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# Polyacrylamide application versus forest residue mulching for reducing post-fire runoff and soil erosion

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## HIGHLIGHTS

- The effectiveness of two soil erosion control treatments was contrasted after a wildfire.
- Chopped bark mulch reduced runoff and soil erosion, whereas dry polyacrylamide did not.
- Rainfall amount and soil cover were key factors respectively for runoff and soil erosion.
- Fire intensity across the burnt slope also affected soil erosion and organic matter content on the eroded sediments.

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## ABSTRACT

For several years now, forest fires have been known to increase overland flow and soil erosion. However, mitigation of these effects has been little studied, especially outside the USA. This study aimed to quantify the effectiveness of two so-called emergency treatments to reduce post-fire runoff and soil losses at the microplot scale in a eucalyptus plantation in north-central Portugal. The treatments involved the application of chopped eucalyptus bark mulch at a rate of 10–12 Mg ha$^{-1}$, and surface application of a dry, granular, anionic polyacrylamide (PAM) at a rate of 50 kg ha$^{-1}$. During the first year after a wildfire in 2010, 1419 mm of rainfall produced, on average, 785 mm of overland flow in the untreated plots and 8.4 Mg ha$^{-1}$ of soil losses. Mulching reduced these two figures significantly, by an average 52 and 93%, respectively. In contrast, the PAM-treated plots did not differ from the control plots, despite slightly lower runoff but higher soil erosion figures. When compared to the control plots, mean key factors for runoff and soil erosion were different in the case of the mulched but not the PAM plots. Notably, the plots on the lower half of the slope registered bigger runoff and erosion figures than those on the upper half of the slope. This could be explained by differences in fire intensity and, ultimately, in pre-fire standing biomass.

## 1. Introduction

In the last few decades, wildfires have become a common and widespread phenomenon in Portugal (Pereira et al., 2005; Shakesby, 2011). One of the principal effects of wildfires is widely held to be a partial or total loss of vegetation and litter cover (e.g. Soto and Diaz-Fierros, 1997; Shakesby, 2011). The resulting reduction in both rainfall interception and plant transpiration enhances runoff generation as well as soil exposure to the direct impact of raindrops (Soto et al., 1998; Wagenbrenner et al., 2006; Ben-Hur et al., 2011; Fernández et al., 2011). Direct effects of wildfires due to soil heating, such as breakdown of aggregates and increased soil water repellency, are generally considered to be key factors in the strong and sometimes extreme hydrological and erosion responses of recently burnt areas (e.g. Coelho et al., 2004; Doerr et al., 2006; Ferreira et al., 2008; Keizer et al., 2008; Varela et al., 2010; Malvar et al., 2011). Fire-enhanced generation of runoff and the associated export of sediments, organic matter, nutrients and pollutants not only have negative consequences for on-site land-use sustainability, but also can endanger downstream aquatic and flood-zone habitats and associated human infrastructures (Shakesby and Doerr, 2006; Ferreira et al., 2008; Robichaud, 2009).

It is generally accepted that fire-enhanced erosion rates are maximal immediately after the wildfire (e.g. 35 Mg ha$^{-1}$ during the first post-fire year in Fernández et al., 2011) and decrease with time to background levels at the end of the so-called window of disturbance (up to 10 years after the wildfire as reported in Swanson, 1981 and in Shakesby and Doerr, 2006). However, the intensity and extent of this period, which depends on fire severity and post-fire climate conditions,

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are still highly uncertain and difficult to quantify (Neary et al., 1999; Cerdà and Doerr, 2005; Cerdà and Lasanta, 2005; Robichaud, 2009).

A variety of measures have been identified that can effectively reduce post-fire soil erosion (e.g. Miles et al., 1989; MacDonald and Larsen, 2009; Robichaud et al., 2013). Arguably, the most widely accepted measure is mulching, i.e., the application of a cover of organic compounds on the soil surface to modify energy and water fluxes and to protect the soil from direct raindrop impact (Bautista et al., 2009). Mulching has been found to successfully control post-fire runoff and soil erosion in many field trials (e.g. Miles et al., 1989; Bautista et al., 1996; Wagenbrenner et al., 2006; Fernández et al., 2011; Prats et al., 2012). A mulch cover of 60% is widely considered the minimum threshold for a significant reduction in soil loss (Pannkuk and Robichaud, 2003; Cerdà and Doerr, 2008; Robichaud et al., 2010). In the case of straw mulch, this threshold cover is typically achieved by applying 2 Mg of straw per ha (Miles et al., 1989; Bautista et al., 1996; Badía and Martí, 2000; Wagenbrenner et al., 2006; Groen and Woods, 2008; Fernández et al., 2011), with costs ranging from 600 to 1200 USD $ha^{-1}$ for aerial and manual application, respectively (Napper, 2006).

Although burnt areas are commonly mulched with straw, this has various disadvantages: high cost, potential introduction of non-native plants, and susceptibility to wind-scattering (Bautista et al., 2009). In recent years, there has been increasing interest in alternative mulch types derived from forest residues, using fibers of different shapes and sizes (Yanosek et al., 2006; Smets et al., 2008). In laboratory experiments, 6-cm long wood strands applied at rates of 4 to 8 Mg $ha^{-1}$ were found to be highly effective, reducing erosion rates by 80% (Foltz and Copeland, 2009; Foltz and Dooley, 2003; Foltz and Wagenbrenner, 2010). In field trials, mulching with 10- to 15-cm long chopped eucalyptus bark fibers markedly reduced post-fire erosion during the first year after the fire (Prats et al., 2012), while mulching with wood chips did not (Fernández et al., 2011). The mulch employed by Prats et al. (2012) had the further advantages of being readily available in the study region (due to the widespread occurrence of eucalyptus plantations in north-central Portugal), not being susceptible to removal by wind, decaying more slowly than straw, and not introducing invasive weeds. The cost of applying the chopped bark mulch, however, differed little from that of applying straw, as the lower costs per Mg were offset by the higher application rates needed to achieve the 60% cover threshold.

A more recent measure to control post-fire erosion is the application of polyacrylamides (PAMs; Rough, 2007; Robichaud et al., 2010). PAMs refer to a family of flocculant agents, comprising a broad class of chemical compounds with different chain lengths, charge types and charge densities. Different PAM formulations have been developed to ensure effective binding with clay particles through direct ionic attractions or cation bridges (Theng, 1982; Vacher et al., 2003). The application of PAMs constitutes a remarkable soil- and water-management technique, due to their extremely low cost (~3 USD per kg), their safety, and their capacity to influence physicochemical processes (Sojka et al., 2007). During the last two decades, the use of PAMs has proven effective for erosion control in furrow irrigation in intensive agriculture (Ben-Hur, 2006; Sojka et al., 2007). Application rates as low as 1 to 50 kg $ha^{-1}$ have been found to noticeably reduce soil losses from agricultural fields as well as from steep road embankments (Agassi and Ben-Hur, 1992; Ben-Hur, 2001; Ben-Hur and Keren, 1997; Ben-Hur and Letey, 1989; Lentz et al., 2002; Levy et al., 1991). The effectiveness of PAMs in reducing post-fire erosion, however, is poorly established. The few studies which have been carried out have produced inconsistent results. Davidson et al. (2009), Riechers et al. (2008) and Inbar (2011) found PAM to be effective, whereas Rough (2007) and Wohlgemuth and Robichaud (2007) did not.

