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Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal

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ABSTRACT

Fire-enhanced runoff generation and erosion are an important concern in recently burnt areas worldwide but their mitigation has received little public and scientific attention in Portugal. The present study addressed this knowledge gap for the two principal fire-prone forest types in Portugal, testing the effectiveness of a type of mulch that is widely available in the study region but has been little utilized and poorly studied so far. For logistic reasons, two somewhat different forest residue mulches were tested in a eucalypt plantation (eucalypt chopped bark) and a nearby Maritime Pine stand (eucalypt logging slash). Arguably, however, more important differences between the two study sites were those in fire severity, resulting in an elevated litter cover prior to mulching at the pine site but not at the eucalypt site, and in experimental design, with eight bounded erosion plots of 16 m^2 installed at the eucalypt site as opposed to only four at the pine site (due to its limited size). Mulching was applied four months after the wildfire and two months after installation of the plots. Rainfall, runoff and sediment and organic matter losses were measured on a 1- to 2-weekly basis. Mulching proved highly effective at the eucalypt site, on average reducing the runoff coefficient from 26 to 15% and sediment losses from 5.41 to 0.74 Mg ha^{-1}. This mulching effect was also statistically significant, albeit only for the more important runoff and erosion events, and corresponded to a significant role of litter cover in explaining the variation in runoff and erosion. At the pine site, by contrast, mulching had no obvious effect. In all probability, this was first and foremost due to the comparatively small amounts of runoff and sediments produced by the untreated pine plots (5% and 0.32 Mg ha^{-1}) and, as such, due to the extensive needle cast following a low severity fire.

1. Introduction

Wildfires are a common phenomenon in present-day Portugal, having affected on average 110,000 ha of rural lands per year between 1980 and 2010 (AFN, 2011). This can be attributed, besides climate conditions, to a combination of socio-economic factors, in particular the large-scale replacement of native Portuguese forest by commercial plantations of fire-prone tree species such as pine and eucalypt and the decline in traditional practices like grazing and coppicing that reduced the accumulation of flammable materials (Pereira et al., 2006a; Radich and Alves, 2000; Shakesby et al., 1996). The frequency of forest fires in Portugal is also not expected to diminish substantially in the next decades, in part due to an increase in meteorological conditions propitious to wildfires (Pereira et al., 2006a,b).

Wildfires are well documented to increase runoff generation and soil erosion, as mentioned in various studies in Portugal (e.g. Coelho et al., 2004; Ferreira et al., 2008; Malvar et al., 2011; Shakesby et al., 1996). Apart from heating-induced changes in soil properties such as soil water repellency and aggregate stability (Shakesby and Doerr, 2006; Varela et al., 2010), removal of the protective vegetation and litter cover is a key factor in fire-enhanced runoff and sediment losses (Shakesby, 2011). For this precise reason, a commonly applied emergency treatment for reducing post-fire erosion risk, such as mulching, is based on the principle of applying materials that provide an effective ground cover (Cerdà and Doerr, 2008; Robichaud et al., 2000). In Portugal, however, mulching or other types of emergency treatments have rarely been employed in land management of recently burnt areas, although this is changing due to the implementation of PRODER-funded measures (under sub-Action 2.3.2.1) in selected areas that were affected by wildfires during the summer of 2010.

In Portugal, post-fire emergency treatments have also received little research attention. Prior to the present work, the only field study into the effectiveness of post-fire soil conservation measures was that

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reported by Shakesby et al. (1996) and Walsh et al. (1994). Similar to this study, mulch composed of forest residues from logging was applied in a eucalypt and a pine plantation. However, mulching was done two to three years after the wildfire rather than within the first few months—as was the case in this study—when soil erosion risk is supposedly at its maximum (Shakesby and Doerr, 2006).

Outside Portugal, the effectiveness specially of straw mulches has been exhaustively studied under field conditions (e.g. Badía and Martí, 2000; Bautista et al., 1996; Fernández et al., 2011; Groen and Woods, 2008; Riechers et al., 2008; Rough, 2007; Wagenbrenner et al., 2006). This is particularly true in comparison with mulches from woody plant material and, more specifically, wood chips (Fernández et al., 2011; Kim et al., 2008; Riechers et al., 2008). Often-cited advantages of straw, besides its elevated effectiveness in reducing soil erosion, are its wide availability, low costs and low specific weight. Whilst the availability of straw may be limited in many parts of the world (Foltz and Wagenbrenner, 2010), including Portugal, the low specific weight can become a disadvantage in areas with strong winds, especially during the period between straw application and the first rainfall events (Robichaud et al., 2000). In recent years, forest residues have become increasingly harvested in Portugal for use in biomass energy plants and, as such, can be a viable alternative to straw, in spite of the logistic implications of its higher specific weights. Nonetheless, the effectiveness of woody mulches under field conditions remains unclear. Namely, Shakesby et al. (1996) found their forest residue mulch to be ineffective at one of the two study sites, whilst Fernández et al. (2011) and Riechers et al. (2008) reported wood chip mulch to be less effective than straw mulches. Evidence from rainfall simulation experiments suggested that the shape of the woody materials could be of critical importance, with wood shreds and strands rather than wood chips being as effective as straw (Foltz and Dooley, 2003; Yanosek et al., 2006).

The present study had as it main aim to contribute to a better knowledge and understanding of hydrological and erosion processes following wildfire and, in particular, how they are influenced by mulching. More specifically, the following research gaps were addressed: (i) short- to medium-term post-fire conditions, i.e. the first 1.5 years of the fire-induced window-of-disturbance; (ii) high-resolution temporal patterns (approximately weekly) in post-fire runoff and erosion as well as in key explanatory variables, including soil water repellency (for its supposed role in eucalypt stands, especially after Leighton-Boyce et al., 2007; Malvar et al., 2011; Sheridan et al., 2007); (iii) effectiveness of forest residue mulching in the two principal fire-prone forest types in Portugal, i.e. eucalypt and maritime pine plantations.

2. Materials and methods

2.1. Study area and sites

The study area was located in north-central Portugal, in the locality of Pessegueiro do Vouga, municipality of Sever do Vouga (40° 43′ 05″N; 8° 21′15″W; 100 m.a.s.l. of elevation). On 10 August 2007, a wildfire destroyed a relatively small area (approximately 10 ha). The burnt area was predominantly covered by plantations of eucalypt (*Eucalyptus globulus* Labill.) but included a few, comparatively small stands of maritime pine (*Pinus pinaster* Ait.). Although this situation allowed the study of the two predominant fire-prone forest types in Portugal, the limited number and size of the available pine stands implied compromises in terms of site selection as well as experimental design (see Section 2.2). The eucalypt study site was selected for its steep slope and comparatively higher fire severity, as indicated by the total consumption of the canopies. The pine site was chosen for its closeness, comparative slope and exposition to the eucalypt site, although it presented a markedly lower fire severity, with the canopies only partially consumed by the fire (Table 1).

Table 1
General description of the two study sites and of the experimental design. Values followed by different letters are statistically different ($p<0.05$, pair-wise t-test).

