturbances (Shakesby, 2011; Nyman et al., 2013).

Vegetation cover (Fig. 2c), which was expected to be important in explaining soil erosion patterns (Benavides-Solorio and MacDonald, 2001, 2005; Fernández et al., 2008; Larsen et al., 2009; Prats et al., 2016a), did not improve model results likely due to the lack of variability over time.

The dynamics of temperature and rainfall patterns in Mediterranean areas can strongly affect evapotranspiration processes, causing the succession of wet and dry soil moisture conditions throughout the year (Latron et al., 2009). These shifts in soil moisture can induce shifts in SWR (repellent/wettable) if certain site-specific soil moisture thresholds are achieved (Malvar et al, 2016). According to previous studies, the processes inducing runoff generation differ between wet and dry periods. Under wettable conditions, runoff is produced by saturation overland flow, whereas in repellent conditions, Hortonian overland flow is the dominant process (Ferreira et al., 2000, 2008; Leighton-Boyce et al., 2005; Morgan, 2005). In the Colmeal study area, the low soil moisture values and the occurrence of SWR in the fourth year after fire were most likely responsible for the high runoff coefficients observed in this period (Vieira et al., 2016), indicating that runoff was mainly generated by Hortonian overland flow.

The results of this study suggest that a separation between wet and dry periods based on soil moisture conditions could help explain runoff variability in burned areas. However, the definition of wet and dry conditions is not straightforward. For instance, some researchers have based their classification on the rainfall amounts that precede each event (González-Pelayo et al., 2010; Martínez-Murillo et al., 2016), whereas others consider the total rainfall amounts for a given period (Gabarrón-Galeote, et al., 2013; Santos et al., 2016). In this particular case, none of the approached was followed because some months had several rainfall events and the sum of monthly rainfall amounts was not always representative of individual processes such as saturation or reduced infiltration.

The runoff model for dry conditions resulted in stronger correlations with rainfall amounts (44%) and soil moisture (13%), than that for wet conditions (20% and 10%, respectively, for rainfall and soil moisture; Table 3), which is consistent with a process of Hortonian overland flow (Ferreira et al., 2000; 2008; Calvo-Cases et al., 2003; Mayor et al., 2007). In the case of the erosion model, results provided evidence that rainfall intensity is more important under dry (36%) than under wet conditions (13%). Based on these results, it appears that the two models are less able to explain data variability for wet (45% and 33%) than for dry conditions (70% and 53%), possibly due to the lack of a relationship with infiltration-related variables.

The fact that antecedent minimum soil moisture was negatively related to runoff in saturated soils suggests that the methodology used to define wet and dry periods might need some improvement, because other authors (Ferreira et al., 2000) have found a positive relationship between soil moisture and runoff when this is generated by saturation and a negative relationship in the case of Hortonian overland flow. Nonetheless, only an analysis at an event time-scale would allow to clearly distinguish between the two processes.

5. Conclusions

The main conclusions that can be drawn from this analysis of the key factors controlling the post-fire hydrological and erosive response at micro-plot scale in a recently burned Mediterranean forest are:

(1) Post-fire runoff generation is largely explained by rainfall amounts and SWR-related variables, while erosion processes are better explained by rainfall intensity and ground cover variables.

(2) Pre-fire land management impacts are still visible in the post-fire period, since differences in the relationship between runoff and rainfall were found between unplowed and plowed sites. Regarding the erosive response, bare soil cover was a major factor controlling soil erosion at the unplowed site, whereas at the plowed sites stone cover was more relevant.

(3) The statistical model considering wet and dry periods provided evidence that runoff can occur either by saturation or Hortonian overland flow. According to this model, runoff and erosion were better explained by rainfall-related variables under dry than under wet conditions.

(4) The MRM analysis improved the understanding on the key variables influencing the hydrologic and erosive response of a burned Mediterranean forest. The results of this analysis should be considered when adapting hydrological and erosion models to post-fire environments, especially those with past disturbances and soil moisture shifts.

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Tables

Table 1 - General characteristics of the study sites. U unplowed site, DP downslope plowed site, and CP contour plowed site.