The main objective of the present study was to evaluate the effectiveness of two erosion-mitigation techniques – mulching with forest residues (chopped bark) and surface application of a dry granular anionic PAM – during the first year after a wildfire in a eucalyptus plantation in north-central Portugal. The specific objectives were to: (i) assess the performance of both techniques at a high temporal resolution (monitoring every 1 or 2 weeks); (ii) determine the spatial variation in overland-flow generation and soil losses from the base to the top of a 40-m long slope; and (iii) determine the key factors explaining overland flow and soil losses for the treatments, together and separately.

## 2. Material and methods

### 2.1. Study area

The study area was located near the Ermida hamlet in the Sever do Vouga municipality of north-central Portugal. The area was affected by a wildfire that consumed 295 ha between 26 and 28 July 2010 (AFN, Autoridade Florestal Nacional, 2012). The burnt area not only consisted mainly of eucalyptus (*Eucalyptus globulus* Labill.) plantations, but also included some maritime pine (*Pinus pinaster* Ait.) plantations and a stand of cork oak (*Quercus suber* L.). The eucalyptus trees in the region are typically planted as monocultures for paper pulp production, and harvested every 7–14 years. After logging, the eucalyptus trees are left to regrow from the stumps two or three times, after which a new plantation cycle is begun (Ferreira et al., 1997; Leighton-Boyce et al., 2005; Prats et al., 2012).

The climate of the study area can be classified as humid mesothermal (Csb in the Köppen classification), with moderately dry but extended summers (DRA-Centro, Direcção Regional do Ambiente do Centro, 1998) when the bulk of the wildfires occurs. The mean annual temperature at the nearest weather station of “Castelo Burgães” (40°51′16″N, 8°22′55″W, 306 m a.s.l.; 1990–2010; SNIRH, Serviço Nacional de Informação dos Recursos Hídricos, 2011) was 14.9 °C, while mean monthly temperatures ranged from 9.0 °C in January to 21.1 °C in July. Annual rainfall at the nearest rainfall station of “Ribeiradio” (40°44′39″N, 8°18′05″W; 228 m a.s.l.; 1990–2010; SNIRH, Serviço Nacional de Informação dos Recursos Hídricos, 2011) varied between 960 and 2530 mm, with an average of 1609 mm.

The study area is situated in one of the region's major physiographic units, the Hespheric Massif. The area consists mainly of pre-Ordovician schists and graywackes, but includes Hercynian granites at several locations (Ferreira de Brum, 1978). Within the study area, a steep (25°) but short (40 m) slope with southwest aspect was selected for this study (40°44′05″N, 8°21′18″W, 200 m a.s.l.; Fig. 1). The eucalyptus trees in the study site had been cut just before the fire, as evidenced by the tree logs that were piled up at the base of the slope and were partially charred by the wildfire. Judging from the remaining tree stumps (with diameters of roughly 1 m), the stand had undergone three prior harvestings, and had originally been planted some three decades before the 2010 wildfire. The overall severity of the 2010 wildfire was estimated to be moderate, as inferred from the complete consumption of the logging slash residues, the understory vegetation and the litter layer, as well as from the prevalence of a 1- to 4-cm thick layer of black ash (Table 1). At the base of the slope, however, the presence of gray and white ashes suggested moderate to high severity.

### 2.2. Experimental setup

At the end of August 2010, before any significant rainfall events (Fig. 2), the study site was instrumented with two rainfall gauges (one tipping-bucket gauge with a resolution of 0.2 mm and one storage gauge for validation purposes), and 12 square erosion plots of approximately 0.28 $m^2$ were established (Fig. 1). The 12 plots were organized into four sets (blocks) that were located at about equal distances from the base to the top of the slope (Table 1), while the three plots of each block were placed at 1- to 3-m distance from each other. The plot outlets were connected to tanks with a storage capacity of 30 l for overland-flow collection. The spatial variation in soil properties across the study slope was examined in February 2011 by excavating a soil profile in each block, measuring soil depth, and collecting two samples from

**Fig. 1.** Overview of the hillslope during the installation of the microplots.

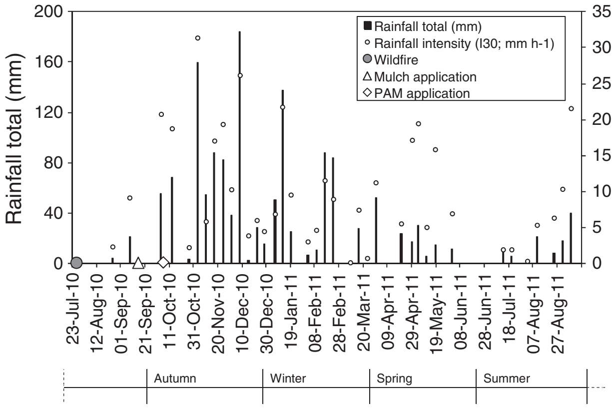

**Fig. 2.** Rainfall total and maximum intensity during 30 min (i30) of the individual, 1- to 2-weekly readouts during the first year after wildfire. Besides the occurrence of the wildfire, also the application dates of the two treatments (forest residue mulch and PAM) are indicated.

each of two soil depths (0–5 and 5–10 cm). These 16 samples were analyzed in the laboratory for bulk density (Porta et al., 2003), granulometric composition (Guitian and Carballas, 1976) and organic matter content (Botelho da Costa, 2004) (Table 1). Whereas soil depth tended to decrease in the upslope direction, the other soil parameters revealed less straightforward spatial patterns. The upper 10 cm of the soils overlying pre-Ordovician schists of the Hespheric Massif (Pereira and FitzPatrick, 1995) had a sandy loam texture and high contents of stones (50–55%) and organic matter (7.9–11.6%).

**Table 1**
General description of the study site and details of the studied treatments. The ground cover corresponds to the average values of the three plots at each slope position, whereas the values of bulk density, stoniness, texture fraction and organic matter content correspond to the average values of the indicated samples collected at 0–5 cm and 5–10 cm depth.

| | Block number | | | |
|---|---|---|---|---|
| | I | II | III | IV |
| *General characteristics* | | | | |
| Position (m from base of slope) | 11 | 18 | 27 | 36 |
| Slope angle (degrees) | 26 | 25 | 24 | 27 |
| Projected plot area ($m^2$) | 0.22 | 0.23 | 0.23 | 0.22 |
| *Ground cover immediately after wildfire (01 September 2010)* | | | | |
| Black ashes (%) | 82 | 88 | 91 | 92 |
| Gray and white ashes (%) | 8 | 6 | 2 | 0 |
| Stones (%) | 5 | 5 | 4 | 2 |
| Litter (%) | 5 | 2 | 3 | 5 |
| *Soil characteristics* | | | | |
| Soil depth (cm) | 74 | 43 | 35 | 35 |
| Bulk density (g $cm^{-3}$) | 1.1 | 1.1 | 1.2 | 1.0 |
| Stoniness (>2 mm, %) | 53.1 | 55.3 | 54.8 | 50.9 |
| Sand fraction (%) | 62.7 | 66.9 | 69.6 | 58.8 |
| Silt fraction (%) | 20.5 | 18.2 | 16.7 | 22.7 |
| Clay fraction (%) | 16.7 | 14.8 | 13.6 | 18.5 |
| Organic matter content (%) | 10.9 | 11.6 | 7.9 | 11.1 |
| *Treatments* | | | | |
| PAM application rate (Mg $ha^{-1}$) | 0.05 | 0.05 | 0.05 | 0.05 |
| Mulch application rate (Mg $ha^{-1}$) | 11.2 | 11.6 | 10.4 | 10.1 |
| Mulch cover (%; on 04 October 2010) | 86 | 89 | 80 | 78 |