Site	Eucalypt	Pine
General characteristics		
Tree	*Eucalyptus globulus* Labill.	*Pinus pinaster* Aiton.
Age and plantation cycle	15; 3rd re-growth	30
Slope angle (°)—average ± sd	25° ± 3.6	24° ± 3.6
Fire severity indicators (Aug. 2007)	Moderate	Low
Ash color	Black, grey	Black
Tree canopy consumption	Total	Partial
Tree scorch height (m)	9	7
Mean litter cover (%)	<10	60
Soil characteristics (0–15 cm)	n = 9	n = 9
Stoniness (%)	54.4 ± 9.3^a	64.7 ± 4.4^b
Sand fraction (%)	39.8 ± 8.3^a	31.6 ± 3.7^b
Silt and clay fraction (%)	5.9 ± 1.3^a	3.6 ± 1.6^b
Soil organic matter (%)	12.2 ± 2.9^a	9.9 ± 2.7^b
Experimental design		
Number of control/treated plots	4/4	2/2
Projected plot surface (m^2)—average ± sd	15.8 ± 1.0	14.3 ± 0.7
Mulching type	Eucalypt chopped bark	Eucalypt logging slash
Application rate (kg m^{-2})	0.87	1.75
Increase in ground cover by mulch (%)	67	76

The climate can be classified as humid meso-thermal with a moderate but extended dry summer (Köppen: Csb; DRA-Centro, 1998). Mean annual temperature at the nearest climate station (Castelo-Burgães: 40° 51′10″N, 8° 22′44″W, 306 m.a.s.l., 1977–2009) is 14.8 °C, while mean monthly temperatures range from 8.9 °C in January to 21 °C in July (SNIRH, 2011). Annual rainfall at the nearest rainfall station (Bouça-Pessegueiro do Vouga: 40° 41′36″N , 8° 22′24″W; 152 m.a.s.l., 1977–2005) is 1546 mm on average but varies strongly from 843 mm in dry years to 2151 mm in wet years (DRA-Centro, 1998).

The soils at both study sites were shallow, 25–30 cm deep Umbric Leptosols (FAO, 1988) developed over Pre-Cambrian schist from the Hespheric Massif (Pereira and FitzPatrick, 1995), as verified by digging out two soil profiles at each site. From the upper 15 cm of these profiles, a total of nine samples were collected in February 2008 and later analysed, using standard laboratory methods (mechanical sieving and loss-on-ignition), to determine the fractions of stones, sand, silt and clay, and organic matter. The topsoil at both study sites was very coarse, with a stone content of over 50% and a sandy texture (Table 1). The between-site differences in the soil fractions were minor but nonetheless statistically significant ($p<0.05$, pair-wise *t*-test).

2.2. Experimental design, field and laboratory measurements

Because of the small size of the maritime pine stands in the burnt area, it was impossible to implement exactly the same experimental design at both study sites. While the eucalypt site was instrumented with eight erosion plots of 2 m wide by 8 m long, only four could be installed at the pine site. The installation of all the plots was completed by 02 October 2007 but the treatment with mulch was not carried out until 10 December 2007. Mulch was applied manually to half of the plots at each site, which were selected randomly. For logistic reasons, somewhat different forest logging residues were used at the two sites (Table 1). For the treatment of the eucalypt plots, chopped bark mulch was obtained at a depot 20 km from the study area, where eucalypt logs are debarked before their transport to a paper pulp factory and the bark is chopped into 10–15 cm wide 2–5 cm long fibers before their transport to a biomass energy plant. On the pine site, in line with Shakesby et al. (1996), the mulch consisted of logging slash residues collected from the soil after clearcutting of an adjacent

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unburned eucalypt stand (300 m distance from the pine site). Due to the differences in material, a higher application rate of the mulch was needed at the pine treated plots to achieve a ground cover comparable to the eucalypt treated plots (i.e. 70–80%, Table 1).

The erosion plots were delimited using metal sheets of 60 cm long by 15 cm high that were inserted into the soil to a depth of 5 to 10 cm. All the plots had a rhomboid shape, with a trench dug at the upper limit to avoid run-on into the plots. Following the design of Shakesby et al. (1991), a modified gerlach trap (Gerlach, 1967) was installed at the base of each plot to intercept the runoff and retain the coarser material using a net with a mesh width of 0.5 mm. The runoff was routed to a tipping-bucket device using a garden hose, and then to a set of three interconnected 70-liter tanks. The main purpose of the tipping-bucket devices was to verify and correct the runoff measurements. From October 2007 onwards, on a weekly basis, runoff was measured and 1500 ml samples were gathered from all individual tanks. Also the sediments accumulated in the gerlach traps were collected. The runoff and sediment samples were subsequently analyzed using standard laboratory procedures (APHA, 1998) to determine sediment and organic matter loads.

During each field trip, rainfall at the two study sites was measured using two automatic rainfall gauges (sensitivity 0.1 and 0.2 mm) in combination with seven totalizer rain gauges for validation purposes.

The moisture content of the topsoil was monitored in two distinct manners. Within the plots, soil moisture was measured with a non-destructive method, using pultrusion tubes inserted into the soil in which a TDR-type Delta-T® PR2-probe is lowered to carry out readings at different depths (including at 0–10 cm, analyzed in this study). Between 22 October and 20 November 2007, one pultrusion tube was installed in each of the twelve plots, and readings were carried out during 37 fieldtrips. Unfortunately, the two tubes of the pine control plots, one in a eucalypt control and one in a eucalypt treated plot malfunctioned most of the time, so the data were not included here. Destructive measurements of soil moisture content were taken outside the plots, in a slope section that was specifically reserved for that purpose and considered representative of the control conditions. In these slope sections, a 20-m long transect comprising three equidistant points was laid out at shifting positions on a total of 31 sampling occasions between October 2007 and December 2008. At each transect point, soil moisture was then measured three times at two depths (0–5 and 5–10 cm), using a Delta-T® ML2-sensor. For technical but especially logistic reasons, destructive moisture readings were not possible on 7 dates in the case of the pine site.

Besides soil moisture, soil water repellency was measured along the above-mentioned transects on each possible sampling occasion following the 'Molarity Ethanol Drop test' (Doerr, 1998). In each transect point, three replicate measurements at four different sampling layers were carried out (soil surface and 0–5, 5–10 and 10–15 cm soil depth). Each measurement involved applying three droplets of increasing ethanol concentration to fresh parts of the soil until infiltration of at least two of three droplets of the same concentration within 5 s. Like in Keizer et al. (2005, 2008), the following nine volumetric ethanol percentage concentrations and, in between brackets, corresponding ethanol classes were used: 0 (0), 1 (1), 3 (2), 5 (3), 8.5 (4), 13 (5), 18 (6), 24 (7), 36 (8). In this study, the overall frequency of the two highest ethanol classes measured in all the depths was analyzed as a combined indicator of repellency severity and homogeneity.