		U	DP	CP
Forest type		Eucalypt	Eucalypt	Eucalypt
Pre-fire soil operations		Unplowed	Downslope plowing	Contour plowing
Plot angle (°)		27 (5.5)	30 (4.5)	24 (6.6)
Downslope random roughness		1.12 (0.03)	1.53 (1.07)	2.00 (0.77)
Soil depth (cm)	O horizon	0 - 4	0 - 3	0 - 3
	A horizon	A1 - 0-10 A2 10-22*	A1 - 0-14 A2 14-56*	A1 - 0-15 A2 15-29*
	B horizon	-	-	29 - 36
	C horizon	22	56 -	36 - 60
	R horizon	-	-	60 -
Soil type classification (WRB, 2006)		Haplic umbrisol & Umbric regosol	Humic cambisol & Haplic umbrisol	Humic cambisol & Haplic umbrisol
Soil texture class		Sandy Loam		
Bulk density (g/cm3)		0.83 (0.10)	1.05 (0.16)	0.85 (0.24)
Stone content (%)		42 (6)	40 (11)	46 (12)

(*)- Presence of ash in the profile.
Standard deviation in parentheses.
Values in bold are the limit of the profile depth.

Table 2 - Multiple regression model (MRM) for monthly runoff (square root) and sediment losses (fourth root) for all the study sites combined (General model) (n=442)

Runoff (mm)$^{(-\_)}$								Sediment Losses (g.m^{2})$^{(-\_)}$							
Summary of Forward Selection								Summary of Forward Selection							
	Variable	Partial R-Square	Model R-Square	Parameter Estimate	C(p)	F Value	Pr > F		Variable	Partial R-Square	Model R-Square	Parameter Estimate	C(p)	F Value	Pr > F
1	Rain (mm)	0.34	0.34	0.029	266.8	226.6	<.0001	1	I30$_{max}$ (mm h^{-1})	0.18	0.18	0.021	183.9	98.9	<.0001
2	Sm $_{min}$ (% v/v)	0.09	0.43	-0.121	169.9	71.7	<.0001	2	Bare soil (%)	0.13	0.32	0.059	84.8	85.3	<.0001
3	Ashes (%)	0.07	0.5	-2.235	99.4	59.5	<.0001	3	SWR $_{Wettable}$ (%)	0.03	0.34	-0.012	65.8	18.4	<.0001
4	SWR $_{Wettable}$ (%)	0.04	0.54	-0.071	62.4	34.5	<.0001	4	Sm $_{min}$ (% v/v)	0.03	0.37	-0.015	37.6	18.4	<.0001
5	Bare soil (%)	0.03	0.57	0.118	31.0	31.6	<.0001	5	Ash (%)	0.03	0.40	-0.012	18.3	20.8	<.0001
6								6	Rain (mm)	0.02	0.41	0.002	55.3	11.2	0.0009
7								7	Litter+veg. (%)	0.01	0.42	0.025	14.0	6.2	0.0133
8								8	Stones (%)	0.01	0.43	0.019	9.0	7.0	0.0083
		total	0.57							total	0.44				

Table 3 Multiple regression models (MRMs) for monthly runoff (square root) and sediment losses (fourth root) for each study site (Land management model): Unplowed ( ), Downslope plowed ( ), and Contour plowed ( ).

Runoff (mm)$^{(-\_)}$								Sediment Losses (g.m^{2})$^{(-\_)}$							
	Summary of Forward Selection								Summary of Forward Selection						
	Variable	Partial R-Square	Model R-Square	Parameter Estimate	C(p)	F Value	Pr > F		Variable	Partial R-Square	Model R-Square	Parameter Estimate	C(p)	F Value	Pr > F
1	Rain (mm)	0.24	0.24	0.019	122.0	51.2	<.0001	1	I30$_{max}$ (mm h^{-1})	0.23	0.23	0.022	95.4	47.2	<.0001
2	Bare soil (%)	0.12	0.36	0.277	78.2	31.0	<.0001	2	Bare soil (%)	0.19	0.42	0.075	35.6	51.2	<.0001
3	SWR$_{Wettable}$ (%)	0.1	0.46	-0.085	42.3	30.4	<.0001	3	Ash (%)	0.04	0.46	-0.046	24.2	11.9	0.0007
4	Ash (%)	0.07	0.53	-0.206	19.0	23.2	<.0001	4	SWR$_{Wettable}$ (%)	0.03	0.49	-0.012	15.4	10.2	0.0017
5	Sm$_{min}$ (% v/v)	0.03	0.56	-0.089	9.9	10.9	0.0012	5	Rain (mm)	0.02	0.51	0.002	10.1	7.1	0.0087
6	I30$_{max}$ (mm h^{-1})	0.01	0.57	0.037	7.0	4.9	0.0284	6	Sm$_{min}$ (% v/v)	0.01	0.52	-0.019	8.1	4.0	0.0477
		total	**0.57**							total	**0.52**				
1	Rain (mm)	0.43	0.43	0.027	40.9	90.6	<.0001	1	I30$_{max}$ (mm h^{-1})	0.19	0.19	0.02	29.7	27.3	<.0001
2	SWR$_{Wettable}$ (%)	0.09	0.52	-0.089	16.7	23.5	<.0001	2	Stones (%)	0.11	0.31	-0.011	12.3	18.0	<.0001
3	Ash (%)	0.06	0.58	-0.425	1.3	17.8	<.0001	3	Rain (mm)	0.04	0.34	0.002	8.0	6.1	0.0147
								4	SWR$_{Wettable}$ (%)	0.03	0.37	-0.013	4.3	5.7	0.0185
		total	**0.58**							total	**0.37**				
1	Rain (mm)	0.49	0.49	0.03	61.1	150.9	<.0001	1	I30$_{max}$ (mm h^{-1})	0.20	0.20	0.022	35.6	38.3	<.0001
2	Ash (%)	0.12	0.61	-0.225	12.2	48.1	<.0001	2	Stones (%)	0.04	0.24	-0.02	26.9	9.2	0.0028
3	SWR$_{Wettable}$ (%)	0.02	0.63	-0.051	4.4	9.7	0.0022	3	Ash (%)	0.04	0.28	0.002	14.4	7.9	0.0055
								4	Rain (mm)	0.03	0.31	-0.028	20.8	7.4	0.0074
								5	SWR$_{Wettable}$ (%)	0.03	0.34	-0.013	9.2	7.0	0.009
		total	**0.63**							total	**0.34**				