A randomized block design was employed to assess the effectiveness of the two erosion-mitigation techniques. The two treatments were randomly allocated to two of the three plots in each block, leaving the last plot untreated (control). The forest residue mulch consisted of chopped eucalyptus bark and was purchased from the Socasca S.A., at the standard market price of 30 € per Mg. The mulch was applied manually on 15 Sep 2010 at a rate of 10–12 Mg $ha^{-1}$, which provided 80–90% ground cover (Table 1). A dry granular anionic PAM with high molecular weight (Superfloc 110-c Series N/A-100) was chosen for this study, because of its effectiveness in prior studies (Chaudhari and Flanagan, 1998; Flanagan et al., 2002; Yu et al., 2003; Ajwa and Trout, 2006), including in a recently burnt area (Inbar, 2011). It was spread out manually over the soil surface on 4 October 2010 at a rate of 50 kg $ha^{-1}$. The delay in the PAM application relative to the mulching was due to difficulties in obtaining the Superfloc 110-c polymer. As a consequence of this delay, rainfall prior to the PAM application was considerably higher than that prior to the mulching (81 mm vs. 25 mm, respectively). Therefore, the present study does not include the initial post-fire period up until 4 October 2010.

### *2.3. Field data collection and laboratory analyses*

From 1 September 2010 to 7 September 2011, the rainfall accumulated in the storage gauge and the overland flow collected in the tanks were measured at 1- to 2-week intervals, depending on the occurrence of rainfall. Whenever there was more than 250 ml of runoff in a tank, a sample was collected (in a 1.5-l bottle) and transported to the laboratory for analysis. In total, some 400 runoff samples were collected during 34 readouts. The sediment concentration of these samples was determined in the laboratory by filtration, using a paper filter with a pore diameter of 12 μm, followed by drying at 105 °C for 24 h. Subsequently, the organic matter content of the filtered and dried sediments was measured by loss-on-ignition method (550 °C for 4 h).

The ground cover of the 12 erosion plots was determined on six occasions during the study period, i.e., immediately before and after applying the treatments (on 1 Sep and 3 Nov 2010), and then at 2- to 4-month intervals until November 2011. The following five cover categories were recognized: bare soil, stones (including rock outcrop), litter (including the applied mulch), ash (including charred plant material), and vegetation. Ground cover was quantified by laying a square grid of 0.5 m × 0.5 m at a fixed position over the plots, and recording the cover category at the 100 points of intersection between the grid's 10 equidistant rows and 10 equidistant columns.

### *2.4. Data analysis*

The SAS system (Littell et al., 1996, 2006) was used to carry out the following statistical analyses: (i) one-way ANOVA, to assess whether the three treatments (control, PAM, and mulching) resulted in significant differences among their overall values of runoff (specific), soil losses and organic matter content of the eroded sediments over the entire study period (4 October 2010–7 September 2011) as well as in the cover of the five cover categories immediately after the wildfire (September 2010) and 1 year later; (ii) two-way ANOVA, to determine the (combined) effects of the three treatments and of the plots' four positions across the slope on the overall values of runoff (specific), soil losses and organic matter content of the eroded sediments; (iii) two-way repeated-measures ANOVA, to assess the (combined) effects of the three treatments and the time-since-treatment on the 1- to 2-weekly values of runoff (specific), soil losses and organic matter content of the eroded sediments; (iv) post-hoc tests of least squares differences (LSDs) adjusted by the Tukey–Kramer method (Tukey, 1953; Kramer, 1956), to assess whether the plots treated with mulch and PAM produced significantly different overall or 1-/2-weekly values of runoff, (specific) soil losses and organic matter content compared to the untreated plots; and (v) multiple linear regression, using the REG stepwise forward selection procedure in combination with the collinearity test to select, among a set of 10 independent variables, those that explained a significant ($p \leq 0.05$) fraction of the variation in the 1- to 2-weekly values of runoff, (specific) soil losses and organic matter content and, at the same time, had a condition index below 30 (Belsley et al., 1980; Littell et al., 1996). The 10 independent variables included in the REG procedure consisted of two rainfall-related variables ("rain" — rainfall amount; "i30" — maximum rainfall intensity in 30 min), the five cover categories and three time-invariant variables ("depth" — soil depth, "position" — position of the plots across the slope, "angle" — slope angle of the individual plots).

In the case of the two-way repeated-measures ANOVAs, the assumption of normality of the residuals was rejected for the original values of runoff (mm), soil loss (g $m^{-2}$) and specific soil loss (g $m^{-2}$ $mm^{-1}$ runoff) (Kolmogorov–Smirnov test: $p < 0.05$). To remediate this, the runoff and (specific) soil loss data were log10 fourth root transformed, respectively, and the six readouts with the least rainfall (<6 mm) were eliminated from the data set. The resulting data sets were also used in the multiple linear regression analyses. The variance–covariance structure of the repeated-measures ANOVAs was modeled with the heterogeneous auto-regressive variance, because it gave the smallest values for the Akaike Information Criterion (AIC; Akaike, 1987) and the −2 restricted log likelihood (Littell et al., 2006).

## 3. Results

### *3.1. Overall rainfall, runoff and erosion values*

Total rainfall during the entire study period from 1 September 2010 until 7 September 2011 amounted to 1500 mm, closely approximating the long-term mean annual rainfall at the nearest Ribeiradio station (1609 mm). From the 1481 mm of rain that fell during the post-treatment period (i.e. after 4 October 2010), more than half (55%) was, on average, converted to overland flow over the untreated plots (control treatment) and produced 848 g $m^{-2}$ of soil loss (Table 2). This soil loss was accompanied by an even greater loss of organic matter, as the sediments eroded from the control plots had an average organic matter content of 61%. Mulching had a significant and prominent impact on runoff generation, but in particular on soil loss (one-way ANOVA: $p < 0.05$ and $p < 0.01$, respectively). The runoff in the mulched plots was, on average, 52% lower than in the control plots, whereas the associated soil losses were 93% lower. The effect of PAM, on the other hand, was less marked and not significant (one-way ANOVA: $p = 0.3$) and, at the same time, opposite for runoff and erosion, reducing the average runoff by 16% while increasing the average soil losses by 23%. Thus, the overland flow generated by the PAM plots transported, on average, 50% more soil per unit of runoff than the overland flow produced by the control plots (1.58 vs. 1.05 g $m^{-2}$ $mm^{-1}$ runoff), and this difference was statistically significant (one-way ANOVA: $p < 0.05$). The same was not applied to the organic matter losses, as they made up equivalent fractions of the sediments eroded from the PAM, mulched and control plots (51 vs. 61%).