The ground cover within the 12 erosion plots was measured eight times at regular intervals between 31 October 2007 and 2 June 2008, and again at the end of the study period. A grid of 1 × 1 m divided in rows and columns of 10 cm wide was placed at three fixed positions in the lower, middle and upper parts of each plot. At the 100 intersection points between rows and columns, the ground cover was recorded in the field according to the following four categories: "stones" (rock outcrop and stones bigger than 2 mm); "bare soil" (which included ashes and charcoal); "litter" (including the applied mulch) and vegetation.

2.3. Data analysis

The effect of mulching in overland flow and sediment losses was tested by means of a two-way repeated measures analysis of variance (Ott and Longnecker, 2001). The number of days since wildfire and the read-out dates were used as periods of repeated measurements for runoff amount, runoff coefficient, sediment losses and organic matter losses. The underlying assumptions of normality and homoscedacity were verified, and both the runoff and erosion values had to be transformed, by taking the square and fourth roots, respectively, for the Kolmorogonov–Smirnov test not to reject normality at $\alpha = 0.05$. In addition, the three smallest rainfall events (<3.6 mm) had to be excluded for the transformed data to meet the normality assumption.

Multiple regression models were constructed to determine how well the observed runoff and erosion could be explained by selected independent variables. This was done using a stepwise forward selection procedure, i.e. the REG procedure (Littell et al., 1996), in which the independent variables were selected in order of their significant contribution ($p < 0.05$) to the explained variance. As in the repeated measures ANOVA, the square and fourth roots, for runoff amount and sediment losses were used, since model residuals met the normality assumption without exception. Due to missing data, various data sets comprising different combinations of read-outs and sets of independent variables were analysed. The complete data set involved 32 read-outs and six independent variables, i.e. rainfall amount and intensity, and the above-mentioned four ground cover classes. The "limited" data set involved 5 fewer read-outs but one more independent variable (i.e. soil moisture as measured with the PR-probe); whilst the "partial" data set involved 12 fewer read-outs but two more independent variables (i.e. soil moisture as measured with the ML2-sensor and frequency of extreme repellency).

3. Results

3.1. Overall rainfall, runoff and erosion values

In terms of total rainfall, the treatment period agreed well with average climate conditions. Between 10 December 2007 and 23 December 2008 1546 mm of rainfall were registered in the study area, exactly the same as the above-mentioned, long-term mean annual rainfall at the nearby Bouça station. Rainfall was much less during the pre-treatment period (138 mm) and even insignificant between the occurrence of the wildfire on 10 August 2007 and the completion of the plot installation on 02 October 2007 (approximately 10 mm, Fig. 1).

Prior to mulching, the control and the to-be-treated plots at the eucalypt site produced, on average, basically the same runoff amounts as well as sediment and organic matter losses (Table 2). At the pine site, by contrast, the control plots generated, on average, 40% less runoff and 55–60% less sediment and organic matter than the to-be-treated plots. As for between-site comparability, the to-be-treated pine plots differed little from the eucalypt plots in average runoff amounts (5–10% less) but noticeably more in average sediment losses (34–40% less).

Following mulching, the control and treated plots at the eucalypt site revealed marked differences in runoff and especially erosion, with the treated plots producing 43% and even 86% lower amounts of overland flow and sediment losses, respectively (Table 2). In the case of the pine site, on the other hand, the average differences between the control and treated plots were almost inexistent, but still

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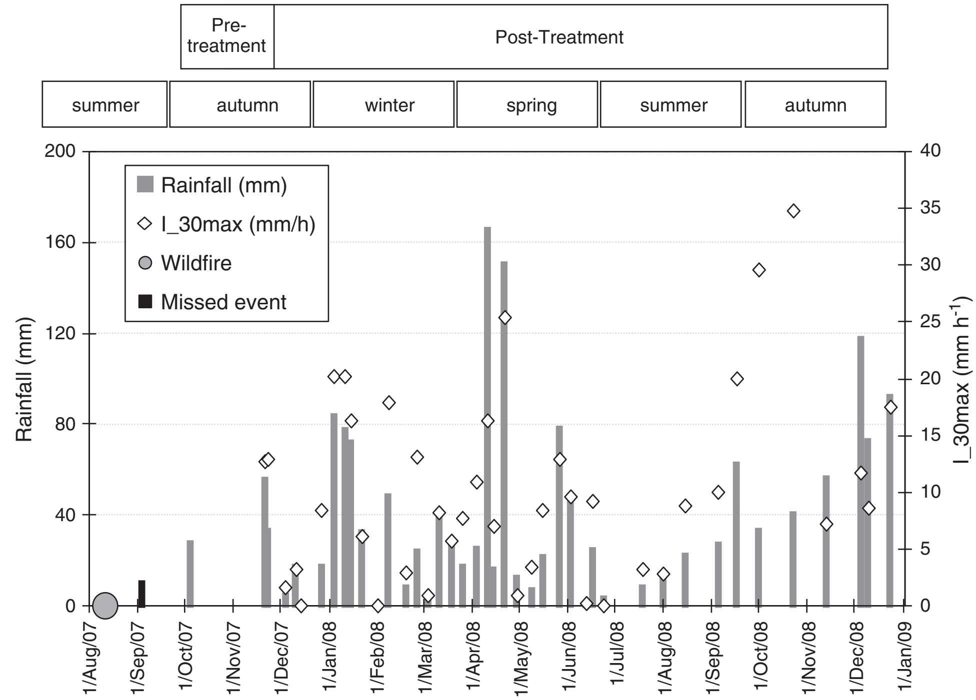

Fig. 1. Rainfall total and intensity of the individual measurements periods during the first 16 months after the wildfire in August 2007.

the control plots produced less runoff and sediments (10% and 16%, respectively) than the treated ones. Even so, the runoff ratios of post- to pre-treatment phases suggested that mulching was effective at the pine site as well. Namely, because those ratios were noticeably higher in the case of the control plots than of the treated plots, for runoff (4.1 vs. 2.6) and also for sediment losses (5.8 vs. 2.8). Similarly, the differences that existed between the control plots at the two study sites during the pre-treatment period were markedly amplified during the subsequent study period. Compared to the concurrent values at the eucalypt site, overland flow generation at the pine control plots dropped, on average, from 55% to 20%, and sediment and organic matter losses from roughly 30% to just over 5%.

3.2. Temporal patterns in rainfall, runoff and erosion

Despite the fact that the control and treated plots at the eucalypt site differed strongly in their overall runoff and erosion figures, the repeated measures ANOVAs did not reveal an unequivocal role of the mulching with chopped eucalypt bark. This was due to the presence of significant interactions between treatment and time-since-fire effects ($p<0.05$). The runoff coefficient constituted an exception ($p=0.3$), varying significantly with both factors individually ($p<0.05$). In the case of the absolute runoff response, the significant interaction could be attributed to the smaller rainfall events. Removal of the 11 read-outs with less than 17.5 mm rainfall from the original data set of 32 read-outs turned the interaction effect insignificant (albeit only just: $p=0.05$), such that both the treatment and the time-since-fire came to have a separate significant effect on runoff amounts. In the case of the sediment and organic matter losses, on the other hand, the bulk of the read-outs (27) needed to be removed from the data set to eliminate the significant interaction effect, reflecting the fact that sizeable sediment losses occurred much less frequently than substantial runoff amounts (Fig. 2).