Table 4 Multiple regression models (MRMs) for monthly runoff (square root) and sediment losses (fourth root) for wet ( ) and dry periods ( ). The wet or dry condition was stablished according to the increase (wet) or decrease (dry) in the mean monthly soil moisture value with respect to the previous month.

Runoff (mm)$^{(-)}$								Sediment Losses (g.m^2)$^{(-)}$							
Summary of Forward Selection								Summary of Forward Selection							
	Variable	Partial R-Square	Model R-Square	Parameter Estimate	C(p)	F Value	Pr > F		Variable	Partial R-Square	Model R-Square	Parameter Estimate	C(p)	F Value	Pr > F
1	Rain (mm)	0.20	0.20	0.025	141.1	64.7	<.0001	1	Bare soil (%)	0.13	0.13	0.013	81.5	38.9	<.0001
2	Sm $_{min}$ (% v/v)	0.10	0.31	-0.132	91.8	38.0	<.0001	2	I30 $_{max}$ (mm h^{-1})	0.09	0.22	0.042	50.6	27.8	<.0001
3	Ash (%)	0.08	0.39	-0.232	54.0	33.3	<.0001	3	Sm min (% v/v)	0.04	0.25	-0.025	27.6	12.8	0.0004
4	SWR $_{Wettable}$ (%)	0.03	0.42	-0.067	38.9	15.1	0.0001	4	Ash (%)	0.03	0.29	-0.035	39.6	11.4	0.0009
5	Bare soil (%)	0.03	0.45	0.111	26.7	13.2	0.0003	5	Rain (mm)	0.02	0.31	0.002	21.6	7.5	0.0065
6								6	SWR $_{Wettable}$ (%)	0.02	0.33	-0.011	15.5	7.8	0.0056
			0.45								0.33				
1	Rain (mm)	0.44	0.44	0.041	158.6	141.8	<.0001	1	I30 max (mm h-1)	0.36	0.36	0.005	63.3	100.3	<.0001
2	Sm $_{min}$ (% v/v)	0.13	0.57	-0.121	81.7	55.0	<.0001	2	Bare soil (%)	0.07	0.43	0.023	38.4	22.5	<.0001
3	Ash (%)	0.07	0.64	-0.241	43.0	33.5	<.0001	3	Sm min (% v/v)	0.04	0.46	0.008	13.3	13.5	0.0003
4	Bare soil (%)	0.04	0.67	0.117	11.1	22.2	<.0001	4	Ash (%)	0.03	0.49	-0.028	30.9	8.3	0.0045
5	SWR $_{Wettable}$ (%)	0.02	0.70	-0.057	31.9	11.4	0.0009	5	Rain (mm)	0.02	0.51	0.004	25.4	6.7	0.0104
								6	Litter+veg. (%)	0.02	0.53	0.006	8.8	6.5	0.0117
			0.70								0.53				

Figure captions

Figure 1 - Location of the Colmeal study area (left); Detailed topographic map of the burned catchment with the specific location of each study site (U unplowed site, DP downslope plowed site, and CP contour plowed site) and of the installed equipment (right).