**Table 2**
Average values of total runoff volumes, total and specific soil losses, and organic matter contents in the eroded materials for control (untreated), polyacrylamide (PAM) and mulched plots over the entire post-treatment period (4 October, 2010–7 September, 2011). PAM and mulch effectiveness exhibits positive and negative signs in order to highlight the enhancing or reducing effect of the treatment. Significant differences between the untreated and treated plots, according to one-way ANOVA, are in bold ($p < 0.05$) or underlined and bold ($p < 0.01$).

| | Runoff | Soil losses | | Organic matter content (% w/w) |
|---|---|---|---|---|
| | Volume (mm) | Total (g $m^{-2}$) | Specific (g $m^{-2}$ $mm^{-1}$) | |
| Control | 785 | 848 | 1.05 | 61 |
| PAM | 657 | 1047 | 1.58 | 51 |
| Mulch | 378 | 63 | 0.17 | 63 |
| PAM effectiveness (%) | −16 | +23 | **+50** | −16 |
| Mulch effectiveness (%) | **−52** | **−93** | **−84** | +3 |

Overall (specific) soil losses over the entire post-treatment period differed significantly among the three treatments as well as among the four slope positions (Table 3). In contrast, overall runoff volumes did not differ significantly among treatments or among slope positions. Overall organic matter contents in the eroded sediments also did not differ significantly among the treatments but they did among the slope positions. The specific contrasts of the treated (mulching/PAM) vs. control plots were in line with the above-reported one-way ANOVA results. Mulching resulted in reductions in overall (specific) soil losses and runoff that were highly ($p < 0.001$) and marginally ($p = 0.05$) significant, respectively. Applying PAM, on the other hand, only produced a significant change in specific soil losses ($p < 0.01$) and this corresponded to an increase rather than a reduction.

The significant role of slope position was more obvious for the overall soil losses compared to the specific soil losses, especially for the control and PAM plots compared to the mulched plots (Fig. 3). From the base to the top of the slope, overall soil losses of the control and PAM plots decreased from 1800 to 1300 g $m^{-2}$, respectively, to roughly 400 g $m^{-2}$. Albeit not significant, a similar trend of decreasing values in the upslope direction was also observed for the runoff volumes of the control and PAM plots in particular. In contrast, the organic matter contents in the eroded sediments revealed a clear tendency toward an increase in the upslope direction.

### *3.2. Temporal patterns in rainfall, runoff and erosion*

During the study period from 1 September 2010 to 7 September 2011, rainfall was measured on a total of 34 occasions (Fig. 2). In three instances, rainfall exceeded 100 mm, twice during the autumn of 2010 (159 and 184 mm) and once during the winter of 2010/11 (138 mm). These highest rainfall totals coincided with the highest maximum rainfall intensities, with i30 values amounting to 31, 26, and 22 mm $h^{-1}$, respectively. The most extreme rainfall events in autumn 2010 produced the two principal peaks in runoff and soil losses in the control and PAM plots, but only in runoff in the mulched plots (Fig. 4).

The two-way repeated-measures ANOVAs of the 1- to 2-weekly runoff volumes and (specific) soil losses revealed significant effects for both factors – treatments and time-since-treatment – but also for their

**Table 3**
Two-way ANOVA of the effects of control (untreated), polyacrylamide (PAM), and mulch treatments and slope position on total runoff volumes, total and specific soil losses, and organic matter contents in eroded materials over the entire post-treatment period (4 October, 2010–7 September, 2011). Significant F-values and t-values – in the case of the specific contrasts between treated and untreated plots – are in bold ($p < 0.05$) or underlined and bold ($p < 0.01$). Abbreviation "DF num, den" are degrees of freedom for numerator and denominator.

| Source of variation | | DF num, den | Runoff | Soil losses | | Organic matter content (% w/w) |
|---|---|---|---|---|---|---|
| | | | Volume (mm) | Total ($g\ m^{-2}$) | Specific ($g\ m^{-2}\ mm^{-1}$) | |
| Between effects | Treatment | 2.6 | 2.72 | **46.33** | **186.33** | 1.96 |
| | Slope position | 1.6 | 2.70 | **8.89** | **5.53** | **8.17** |
| | Treatment × slope | 2.6 | 0.19 | 1.73 | 2.58 | 1.12 |
| Specific contrasts | Control vs. PAM | 6 | 0.67 | −0.80 | **−4.01** | 1.54 |
| | Control vs. mulch | 6 | 2.27 | **7.91** | **14.35** | −0.31 |

interaction (Table 4). Thus, the role of the treatments in overland flow generation and soil erosion was not unequivocal during the entire post-treatment period. Nonetheless, the specific contrasts of the mulched vs. control plots revealed significant differences in runoff as well as (specific) soil losses ($p < 0.01$). Furthermore, the interaction terms could be rendered insignificant by removing the readouts with the smallest rainfall amounts from the data set, while the individual factors continued to be significant. In the case of runoff, this could be achieved by eliminating the 11 readouts with less than 22 mm rainfall; in the case of (specific) soil losses, however, it required excluding all but 4 of the 28 readouts. The two-way repeated-measures ANOVA of the organic matter contents revealed a significant role of time-since-treatment but not of the treatments themselves. For all plots together, there was an overall decrease of 4% in the organic matter contents of the sediments eroded during the autumn of 2010 and those eroded during the summer of 2011. This decrease was most pronounced for the PAM plots (5.2%) and least pronounced for the control plots (2.6%).

For the individual readouts, LSDs between control and mulched plots were usually statistically significant, both in terms of runoff (23 readouts) and soil loss (27 readouts) (Fig. 4). In contrast, LSDs between control and PAM plots were only significant on one occasion for runoff and soil losses. Fig. 4 illustrates the importance of the interaction term between treatments and time-since-treatment for the soil losses. In the first two readouts after the wildfire, the PAM plots produced noticeably more erosion than the control plots, whereas the opposite was true in early spring 2011 (Fig. 4).

The reduction in average runoff and soil losses in the treated (PAM and mulching) vs. untreated plots was plotted (as percentage of the untreated plot values) against the weekly maximum rainfall intensities (i30; Fig. 5). The reduction in runoff decreased in a clear and similar manner with increasing i30 for both treatments, although mulching was consistently more effective than PAM at reducing runoff. The effectiveness of PAM in reducing soil loss also appeared to diminish with increasing i30, although variability between readouts was more pronounced than for runoff. In contrast, the effectiveness of mulching in decreasing soil losses was basically unaffected by i30.

### *3.3. Statistical modeling of the temporal runoff and erosion patterns*

The hydrological and erosion response of all 12 treated and untreated plots together could be explained by the 10 independent variables included in the forward selection procedure (Table 5: 70–80% of the total variance). This was clearly less valid for the organic matter contents in the eroded sediments (40% of the total variance being explained). In the case of the (log-transformed) runoff volumes, 66% of the variation could be explained by a single variable—rainfall amount. In the case of the (fourth-root-transformed) soil losses, on the other hand, 61% of the variation was explained by two factors of similar importance—maximum rainfall intensity (i30) and litter cover. Runoff, soil losses and organic matter contents were plotted against the principal explanatory variables (Fig. 6).