In the case of the pine site, the repeated measures ANOVAs did not even hint at significant interaction effects, either for runoff amounts and coefficients or for sediment and organic matter losses ($p=0.8$). From the individual factors, mulching with eucalypt logging slash did not play a significant role in the case of any of these four parameters ($p=0.3$) but time-since-fire did in all four instances ($p<0.05$).

The pronounced temporal variation in rainfall, runoff and sediment losses was summarized by season (Table 2), and so were the corresponding temporal patterns in treatment effectiveness (Fig. 3). The overland flow generated by the untreated eucalypt plots exhibited a strong seasonal variation. It varied with roughly a factor 3 from around 50 mm during the driest seasons (autumn 2007 and summer 2008) to about 150 mm during winter 2007/08 and autumn 2008, whilst the rainiest season (spring 2008) assumed an intermediate position with 110 mm. Spring 2008 also stood out for producing comparatively little runoff in the case of the untreated pine plots, its mean runoff coefficient being at least twice as low as that of the other four seasons. Amongst these other seasons, autumn 2007 or,

Table 2
Pre- and post-treatment and season-wise runoff and erosion for the control plots (EC and PC) and treated plots (ET and PT) at the Eucalypt and Pine study sites.

	No. of read-outs	Rainfall amount	Total runoff (mm)				Mean runoff coefficient (%)				Total sediment losses (Mg ha^{-1})				Total organic matter losses (Mg ha^{-1})			
		(mm)	EC	ET	PC	PT	EC	ET	PC	PT	EC	ET	PC	PT	EC	ET	PC	PT
Pre-treatment (autumn 2007)	5	138	41	43	23	39	30	31	16	28	0.21	0.22	0.06	0.13	0.11	0.11	0.03	0.08
Post-treatment (winter 2007–autumn 2008)	35	1546	466	267	93	102	30	17	6	7	5.41	0.74	0.32	0.37	2.47	0.32	0.17	0.13
Winter 2007–2008	11	434	158	98	42	57	36	23	10	13	1.40	0.22	0.09	0.15	0.65	0.10	0.05	0.05
Spring 2008	12	565	110	42	12	12	19	7	2	2	2.07	0.12	0.03	0.03	0.95	0.06	0.02	0.01
Summer 2008	6	135	48	36	11	10	36	26	8	8	0.26	0.10	0.08	0.09	0.14	0.04	0.04	0.03
Autumn 2008	6	412	150	92	28	24	36	22	7	6	1.69	0.30	0.12	0.10	0.72	0.12	0.06	0.03

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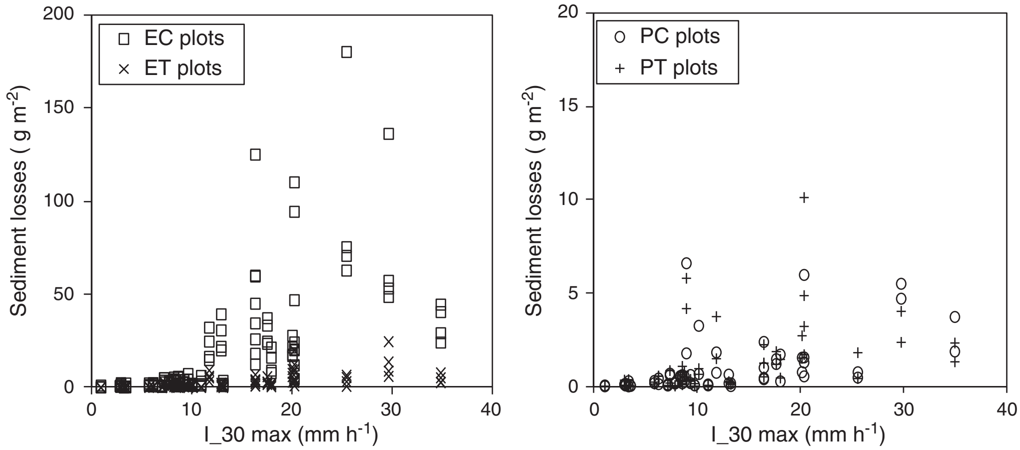

Fig. 2. Relationship of sediment losses with rainfall intensity for the treated (ET and PT) and control (EC and PC) plots at the eucalypt site (left) and pine site (right).

in other words, the first season following the wildfire was exceptional for precisely the opposite reason but only in the case of the untreated plots at the pine site.

Unlike runoff, sediment losses at the untreated eucalypt plots closely followed the seasonal pattern in rainfall. They were, on average, a factor 10 higher during spring 2008 than during autumn 2007 (2.07 vs. 0.21 Mg ha^{-1}). The discrepancy between the hydrological and erosion response of the untreated eucalypt plots was to a large extent due to two extreme events of roughly 150 mm that occurred during April 2008 and produced 80% of the season's sediment losses as opposed to 50% of the season's runoff. In the case of the untreated pine plots, the seasonal variation in sediment losses neither agreed well with that in runoff nor with that of rainfall. Instead, specific sediment losses were clearly lower during the first three seasons (averaged to 0.22 g m^{-2} mm^{-1} runoff) than during autumn and especially summer 2008 (0.41 and 0.76 g m^{-2} mm^{-1} runoff, respectively).

The effectiveness of mulching with eucalypt chopped bark varied between the four seasons in much the same manner as rainfall did (Fig. 3). The relative reductions in both runoff and sediment losses at the eucalypt site were at their minimum during the driest season (summer 2008) and at their maximum during the rainiest season (spring 2008). Throughout the treatment period, mulching was consistently more effective in reducing erosion than overland flow at the eucalypt site, and markedly so. Mulching effectiveness revealed completely distinct patterns at the pine site compared to the eucalypt site. First, effectiveness contrasted sharply between the first post-treatment season and the three subsequent seasons (i.e. between markedly negative and roughly zero to marginally positive) and second, effectiveness differed little between runoff and erosion.

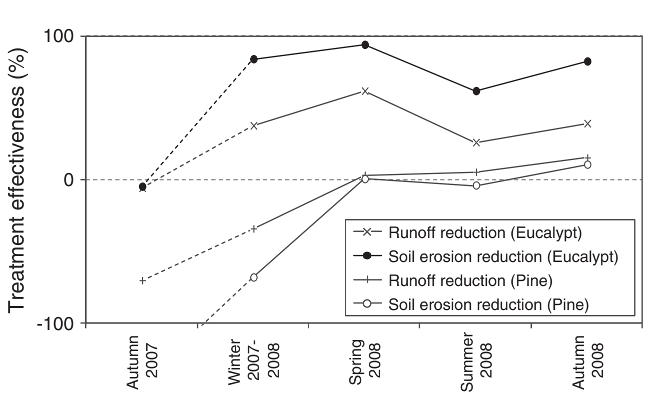

Fig. 3. Seasonal patterns in the average effectiveness of mulching with eucalypt chopped bark at the eucalypt site and with eucalypt logging slash at the pine site in reducing runoff and sediment losses.