Figure 2 - Average (a) litter, (b) stones, (c) vegetation, (d) ash and (e) bare soil cover at each study site (n=4). Standard error indicated by error bars.

Figure 3 Average monthly rainfall at Góis meteo-station from 1917 to 1997 (SNIRH, 2016).

Figure 4 Average seasonal soil moisture (a) and soil water repellency frequency (n=180).

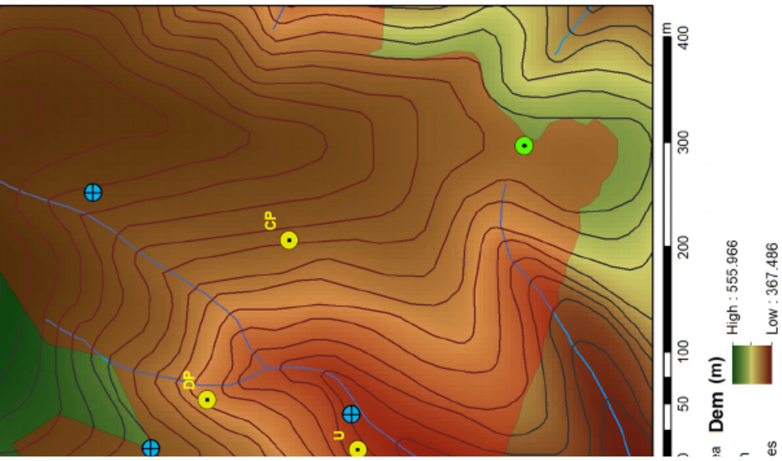
Figure 5 Average monthly rainfall and runoff in the four years following the wildfire at the unplowed (U), downslope plowed (DP) and contour plowed (CP) sites. Wet periods in blue and dry periods in white backgrounds.

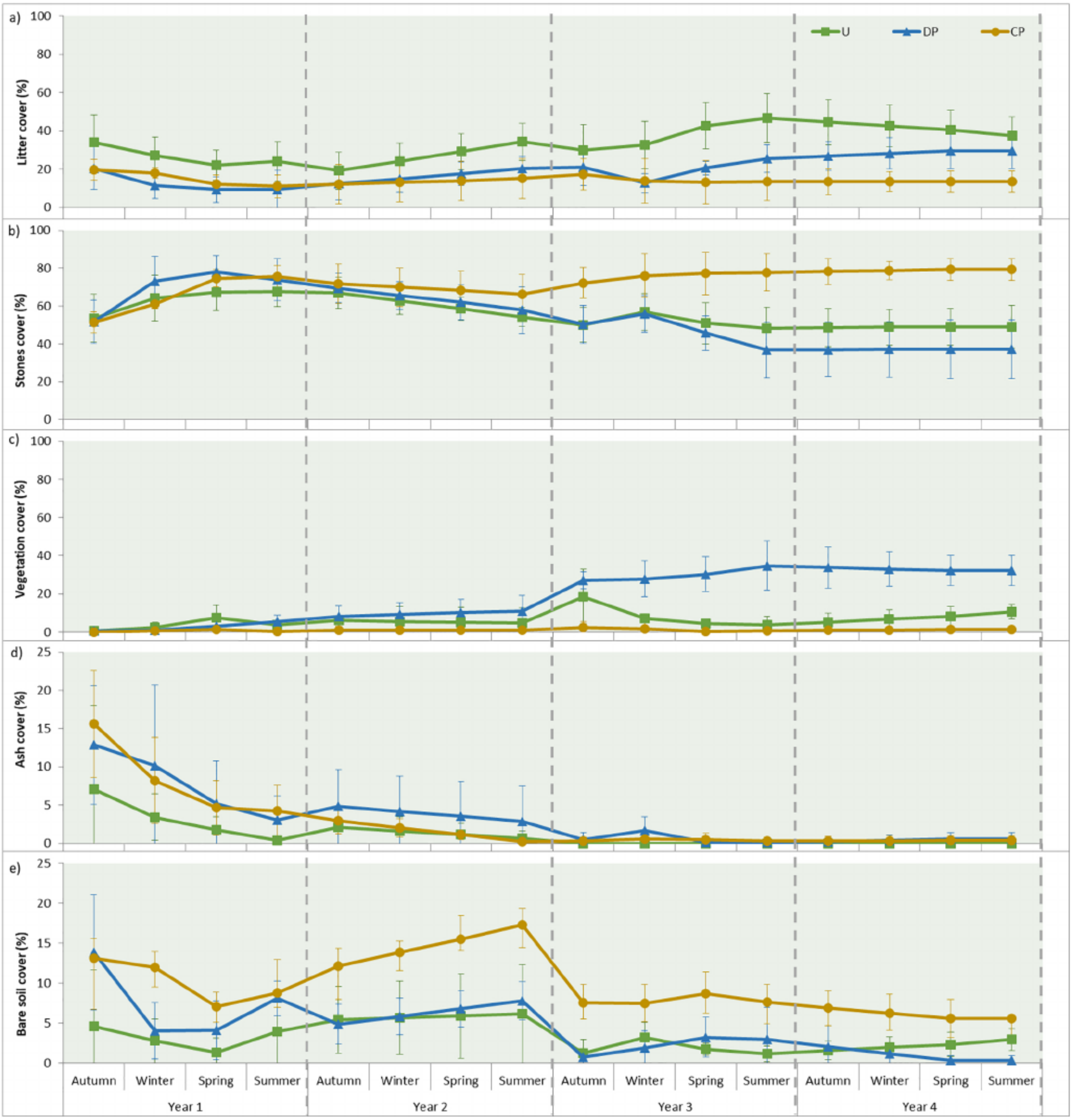
Figure 6 Average monthly rainfall erosivity, $I30_{max}$ and erosion in the four years following the wildfire at the unplowed (U), downslope plowed (DP) and contour plowed (CP) sites. Wet periods in blue and dry periods in white backgrounds.