The multiple regression models explaining runoff were basically the same for each of the three treatments separately as well as for the 12 plots together, showing a consistent prevalence of the role of rainfall amount (Table 5). The treatment-specific models explaining soil losses were also similar for the three treatments. However, they differed markedly from the model for all 12 plots together, as litter cover was no longer a key explanatory variable. In a similar fashion, bare soil cover was no longer an important factor in explaining the organic matter contents in the individual treatments. The separate models explaining organic matter contents lacked a clear consistency, including the range of the explained variation from 27% in the case of the mulched plots to roughly twice as much (56%) in the case of the PAM plots.

The important role of litter cover in the erosion model for all 12 plots together reflected a conspicuous difference in the mulched vs. PAM and control plots. Even at the end of this study, in September 2011, this difference was, on average, about 65% (Fig. 7). Aside from litter cover, the concurrent stone, ash and bare soil covers differed significantly among the treatments (one-way ANOVA: $p < 0.01$), being, for obvious reasons, lower in the mulched vs. PAM and control plots.

## 4. Discussion

### *4.1. Post-fire erosion risk in recently burnt eucalyptus plantations*

The soil losses in the control plots plainly justified the application of emergency measures immediately after the wildfire. The roughly 8 Mg $ha^{-1}$ $yr^{-1}$ clearly exceeded the range of values compiled by Shakesby (2011) for recently burnt Mediterranean ecosystems (0.3–3 Mg $ha^{-1}$ $yr^{-1}$), as well as the threshold of 1 Mg $ha^{-1}$ $yr^{-1}$ for tolerable soil loss proposed by Verheijen et al. (2009). The present figures were also somewhat higher than those reported by Shakesby et al. (1996): 4.9 Mg $ha^{-1}$ $yr^{-1}$, and Prats et al. (2012): 5.4 Mg $ha^{-1}$ $yr^{-1}$, for recently burnt eucalyptus stands in north-central Portugal. An explanation for these latter differences could be a scaling effect (e.g., Boix-Fayos et al., 2007; Ferreira et al., 2008), since Shakesby et al. (1996) and Prats et al. (2012) employed much larger plots than those in the present study (16 vs. 0.25 $m^2$). However, recent studies (Cerdà et al., 2013; Garcia-Estringana et al., 2013) showed that the scaling effect would influence first and foremost the generation of overland flow, but not so clearly the soil erosion. Furthermore, the specific soil losses in the control plots of the present study (1.05 g $m^{-2}$ $mm^{-1}$ runoff) were lower than those in Prats et al. (2012) and especially Shakesby et al. (1996) (1.15 and 1.68 g $m^{-2}$ $mm^{-1}$ runoff, respectively). It is worth stressing that, aside from mineral soil, organic matter was also eroded in large quantities from the control plots, on average some 5 Mg $ha^{-1}$ $yr^{-1}$. The implications of these organic matter losses are not restricted to on-site soil fertility (e.g., Malvar et al., 2011; Shakesby, 2011), but extend to off-site impacts of ash-loaded runoff, which has been recently shown to induce eco-toxicological effects (Campos et al., 2012).

### *4.2. Effectiveness of mulching*

The present results on mulching's overall effectiveness agreed well with those of the two previous studies that tested the effectiveness of

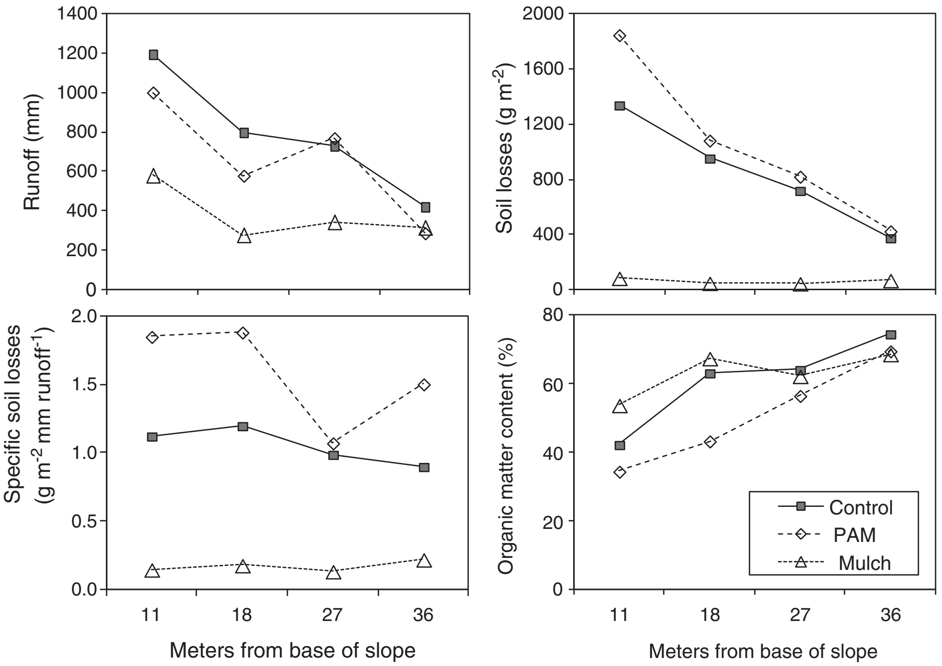

**Fig. 3.** Overall values of runoff, (specific) soil losses and organic matter content of the eroded sediments for the individual microplots over the entire post-treatment period (4 October 2010–7 September 2011).

forest residue mulching in recently burnt eucalyptus stands (Shakesby et al., 1996; Prats et al., 2012). All three studies found an overall reduction in soil losses on the order of 90% (Fig. 8: studies 1, 2 and 3). Moreover, the overall reduction in runoff was similar in this study (52%) and in Prats et al. (2012; 41%), whereas it was markedly lower in Shakesby et al. (1996; 3%). The slightly greater reduction in runoff found here compared to Prats et al. (2012) could be due to the slight difference in mulch-application rates (10–12 vs. 9 Mg ha$^{-1}$), possibly combined with the aforementioned scaling effect. The major difference in runoff reduction compared to Shakesby et al. (1996) is more difficult to explain, but could involve methodological aspects. The mulch in Shakesby et al. (1996) was applied at a much higher rate (46 Mg ha$^{-1}$) but was composed of eucalyptus residues that came directly from logging, i.e. they were not chopped like the residues applied in this study and by Prats et al. (2012). As a result, the mulch in Shakesby et al. (1996) might have acted principally as a low-vegetation cover rather than as a litter layer, intercepting rainfall but not slowing down overland flow or enhancing its (re-)infiltration.