3.3. Temporal patterns in ground cover, soil moisture and water repellency

In November 2007, the plots at the two study sites differed markedly in their ground cover (Fig. 4). Whilst the mean litter cover of the control and to-be-treated eucalypt plots was around 10%, that of the pine plots was roughly 50%, mainly due to needle cast from the scorched pine canopies (which continued until late January 2008). At the same time, a major discrepancy also existed in the total cover of bare soil and ashes, amounting to 70% at the eucalypt plots vs. 40% at the pine plots. These site differences were by and large eliminated by mulching, resulting in a mean litter cover of about 70% for the treated plots at the pine as well as eucalypt site. One year later, however, the mean litter cover was basically the same at the treated pine plots but had decreased noticeably at the treated eucalypt plots (20%). Also in the case of the untreated plots, the pine site revealed less pronounced cover changes than the eucalypt site, where an increase in average stone cover of roughly 20% occurred at the expense of a decrease in particular in ash cover. Worth special

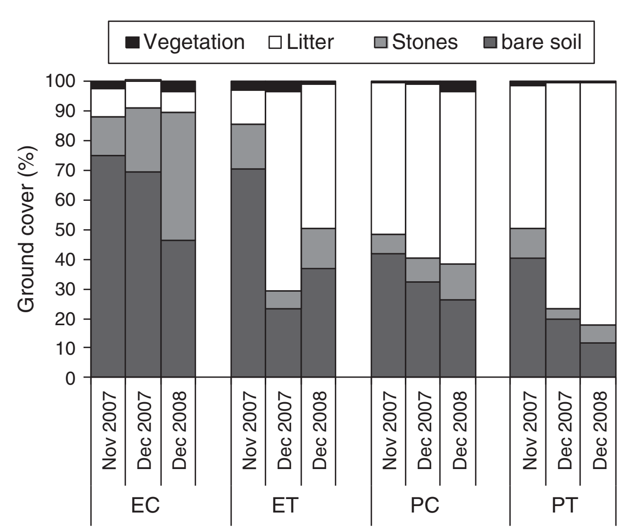

Fig. 4. Mean cover of the four cover categories at the control and treated plots at the eucalypt and pine study sites (EC, ET, PC and PT, respectively) immediately before and after the mulching (November and December 2007) and at the end of this study (December 2008).

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mention is perhaps the very limited recovery of the vegetation, even by December 2008.

Soil moisture content varied markedly in the course of this study but revealed straightforward temporal patterns. As shown for the PR2-probe values (Fig. 5), the mean moisture content tended to: (i) increase—more or less gradually—from minimum values during autumn 2007 to maximum values during spring 2008; (ii) decrease again during the summer of 2008, albeit to higher values than at the start of the measurement period; (iii) attain higher values towards the end of the study than one year earlier. The PR-probe data also suggested that mulching significantly increased soil moisture content at the eucalypt site (repeated measures ANOVA: $n=32$, $p<0.05$), with the overall mean value being 15 and 20% vol. for the control and treated plots, respectively. In spite of the above-mentioned technical problems with the PR-tubes in the pine control plots, such a treatment effect could also be inferred for the pine site. Namely, the mean PR-probe values did not differ significantly between the treated pine and the treated eucalypt plots (repeated measures ANOVA: $n=32$, $p=0.3$), on the one hand, and on the other, the mean ML2-sensor values—measured in untreated slope parts—did not differ significantly between the pine and eucalypt site (pair-wise Student *t*-test: $n=29$, $p=0.06$). Although the two sensors gave distinct results in terms of absolute values, they did produce broadly similar temporal patterns, as evidenced by the strong relationship between PR-probe and ML-sensor on the untreated conditions at the eucalypt site (Pearson correlation coefficient: 0.70, $n=29$, $p<0.05$).

The frequency of extreme repellency (%FR) revealed more irregular temporal patterns than soil moisture (Fig. 5). Even so, both study sites revealed a broad tendency at their untreated slope parts for %FR to: (i) increase from October 2007 to maximum values in December 2007; (ii) decrease subsequently to minimum values during spring 2008; (iii) again increase towards the summer of 2008, most notably so at the pine site. The actual %FR values, however, tended to be noticeably lower at the pine compared to the eucalypt site. Extreme repellency was also found to be significantly less frequent at the pine site than at the eucalypt site during the winter of 2007/2008 (pair-wise Student *t*-test: 42 vs. 81%, $n=10$, $p<0.05$) as well as during the spring of 2008 (pair-wise Student *t*-test: 18 vs. 49%, $n=7$, $p<0.05$).

3.4. Key factors explaining runoff and erosion

The hydrological and erosion response of the 12 plots throughout the treatment period could be clearly explained the two rainfall and the four ground cover variables included in the forward selection procedure (Table 3). Almost 60% of the variation in (square-root transformed) runoff could be accounted for by four of the variables, whilst three variables sufficed to explain 70% of the variation in (fourth-root transformed) sediment losses. In both instances, the principal covariate concerned rainfall; however, it corresponded to rainfall intensity in the case of sediment losses as opposed to rainfall total in the case of runoff. Amongst the cover-related variables, litter cover was the most important factor, explaining roughly a third less variance than rainfall total and rainfall intensity, respectively for runoff and sediment losses models.

The regression results for the eucalypt site alone were similar to those for both sites together. This equally applied for the treatment