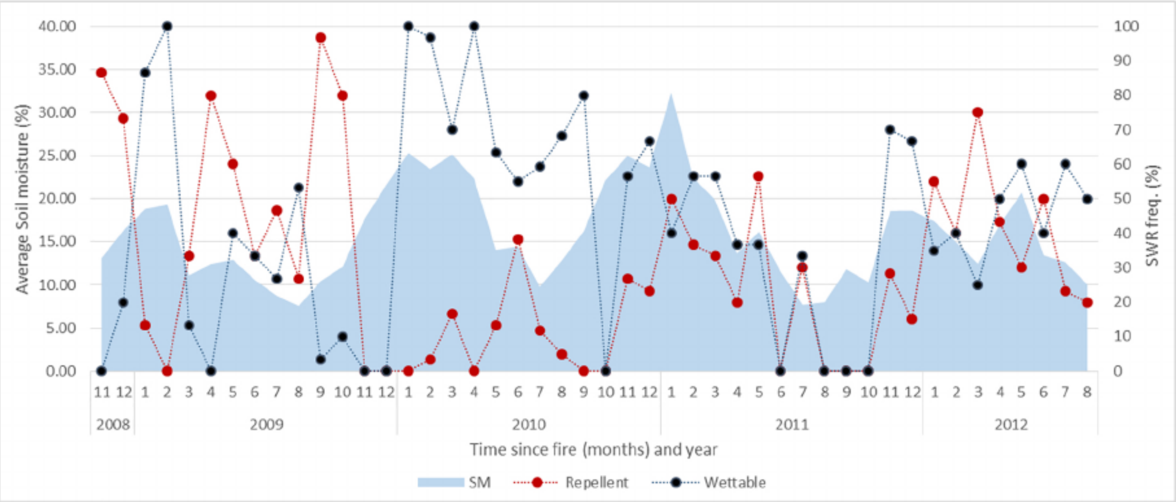
Figure 7 Scatter plots of runoff rainfall (n=464) and erosion I_{30}max (n=378) for the different land management practices (plowed and unplowed, and b) and soil moisture conditions (wet and dry, c and d).