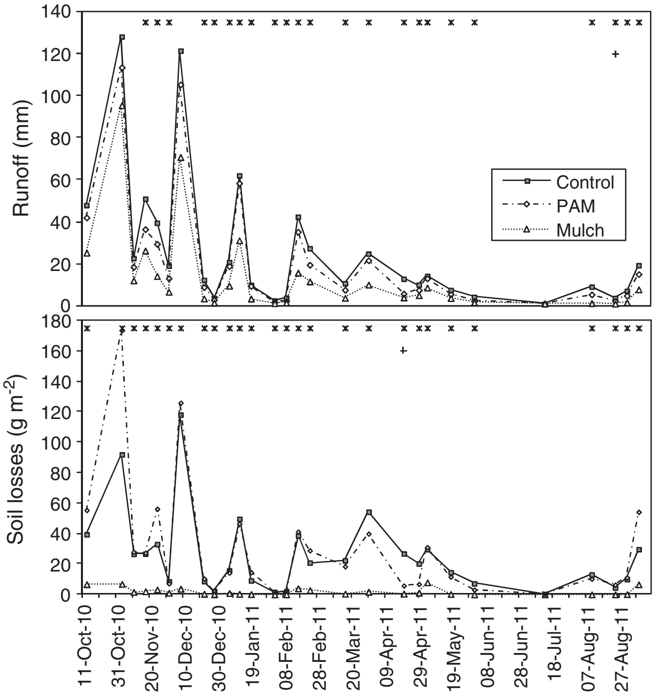

**Fig. 4.** Temporal patterns in average runoff and soil loss values for the three treatments (control, PAM and mulch) during the post-treatment period (4 October 2010–7 September 2011). Significant LSD's ($p < 0.05$) between the control plots and the mulched and PAM plots for the individual readouts are marked with an asterisk (*) and a cross (+), respectively.

Mulching with forest residue, as described in this study, seems to constitute a more effective post-fire treatment than mulching with wood chips (e.g., Kim et al., 2008; Riechers et al., 2008; Fernández et al., 2011; Fig. 8: studies 4, 5 and 6). A key factor was probably the greater size of the fibers, promoting adherence to the soil surface. Riechers et al. (2008) found that an initial 80% cover of wood chips is drastically reduced as the chips float off under sufficient overland flow.

The temporal patterns of mulching effectiveness throughout this study also fit well with other studies with comparable data sets (Bautista et al., 1996; Badía and Martí, 2000; Prats et al., 2012). The differences in mulch type (straw or forest residue) and experimental design (especially monitoring intervals) notwithstanding, these three prior studies and the present one agreed in that: (i) mulch effectiveness was not unequivocal due to a significant interaction between treatment and time-since-treatment; (ii) mulch effectiveness was more often significant for large and intense compared to small and weak rainfall events; (iii) mulch effectiveness was greater in terms of reducing soil erosion compared to overland flow; (iv) soil erosion produced by mulched plots was less easily explained than soil erosion produced by untreated, control plots. Furthermore, in the case of the present study, the short monitoring intervals (1 to 2 weeks) highlighted the fact that runoff reduction by mulching is dependent on rainfall characteristics (intensity and amount), whereas soil erosion reduction was basically constant throughout the post-treatment period. The two last readouts with elevated maximum rainfall intensities (~20 mm h$^{-1}$) suggested a decrease in the mulch's effectiveness in reducing soil losses, which could be due to decomposition of the chopped bark mulch. Even so,

**Table 4**
Two-way repeated-measures ANOVA of the effects of treatment and time-since-treatment on the 1- to 2-weekly values of runoff, (specific) soil losses and organic matter contents during the post-treatment period (4 October 2010–7 September 2011: 28 readouts). Significant F-values and t-values – in the case of the specific contrasts between treated and untreated plots – are in bold ($p < 0.05$) or underlined and bold ($p < 0.01$). Abbreviation "DF num, den" are degrees of freedom for numerator and denominator.

| Source of variation | | DF num, den | Runoff (mm) | Soil losses | | Organic matter content (% w/w) |
|---|---|---|---|---|---|---|
| | | | | ($g\ m^{-2}$) | ($g\ m^{-2}\ mm^{-1}$) | |
| Within effects | Treatment | 2.9 | **15.45** | **73.40** | **68.52** | 3.96 |
| | Time | 27,243 | **209.52** | **38.07** | **6.57** | **2.82** |
| | Treatment × time | 54,243 | **2.98** | **2.79** | **2.37** | 1.27 |
| Specific contrasts | Control vs. PAM | 9 | 1.77 | −0.9 | −2.03 | 2.2 |
| | Control vs. mulch | 9 | **5.45** | **10.45** | **8.97** | −0.41 |

the mulch cover was found to decrease in a roughly linear fashion, by some 2% per month. These results are in close agreement with the value reported by Prats et al. (2012) for eucalyptus residue mulch, but markedly lower than the 4–5% found by Badía and Martí (2000) and Fernández et al. (2011) for straw mulch. This indicates a clear advantage of applying forest residue vs. straw mulch, especially when the window of disturbance is prolonged due to slow recovery of the spontaneous vegetation.

### 4.3. Effectiveness of PAM

As mentioned above, only a few field trials have assessed the effectiveness of PAM in reducing post-fire erosion, giving contradictory results. Comparisons are difficult, mainly due to the differences in PAM type and experimental design in each study (Fig. 8: studies 7 to 12). The greatest reduction was reported by Rough (2007; 80%), but this involved applying PAM mixed into an amended slurry. Riechers et al. (2008) found a 50% reduction in post-fire erosion, but they only measured the first few rainstorms after the fire. The authors applied PAM attached to dry pellets of compressed straw, so that the effect of PAM could not be separated from the effect of the 80–90% ground cover provided by the pellets. Similarly, Davidson et al. (2009) reported a 40% reduction in post-fire erosion by applying PAM attached to compressed paper pellets for a ground cover of 50%. Of the prior studies that also applied PAM in dry granular format, Inbar (2011) found 23% and 50% reductions in post-fire erosion at application rates of 25 and 55 kg ha$^{-1}$, respectively. However, whereas Inbar (2011) used the exact same type of PAM as we did, they removed the ashes before applying it, differing from all of the other studies referred to here. Rough (2007) and Wohlgemuth and Robichaud (2007) reported that applying 5.6 kg ha$^{-1}$ of dry granular PAM does not reduce post-fire soil erosion.

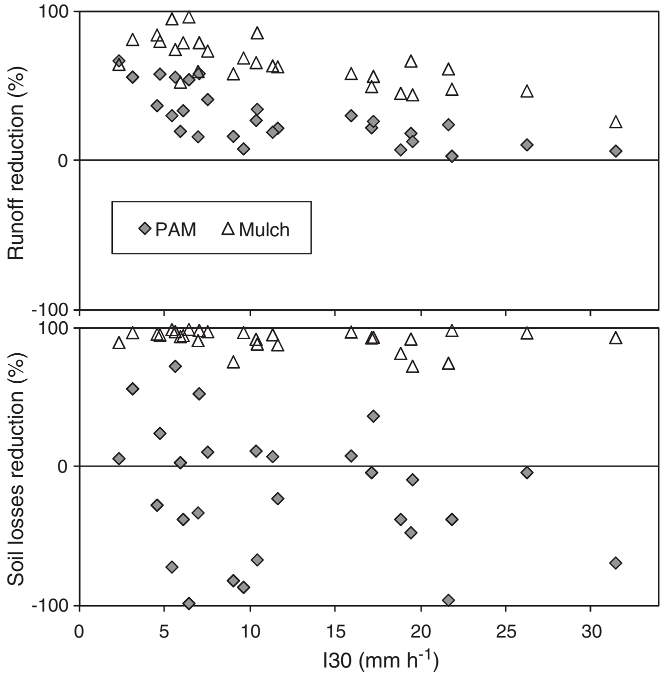

**Fig. 5.** Average reduction in runoff and soil losses at the mulched and PAM plots in relation to maximum rainfall intensity in 30 min (i30; mm h$^{-1}$) for the 28 individual readouts with >6 mm of rainfall during the first year after wildfire.