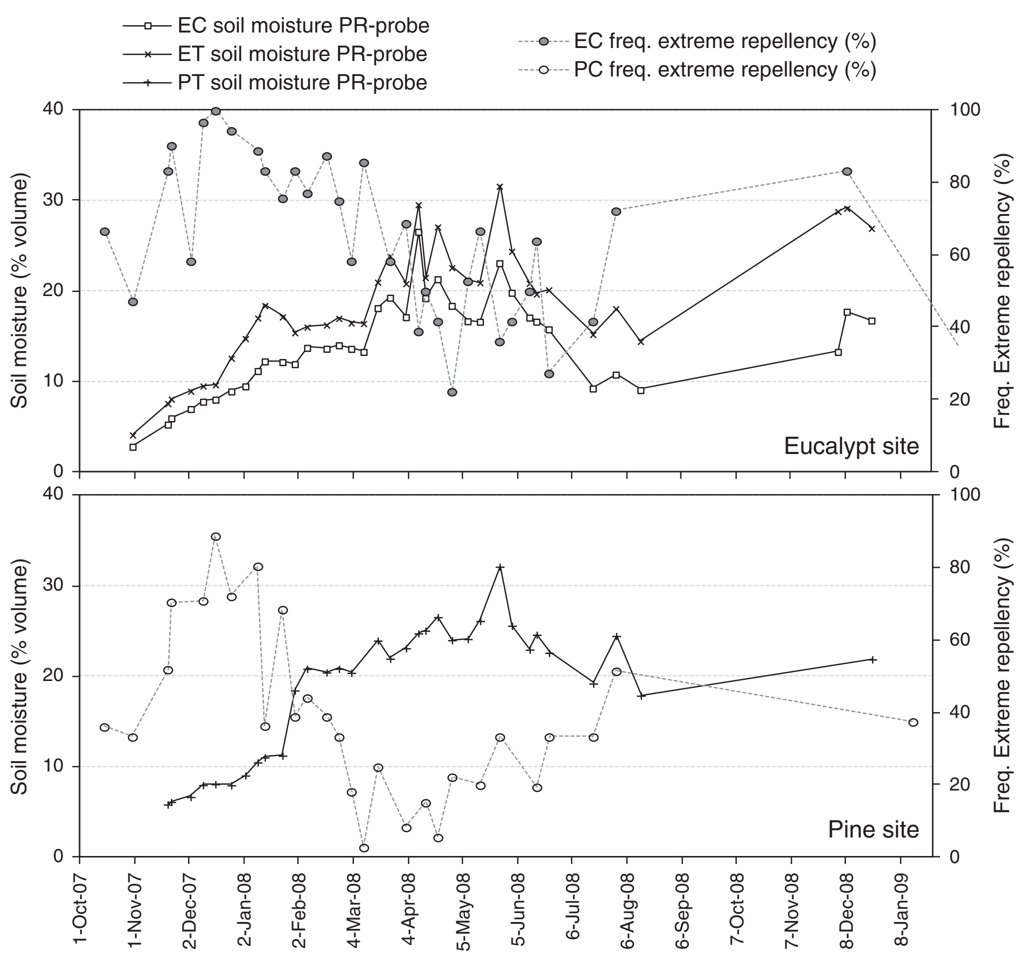

Fig. 5. Mean values of soil moisture content (0–10 cm depth; PR2-probe) and frequency of extreme soil water repellency (0–15 cm depth) for the individual measurement periods at the two study sites. Moisture data were available for the control and treated plots at the eucalypt site (EC and ET) and for control plots at the pine site (PT), whereas the repellency data were limited to the untreated conditions at both sites (EC and PC).

Table 3
Multiple regression models of runoff and sediment losses for various combinations of erosion plots (treated and untreated plots at the two study sites together and separately, and untreated plots at both study sites), measurement periods (32, 27 and 20 read-outs) and sets of independent variables (6, 7 and 8 covariates).

Selected variable	Runoff (mm)			Sediment losses (g m^{-2})		
	Parameter estimate	Variable name	Partial r^2	Parameter estimate	Variable name	Partial r^2
Global model: all 4 pine and all 8 eucalypt plots						
Complete dataset: 32 read-outs						
Covariates: 6—rainfall total (P_tot) and intensity (I_30), covers of bare soil, stones, litter and vegetation						
Intercept	3.39			1.04		
1st var.	0.02	P_tot	0.33	0.04	I_30	0.37
2nd var.	−0.04	Litter	0.20	−0.01	Litter	0.28
3rd var.	0.05	I_30	0.05	0.00	P_tot	0.05
4st var.	−0.03	Stones	0.01			
Cum. r^2			0.59			0.70
Eucalypt model: all 8 eucalypt plots						
Complete dataset: 32 read-outs						
Covariates: 6—rainfall total (P_tot) and intensity (I_30), covers of bare soil, stones, litter and vegetation						
Intercept	3.02			0.92		
1st var.	0.03	P_tot	0.47	0.04	I_30	0.47
2nd var.	−0.04	Litter	0.09	−0.01	Litter	0.21
3rd var.	0.05	I_30	0.04	0.01	P_tot	0.08
4th var.	−0.03	Stones	0.01			
Cum. r^2			0.61			0.76
Pine model: all 4 pine plots						
Complete dataset: 32 read-outs						
Covariates: 6—rainfall total (P_tot) and intensity (I_30), covers of bare soil, stones, litter and vegetation						
Intercept	0.39			0.50		
1st var.	0.01	I_30	0.36	0.03	I_30	0.42
2nd var.	0.06	P_tot	0.04			
Cum. r^2			0.41			0.42
Eucalypt model: all 8 eucalypt plots						
Limited dataset: 27 read-outs						
Covariates: 7—rainfall total (P_tot) and intensity (I_30), covers of bare soil, stones, litter and vegetation, and soil moisture (PR2-probe).						
Intercept	2.52			1.05		
1st var.	0.03	P_tot	0.51	0.04	I_30	0.48
2nd var.	−0.07	Moisture	0.10	−0.01	Litter	0.24
3rd var.	−0.02	Litter	0.04	0.01	P_tot	0.04
4th var.	0.07	I_30	0.02	−0.01	Moisture	0.01
5th var.	0.03	Veget.	0.02			
Cum. r^2			0.68			0.77
Untreated plots model: all 6 untreated plots						
Partial dataset: 20 read-outs						
Covariates: 8—rainfall total (P_tot) and intensity (I_30), covers of bare soil, stones, litter and vegetation, soil moisture (ML2-sensor) and frequency of extreme repellency (						
Intercept	0.09			0.93		
1st var.	0.03	P_tot	0.44	0.01	P_tot	0.55
2nd var.	0.03	Repellency	0.24	−0.01	Litter	0.21
3rd var.	−0.02	Litter	0.03	0.03	I_30	0.02
Cum. r^2			0.73			0.79

period as a whole as well as for the "limited" data set. Even so, the removal of the four pine plots increased somewhat the importance of the principal, rainfall-related covariate, in absolute terms but especially compared to the subsequent covariates (explaining at least twice as much variance). The relationship of sediment losses to the principal covariate—rainfall intensity—was shown in Fig. 2. Furthermore, litter cover was substituted by soil moisture as the second most important factor explaining runoff at the eucalypt site. This was not the case, however, for the site's sediment losses.

The regression results for the pine site alone differed in two important aspects from those for the eucalypt site (Table 3). First, rainfall intensity was the principal factor explaining not just sediment losses (Fig. 2) but also runoff. Second, litter cover did not explain a significant fraction of the variance in either runoff or sediment losses (and neither did any of the other cover categories). This was in line with the above-mentioned finding that there was no significant treatment effect at the pine site.

Soil water repellency and, in particular, the frequency of extreme repellency was found to have a significant effect on runoff at the two study sites but not on sediment losses (Table 3). Nonetheless, the role of extreme repellency of enhancing overland flow generation was clearly secondary compared to that of rainfall total, explaining roughly 50% less variance. Sediment losses varied significantly not just with rainfall total but also with litter cover, notwithstanding the fact that only the untreated plots were included in the analysis.

4. Discussion

The present findings coincided in many aspects (including in terms of plot design) with the results of Shakesby et al. (1996). This was especially true for the post-treatment periods of both studies, differing much less in rainfall amounts than the pre-treatment periods (1546 vs. 1470 mm as opposed to 138 vs. 645 mm). As far as the control plots were concerned, key points of agreement were: (i) the overall runoff coefficients of the eucalypt plots (30 vs. 20%); (ii) the overall sediment losses of the eucalypt plots (5.4 vs. 4.9 Mg ha^{-1}); (iii) the specific sediment loss rates of the eucalypt plots (0.35 vs. 0.33 g m^{-2} mm^{-1} rainfall); (iv) the markedly lower sediment losses of the pine compared to the eucalypt plots (amounting to only 6 vs. 16% of the eucalypt plots). Shakesby et al. (1996) suggested various factors that could contribute to the contrast in sediment losses between their pine and eucalypt plots, of which especially the presence of a pine needle "carpet" would seem relevant in the present context. Pannkuk and Robichaud (2003) equally found needle cast to be effective in reducing post-fire erosion rates. The regression results of the present study also supported that, even in the case of the control plots, litter cover played a significant role in reducing sediment losses. Worth nothing in this respect was that the mean litter cover at the untreated pine plots was approximately 60%, i.e. a commonly accepted threshold for mulch cover to be effective (Robichaud et al., 2000).