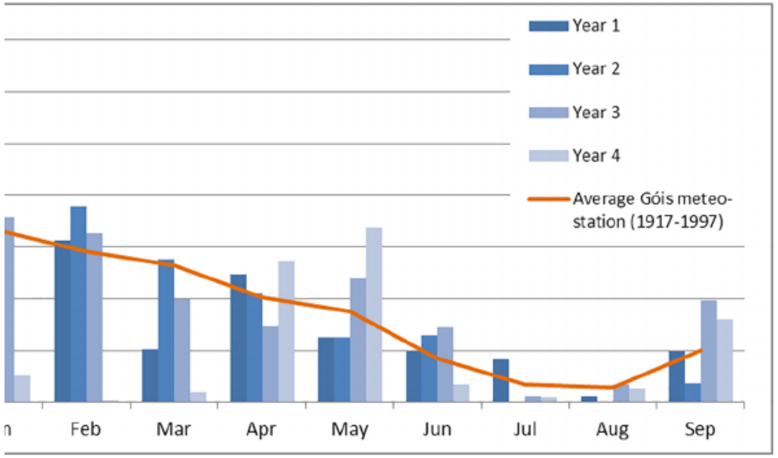
Highlights

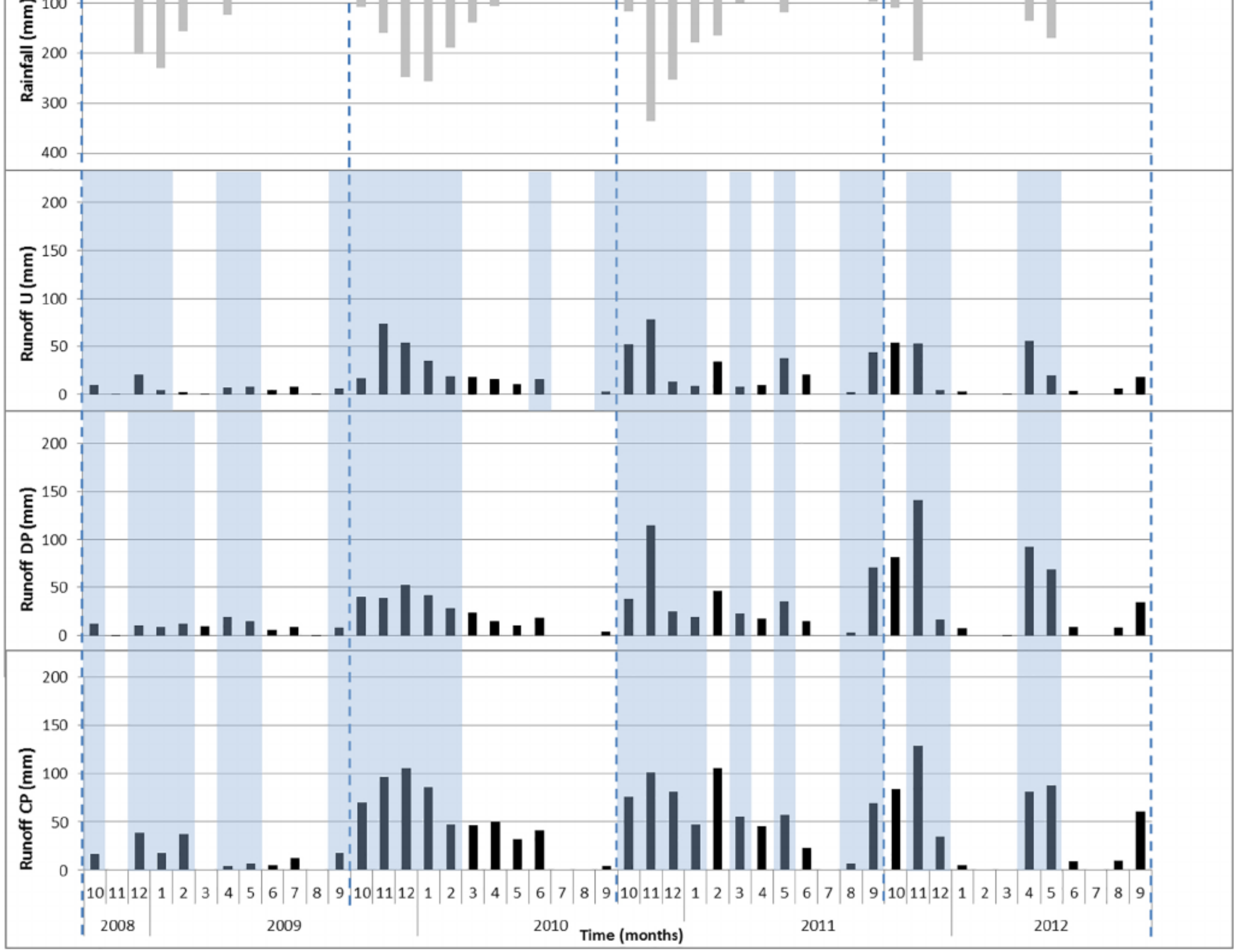
- Post-fire runoff is better explained by rainfall and soil water repellency.
- Post-fire erosion is better explained by rainfall intensity and cover variables.
- Pre-fire land management seem to affect post-fire runoff and erosion processes.
- Statistical models indicate runoff and erosion processes change in wet and dry soil moisture conditions.