The above-mentioned divergent findings on the effectiveness of PAM in reducing post-fire runoff and erosion could be the result of a number of factors, such as not only type of PAM, its application rate and method, but also soil type and texture. PAM is widely held to be most suitable for soils with high clay contents, high cation exchange capacities and divalent, exchangeable cations (Ben-Hur, 2001, 2006; Sojka et al., 2007). Nevertheless, selection of the most suitable PAM formulation for a specific soil is rather complex, since the many PAM formulations have distinct properties due to differences in molecular weight, charge type and charge density. Moreover, the selection of optimal application rate and method is not straightforward either, as clearly demonstrated by Theng (1982), McLaughlin and Brown (2007) and Inbar (2011). At present, the best option for applying PAM in recently burnt areas would appear to be in combination with paper/straw pellets; nevertheless, the added value of adding PAM to the pellets remains questionable, including in economic terms.

The mechanisms by which PAMs reduce post-fire soil erosion are not completely understood, but some aspects have become clear. The present results suggest that poor effectiveness of PAM in recently burnt areas could involve a combined effect of ashes and soil water repellency. PAM might preferentially bind the ashes instead of the soil (Rough, 2007), and both materials might then be removed after the first rainfall events by the repellency-enhanced overland flow (Wallace and Wallace, 1986). The study site exhibited strong to extreme soil water repellency during the initial post-fire period, as is common in recently burnt eucalyptus stands in north-central Portugal (Keizer et al., 2008; Malvar et al., 2011; Prats et al., 2012). A substantial reduction in the ash cover was also observed during the three first rainfall events after the PAM application.

### 4.4. Key factors in post-fire erosion with and without emergency treatments

In this study, litter cover – mainly composed of mulch – was slightly more important than rainfall total or intensity in explaining the differences in soil loss among the 12 plots. A crucial role for protective soil cover in post-fire erosion was also found by Pietraszek (2006), analyzing the evolution of the spontaneous ground cover in a large data set comprising 10 different wildfires of varying ages (0–10 post-fire years). In Pietraszek's (2006) case, bare soil cover explained more than 50% of the variation in erosion rates. As in this study, other multiple linear regression models have been carried out in the north-central Iberian Peninsula, with post-fire mulched and control (Prats et al., 2012), prescribed burnt and unburnt (Vega et al., 2005), and agriculture plowed and vegetated field (Nunes et al., 2011) plots. As in the present study, rainfall intensity was identified as the key factor for soil erosion. This was especially true for the "bare" plots in their experimental designs. For the "cover-protected" plot data sets (mulched, unburnt or

**Table 5**
Stepwise multiple linear regression models of the 1-to 2-weekly values of runoff, soil losses and organic matter contents of eroded sediments during the post-treatment period (4 October 2010–7 September 2011), for the three treatments together as well as separately. The full names of the variables are given in Section 2.4.

| | All plots (n = 12) | | | Control plots (n = 4) | | | PAM plots (n = 4) | | | Mulched plots (n = 4) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Param. estimate | Variable name | Partial $r^2$ | Param. estimate | Variable name | Partial $r^2$ | Param. estimate | Variable name | Partial $r^2$ | Param. estimate | Variable name | Partial $r^2$ |
| *Runoff (mm)* | | | | | | | | | | | | |
| Intercept | −0.01 | | | 0.93 | | | 0.53 | | | 0.03 | | |
| 1st var | 0.01 | Rain | 0.66 | 0.01 | Rain | 0.68 | 0.01 | Rain | 0.70 | 0.01 | Rain | 0.76 |
| 2nd var | 0.01 | Stones | 0.07 | −0.01 | Position | 0.07 | 0.02 | Litter | 0.05 | 0.02 | i30 | 0.04 |
| 3rd var | 0.02 | i30 | 0.02 | 0.02 | i30 | 0.02 | 0.02 | i30 | 0.02 | −0.02 | Veg | 0.03 |
| 4th var | 0.00 | Depth | 0.01 | | | | −0.01 | Position | 0.02 | 0.06 | Stones | 0.02 |
| Total $r^2$ | | | 0.77 | | | 0.77 | | | 0.79 | | | 0.85 |
| *Soil losses (g m$^{-2}$)* | | | | | | | | | | | | |
| Intercept | 1.75 | | | 1.76 | | | 1.93 | | | 0.47 | | |
| 1st var | −0.01 | Litter | 0.32 | 0.04 | i30 | 0.45 | 0.05 | i30 | 0.46 | 0.04 | i30 | 0.44 |
| 2nd var | 0.04 | i30 | 0.29 | −0.02 | Position | 0.08 | −0.03 | Position | 0.14 | −0.03 | Veg | 0.04 |
| 3rd var | −0.03 | Position | 0.04 | 0.01 | Rain | 0.06 | 0.01 | Rain | 0.06 | | | |
| 4th var | 0.00 | Rain | 0.03 | | | | | | | | | |
| 5th var | −0.03 | Veg | 0.01 | | | | | | | | | |
| Total $r^2$ | | | 0.70 | | | 0.59 | | | 0.66 | | | 0.48 |
| *Organic matter content (% of sediments)* | | | | | | | | | | | | |
| Intercept | 47.8 | | | 64.3 | | | 18.3 | | | 82.9 | | |
| 1st var | −0.54 | Bare | 0.30 | −1.55 | Depth | 0.40 | 1.40 | Position | 0.56 | −1.76 | Stones | 0.18 |
| 2nd var | 0.67 | Position | 0.11 | | | | | | | −0.28 | Depth | 0.04 |
| 3rd var | | | | | | | | | | −3.53 | Bare | 0.04 |
| Total $r^2$ | | | 0.41 | | | 0.40 | | | 0.56 | | | 0.27 |

vegetated), the soil erosion models tended to be weaker, with restricted dependency on rainfall intensity and a smaller number of contributing variables. Those findings can be attributed to the buffer effect exerted by an organic cover relative to bare soil. Aside from the provision of higher rainfall interception, Smets et al. (2008) reported that mulching reduces the amount of runoff due to higher storage capacity and soil moisture content, and reduces soil erosion due to both decreased splash erosion and an increased resistance to flow.