As far as the effectiveness of mulching with forest residues was concerned, the results of this study and those of Shakesby et al. (1996) coincided in two aspects: (i) a major decrease in overall sediment losses at the eucalypt site (with 86 vs. 91%); (ii) the lack of such an obvious reduction at the pine site, with sediment losses actually being higher at the control than at the treated plots (16 vs. 50%). Shakesby et al. (1996), however, did not assess treatment effectiveness in the same way as was done here (or in the other post-fire treatment studies listed in Table 4), comparing pre- to post-treatment values instead of the values of treated and untreated plots. Furthermore, Shakesby et al. (1996) opted for testing various mulch application rates at single plots rather than for testing one single rate at various replicate plots. Also in the case of the present study, the limited number of replicate plots implied special caution in interpreting the effectiveness figures for the pine site in particular. The suggestion of an erosion-enhancing effect of mulching at the pine site might well be due to the comparatively low runoff and sediment losses of the untreated pine plots, on the one hand, and, on the other, a marked variability amongst the plots in their hydrological and erosion response, implying a need for more replicate plots.

Even the untreated eucalypt plots did not produce excessive sediment losses during the first 1.5 year after wildfire when compared to the figures reported by some of the other studies on post-fire erosion treatment listed in Table 4. This fitted in well with the well-established tendency for erosion rates to be low in Mediterranean regions, in particular in cases—like the present one and those of Badía and Martí (2000) and Bautista et al. (1996)—where shallow soils and elevated surface stone cover bear witness to a long history of land use (Shakesby, 2011). Nonetheless, the large fraction of organic

Table 4
Compilation of field studies into the effectiveness of mulching-based treatments in reducing post-fire runoff and erosion. The meaning of the abbreviations are as follows: C, control; Effect., effectiveness; Euc., Eucalypt; GT, gerlach trap; LEB, log erosion barrier; mod., moderate; –, not reported; p., pine; PAM, polyacrilamide; plant., plantation; RS, rainfall simulation; sev., severity; SF, silt fence; PW, paired watershed; T, treated.

Treatment type (Mg/ha^{-1}, % cover)	Location, forest type	Fire sev.	Slope (%)	Method/ plot size (m^2)	n of plots		Study period	Annual rainfall	Total ground cover (%)		Runoff/rainfall (%)			Soil erosion ($Mg\ ha^{-1}$)			Reference
					C	T	year, month	$mm\ yr^{-1}$	C	T	C	T	Effect. (%)	C	T	Effect. (%)	
Forest residue mulch																	
Chopped bark (8.7; 67)	C Portugal, Euc. plant.	Mod.	56	GT/16	4	4	yr0	1546	31	77	30	17	41	5.4	0.7	86	This study
Logging slash (17.5; 76)	C Portugal, P. plant.	Low	53	GT/16	2	2	yr0	1546	68	80	6	7	−10	0.3	0.4	−16	
Euc. Logging (46; 89)	C Portugal, Euc. plant.	Mod.	44	GT/16	2	1	yr2	1471	48	95	20	19	3	4.9	0.4	91	Shakesby et al. (1996)
Pine logging (18; 8)	C Portugal, P. plant.	Low	44	GT/16	2	2	yr3	2027	76	78	22	16	28	0.8	1.2	−50	
Wood chip mulch																	
Wood chip (4; 45)	NW Spain, shrub	High	40	SF/500	4	4	yr0	1520	19	56	–	–	–	35.0	33.0	6	Fernandez et al. (2011)
Wood chip (17; 70)	W Korea, Japanese p.	Mod.	51	GT/30	3	3	yr3	1115	43	80	19	11	42	7.6	3.8	51	Kim et al. (2008)
Wood chip (–; 70)	AR USA, Ponderosa p.	High	27	SF/4100	1	1	mth3	487	42	86	–	–	–	65.6	15.9	76	Riechers et al. (2008)
Straw mulch																	
Straw (2.5; 80)	NW Spain, shrub	High	40	SF/500	4	4	yr0	1520	19	84	–	–	–	35.0	12.0	66	Fernandez et al. (2011)
Straw + seeds (1; 53)	NE Spain, semi-arid shrub	Mod.	45	GT/8	4	4	yr1	268	38	99	–	–	–	2.6	0.4	83	Badía and Martí (2000)
		Mod.	45	GT/8	4	4	yr2	268	47	69	–	–	–	3.5	1.4	59	
Straw + seeds (1; 27)	NE Spain, semi-arid shrub	Mod.	45	GT/8	4	4	yr1	268	70	100	–	–	–	1.0	0.4	59	
		Mod.	45	GT/8	4	4	yr2	268	73	85	–	–	–	2.0	0.7	64	
Straw (2; 42)	E Spain, semi-arid p.	Mod.	42	GT/16	3	3	yr1	293	67	89	5	0	91	1.1	0.1	89	Bautista et al. (1996)
Straw (2.2; 78)	CO USA, Ponderosa p.	High	29	SF/16,000	8	3	yr0	198	33	74	–	–	–	6.2	8.8	−42	Wagenbrenner et al. (2006)
		High	29	SF/16,000	12	4	yr1	198	50	75	–	–	–	9.5	0.5	95	
		High	29	SF/16,000	12	4	yr2	198	68	89	–	–	–	1.2	0.0	98	
		High	29	SF/16,000	12	4	yr3	198	88	89	–	–	–	0.7	0.0	100	
Straw (2.2; 100)	MO USA, spruce-fir p.	High	15	RS/0.5	10	10	yr1	480	1	100	47	36	23	7.2	1.0	86	Groen and Woods (2008)
		High	15	RS/0.5	4	3	yr2	480	38	34	27	27	0	4.2	2.2	48	
Straw + seeds (2.2; 94)	CO USA, Ponderosa p.	High	22	SF/2830	4	4	yr1	402	32	55	–	–	–	13.2	0.7	95	Roughs, (2007) (unp.)
		High	22	SF/2830	4	4	yr2	402	58	72	–	–	–	11.0	2.5	77	
Straw rice (4.5; –)	AR USA, Ponderosa p.	High	27	SF/4100	1	1	mth3	487	42	88	–	–	–	48.4	9.1	81	Riechers et al. (2008)
Straw + seeds	NM USA	–	24	SF/25	6	6	yr0	52	–	–	–	–	–	8.3	2.5	70	Dean 2001 (unp.)
		–	24	SF/25	6	6	yr1	156	–	–	–	–	–	12.6	0.7	95	
Hydromulch											–	–	–				
Aerial (2.4; 94)	CO USA, Ponderosa p.	High	22	SF/2830	4	4	yr1	402	32	56	–	–	–	7.2	0.4	94	Roughs,(2007) (unp.)
		High	22	SF/2830	4	4	yr2	402	58	57	–	–	–	4.5	2.3	49	
Hand (2.4; 88)	CO USA, Ponderosa p.	High	22	SF/2830	4	4	yr1	402	32	54	–	–	–	10.2	8.5	17	
		High	22	SF/2830	4	4	yr2	402	58	53	–	–	–	8.5	6.9	19	
Aerial (−; 50)	CA USA, Chaparral	High	23	PW/55,000	1	1	yr0	415	–	50	–	–	–	15.0	21.0	−40	Wohlgemut et al. (2006)
Aerial (−; 100)		High	23	PW/55,000	1	1	yr0	415	–	100	–	–	–	15.0	7.0	53	
PAM Pellets	AR USA, Ponderosa p.	High	27	SF/4100	1	1	mth3	487	42	71	–	–	–	59.2	30.4	49	Riechers et al. (2008)
Barriers																	
Shrub barriers (10 m)	NW Spain, shrub	High	40	SF/500	4	4	yr0	1520	19	24	–	–	–	35.0	30.0	14	Fernandez et al. (2011)
LEB (2–2 m)	W Korea, Japanese p.	Mod.	51	GT/30	3	3	yr3	1115	43	–	19	18	7	7.6	7.5	2	Kim et al. (2008)
LEB + straw + seeds	NM USA	–	24	SF/25	6	6	yr0	52	–	–	–	–	–	8.3	1.9	77	Dean (2001) (unp.)
		–	24	SF/25	6	6	yr1	156	–	–	–	–	–	12.6	0.5	96	