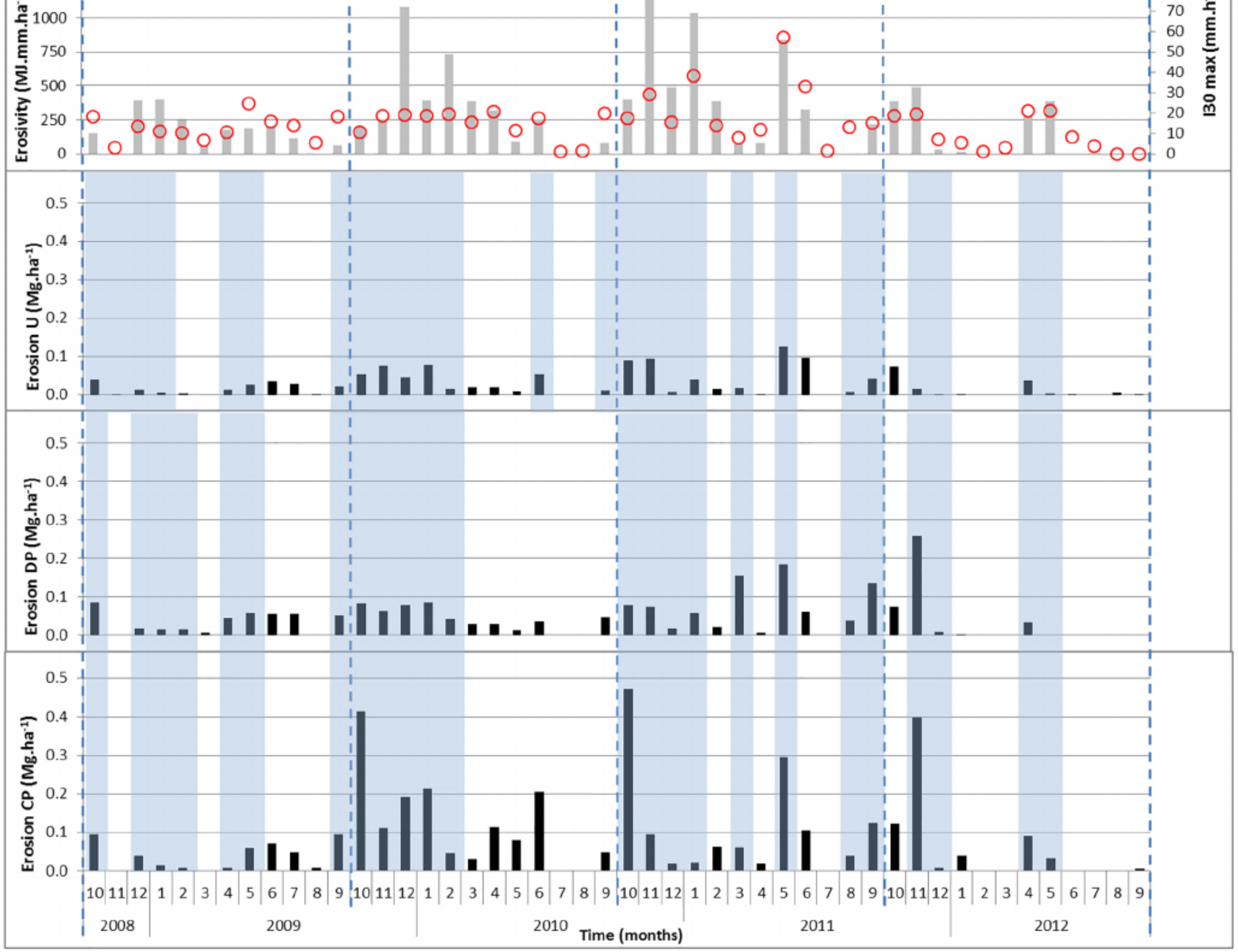

CP
DP
U
m
400
300
200
100
50
Dem (m)
High : 555.966
Low : 367.486

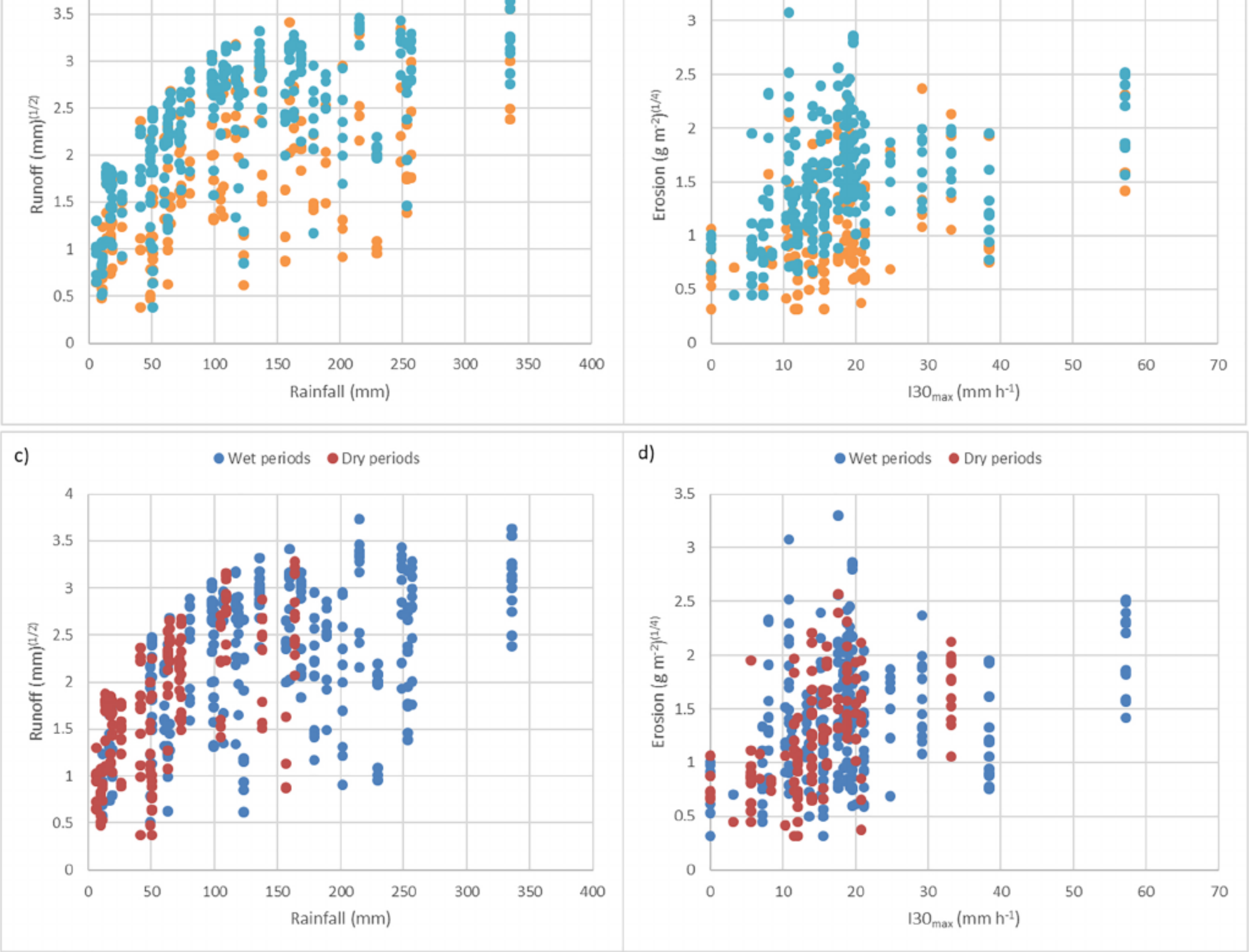

a)
Litter cover (%)
U
DP
CP
b)
Stones cover (%)
c)
Vegetation cover (%)
d)
Ash cover (%)
e)
Bare soil cover (%)
100
80
60
40
20
0
25
20
15
10
5
Autumn
Winter
Spring
Summer
Year 1
Year 2
Year 3
Year 4


Average Soil moisture (%)
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
SWR freq. (%)
100
90
80
70
60
50
40
30
20
10
0
11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8
2008
2009
2010
2011
2012
Time since fire (months) and year
SM
Repellent
Wettable


Year 1
Year 2
Year 3
Year 4
Average Góis meteo-station (1917-1997)
n
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Rainfall (mm)
100
200
300
400
Runoff U (mm)
200
150
100
50
0
Runoff DP (mm)
200
150
100
50
0
Runoff CP (mm)
200
150
100
50
0
10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9
2008
2009
2010
2011
2012
Time (months)


Erosivity (MJ.mm.ha
1000
750
500
250
0
I30 max (mm.h
70
60
50
40
30
20
10
0
Erosion U (Mg.ha-1)
Erosion DP (Mg.ha-1)
Erosion CP (Mg.ha-1)
0.5
0.4
0.3
0.2
0.1
0.0
10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9
2008
2009
2010
2011
2012
Time (months)

Runoff (mm)(1/2)
Rainfall (mm)
Erosion (g m-2)(1/4)
I30max (mm h-1)
c)
Wet periods
Dry periods
Runoff (mm)(1/2)
Rainfall (mm)
d)
Wet periods
Dry periods
Erosion (g m-2)(1/4)
I30max (mm h-1)