Rainfall did not have a significant effect on the organic matter contents of the eroded materials, either in the entire data set or for any of the three treatments alone. In contrast, protective soil cover (or, rather, the lack of it) was a key explanatory variable but only when analyzing all plots together. At the same time, however, time-since-treatment had a significant effect on organic matter contents, whereas treatment did not. These rather complex results probably reflect an increase in bare soil cover in the control and PAM plots combined with an overall

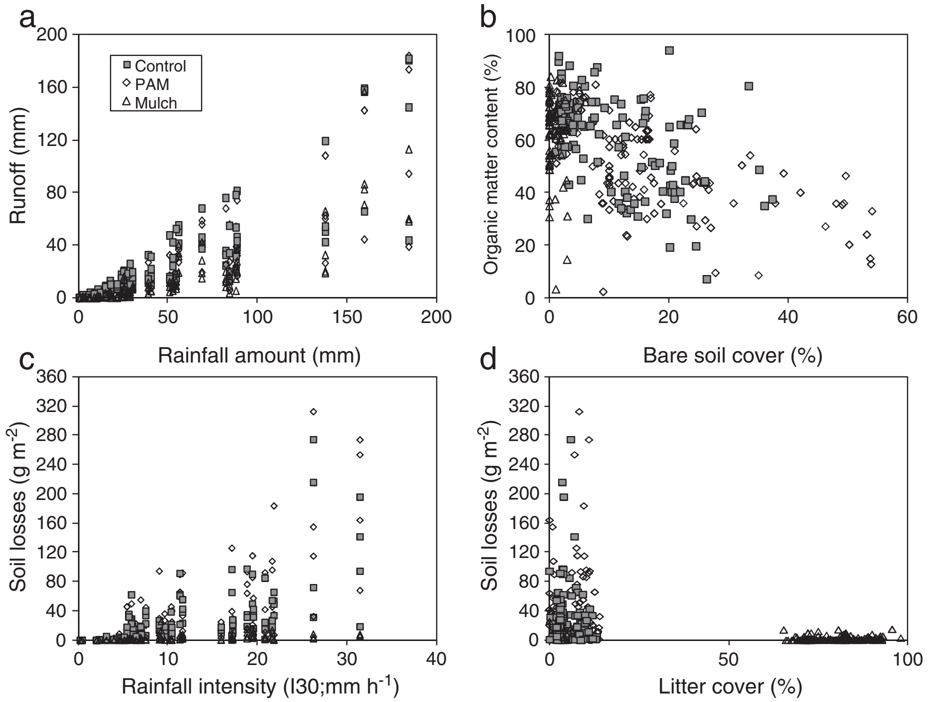

**Fig. 6.** Relationships of runoff and organic matter content of the eroded sediments (top figures) and soil losses (bottom figures) with the principal explanatory variables of the global multiple regression models (see Table 5) for each one of the plots during the first year after wildfire.

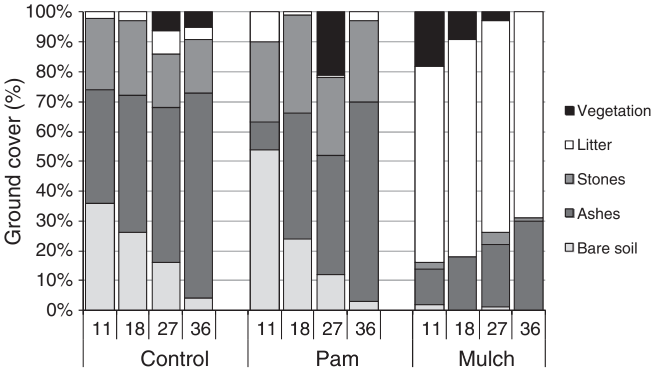

**Fig. 7.** Ground cover percent of the five cover categories at the individual microplots organized by treatment and slope position (in m from the base) in September 2011, one year after wildfire.

minor decrease in organic matter content from 56 to 53%. A similar decrease in organic matter content was observed by Thomas et al. (1999), although this was during the second year after a wildfire. Overall, post-fire organic matter losses have been poorly studied but the few existing data clearly point to their importance and consequently, the urgent need for further studies into the transport of ashes as the principal source of such high organic matter contents, well above that in the topsoil.

The observed spatial pattern of decreasing runoff and erosion in the upslope direction was unexpected, especially since soil depth did tend to decrease in this direction as well. Moreover, the other soil properties measured in this study offered no plausible explanations, as they revealed no obvious spatial patterns. An exception was the cover of gray-white ash, even though it differed only little across the slope (from 0 to 8%). The role of gray-white ash was probably indirect, reflecting differences in soil burn severity and the associated changes in soil properties (e.g. Shakesby and Doerr, 2006; Varela et al., 2010). The hydrological response at the base of the slope – even seen in the mulched plots – was due to higher fire severity, as suggested by the presence of white ash. Bodí et al. (2011a) also found that soils covered with white ash produce a stronger hydrological and erosive response than those covered with black ash. Another possible explanation for the role of gray-white ash is related to its apparently greater susceptibility to being blown away by the wind, giving rise to bare spots. Various studies, such as Leighton-Boyce et al. (2007), Woods and Balfour (2010) and Bodí et al. (2011b) have shown that the presence of ash can decrease the generation of overland flow.

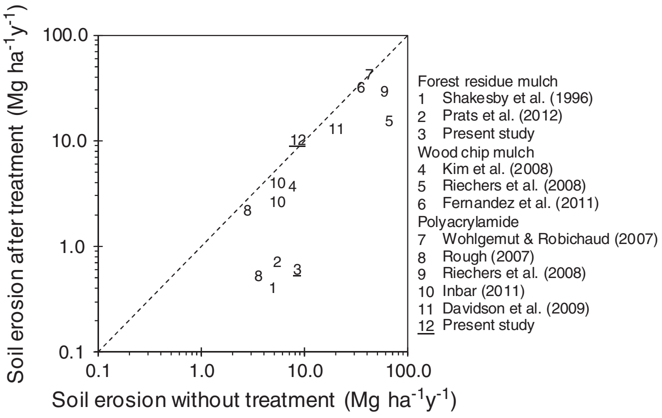

**Fig. 8.** Annual post-fire soil erosion rates on this and other studies assessing the effectiveness of emergency treatments such as forest residue mulch (1 to 3), wood chip mulch (4 to 6) and PAM (7 to 12).

## 5. Conclusions

The main conclusions of the present study on the short-term effectiveness of chopped bark mulch and dry anionic PAM during the first year after a wildfire in a eucalyptus plantation in north-central Portugal were the following:

- a litter cover of 80% provided by the chopped eucalyptus bark was highly effective in reducing runoff and especially soil losses throughout the first post-fire year. These results warrant follow-up studies with longer temporal and spatial scales, as well as with different application rates;
- PAM application did not result in a significant reduction of either runoff or soil losses, except for a very few isolated rainfall events. However, its potential advantages do warrant further research, especially in combination with mulching;
- soil losses from the untreated plots during the first year after the wildfire were comparatively high, both for the study region and for the Mediterranean Basin;
- post-fire runoff and soil losses could be well explained by rainfall- and cover-related variables, opening perspectives for the prediction of treatment effectiveness with a temporal resolution compatible with weather predictions;
- post-fire overland flow generation on a microplot scale depended first and foremost on rainfall amount, whereas the associated interrill soil losses were best related to maximum rainfall intensity.

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