matter observed in the sediment losses should be noted, not only for the implications for medium- to long-term land-use sustainability (e.g. Ferreira et al., 2008; Malvar et al., 2011; Thomas et al., 1999) but also for off-site pollution with pyrolitic toxic organic compounds (Vila-Escalé et al., 2007).

In comparison with other field studies that tested the effectiveness of wood chips mulches (Table 4), the eucalypt chopped bark was highly effective. Riechers et al. (2008) and Kim et al. (2008) reported substantial reductions of 76 and 51% respectively, while Fernández et al. (2011) found that wood chips decreased erosion by a mere 6%. These discrepancies can be due not only to the differences in the application rates, but also, as noted by the last two studies, to the fact that the 5–2 cm long chips pieces floated and were removed along with the sediments. This did not occur with the 10–15 cm long fibres of the chopped bark mulch. In fact, the mulching effectiveness at the eucalypt site can be compared more favourably with the range of values compiled for straw mulch in Table 4 (48–100%).

Arguably, the present results justified the decision to measure runoff and erosion with a high temporal resolution to compensate a possible lack of replicate plots. The repeated measures experimental design allowed valuable statistical inferences on treatment effectiveness as well as on the role therein of selected explanatory variables. An important insight was that even in the case of the eucalypt site the effectiveness of mulching was not time-invariant, being statistically significant only for the larger runoff and erosion events. This reflected the presence of thresholds, below which runoff amounts and sediment losses were too low for the mulching effect to prevail over the inherent variability in the plots' runoff generation and sediment transport processes. Litter cover played a more important role in sediment losses than runoff amounts. This coincided with the effects of mulching described by Smets et al. (2008), decreasing runoff generation by increasing surface storage as well as soil moisture content, on the one hand, and, on the other, decreasing sediment transport by decreasing splash erosion (sediment availability) as well as by increasing resistance to flow (transport capacity). Visual inspection of the treated and untreated eucalypt plots indeed suggested that mulching not only decreased splash erosion (pedestal formation) but also enhanced deposition of ashes and fines. From the few prior studies that assessed mulching effects in terms of both overland flow and erosion, Groen and Woods (2008) and Shakesby et al. (1996: eucalypt site) found a clearly greater impact on sediment losses than runoff. Bautista et al. (1996) and Kim et al. (2008), on the other hand, reported comparable reductions in runoff and erosion, notwithstanding the fact that the effectiveness varied greatly between these studies (42 to 91%).

The role of litter cover, whilst significant, was secondary compared to that of rainfall. With one exception, both rainfall total and rainfall intensity explained significant fractions of the variations in runoff and sediment losses, as was also observed by Bautista et al. (1996). The relative importance of the two rainfall variables, however, tended to differ for runoff and erosion, with rainfall total explaining better runoff amounts and rainfall intensity explaining better sediment losses. The former agreed with the findings of Kim et al. (2008), whereas the latter was in accordance with Wagenbrenner et al. (2006) but not with Fernández et al. (2011). This discrepancy could be due to differences in rainfall regime. The rainfall intensities in the present study were in fact more similar to those in Wagenbrenner et al. (2006) than to those in Fernández et al. (2011), notwithstanding the fact that the former study was carried out in the Colorado Front Range, USA, and the latter in Galicia, north-east Spain.

Following rainfall, soil water repellency was the most important variable explaining overland flow generation but this was only assessed for the untreated conditions. The role of water repellency in enhancing overland flow has often been inferred for burnt as well as unburnt eucalypt stands in particular (e.g. Coelho et al., 2005; Ferreira et al., 2005a; Malvar et al., 2011; Sheridan et al., 2007). However, it has rarely been established in an unequivocal manner, especially due to the destructive nature of repellency measurements and the relationship of repellency with other potential explanatory variables (Shakesby and Doerr, 2006), except perhaps by Leighton-Boyce et al. (2007) using surfactants in rainfall simulation experiments. Even so, water repellency could have been of minor importance at the mulched plots, since mulching was found to increase the soil moisture content at the eucalypt plots.

5. Conclusions

The principal conclusions of this study into the short- to medium-term effects of mulching with forest residues on runoff generation and sediment losses in a recently burnt eucalypt as well as maritime pine plantation in north-central Portugal were:

- whilst sediment losses at the untreated eucalypt plots were not excessively high for post-fire conditions worldwide, those at the untreated pine plots were low even by Mediterranean standards;
- mulching with eucalypt chopped bark was, on average, highly effective at the eucalypt site, with an increase in litter cover from 10 to 70% resulting in a decrease in 45% of runoff amount and in 85% of sediment losses;
- the effect of mulching at the eucalypt site was statistically significant, albeit for noticeably more runoff than erosion events due to the latter's highly irregular nature, and coincided with the significant role that litter cover played in explaining runoff and especially sediment losses;
- mulching at the pine site did not result in less runoff and erosion at the treated plots compared to the untreated plots, probably due to the already elevated effectiveness of the "natural" mulching by needle cast from the scorched pine canopies in combination with a marked variability in hydrological and erosion response amongst the plots;
- rainfall total and intensity explained runoff and sediment losses markedly better than any of the other six variables included in this study, but, besides litter cover, also soil moisture and soil water repellency could explain a significant fraction of the variation in overland flow generation.

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