Catena 169 (2018) 21–30

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

The effectiveness of two contrasting mulch application rates to reduce post-fire erosion in a Portuguese eucalypt plantation

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ARTICLE INFO

Keywords:
Wildfire
Soil erosion
Erosion mitigation
Forest logging residue mulching
Eucalypt plantation

ABSTRACT

Wildfires are well-known to increase runoff and erosion during the initial stages of the window-of-disturbance, and mulching has been widely documented to effectively minimize this impact. However, the relationship between the rate of mulch application and erosion reduction is poorly studied, in spite of its potential importance for optimizing mulching costs and efforts per ha. Therefore, a field experiment was carried out in a recently burnt eucalypt plantation in Central Portugal that had been burnt by a moderate severity fire during August 2015, comparing sediment as well as organic matter losses from three untreated 2 m × 8 m erosion plots with losses from six plots mulched with eucalypt logging residues at two contrasting rates of either 2.6 or 8.0 Mg ha^{-1}. The two mulching treatments resulted in the targeted litter covers of 50 and 79%, and these covers hardly changed over the ensuing year. Over this first post-fire year, the mulched plots produced significantly less mineral soil as well as organic matter losses than the untreated plots. At the same time, the plots with the high mulching rate lost consistently less sediments and organic matter than the plots with the low mulching rate but the differences were not statistically significant over all measurement periods. Total sediment losses over the first post-fire year were, on average, 86 and 96% lower following mulching at 2.6 and 8.0 Mg ha^{-1}, respectively, than without mulching. In absolute values, total losses dropped from 8.0 to 1.1 and 0.3 Mg ha^{-1} y^{-1}, respectively, or, in other words, similar to and well-below the widely-accepted threshold of tolerable soil loss of 1 Mg ha^{-1} y^{-1}. If this threshold value is acceptable to land managers, they could treat a three times larger area with the same amount of mulch.

1. Introduction

The EU-FP7 project RECARE (www.recare-project.eu) had as one of its objectives to test and demonstrate prevention, mitigation and restoration measures against 11 soil threats in 17 case study sites across 15 countries in Europe, with stakeholders deciding on the selection of these measures through two dedicated workshops. In the Portuguese case study, addressing the threat of soil erosion by water, in particular following wildfire, mulching with forest logging residues was selected, from an initial set of traditional and novel post-fire land management practices established by post-fire soil erosion experts, as one of the measures to be tested under field conditions. The main reason for the stakeholders (which covered private and public forest owners and managers as well as representatives from local, regional and national governmental and non-governmental organizations with another stake in post-fire land management) to select mulching was that they were unfamiliar with this measure at the time of the workshops, in 2015. This lack of familiarity with mulching appears to be general phenomenon among forest stakeholders in Portugal (Ribeiro et al., 2015).

Wildfires are a common phenomenon in Portugal, as they are in many other countries in southern European and across the world with climate regimes propitious to fire ignition and spreading (Doerr and Santin, 2016; Moritz et al., 2014; San-Miguel and Camia, 2009). In Portugal, wildfires affect, on average, roughly 100.000 ha of rural lands each year (Cardoso Pereira et al., 2006) but much larger areas in extreme years such as 2003, 2005 and 2017 with c. 426.000, 339.000 and 496.000 ha (ICNF, 2017). The apparently unprecedented and possibly escalating fire regime in Portugal over the past decades is largely attributed to human activities, not only as cause of ignition (Veléz, 2009) but also through land-use changes such as land abandonment and widespread planting of fire-prone tree species (Moreira et al., 2009; Shakesby, 2011; Valente et al., 2015).

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https://doi.org/10.1016/j.catena.2018.05.029
Received 25 January 2018; Received in revised form 13 April 2018; Accepted 21 May 2018
Available online 26 May 2018
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Wildfires have frequently been observed to produce strong and sometimes extreme hydrological and erosion responses in recently burnt areas, especially during the initial stages of the so-called window-of-disturbance and with a key role therein of soil burn severity (Moody et al., 2013; Shakesby, 2011; Vieira et al., 2015). Such fire-enhanced responses have also been reported for eucalypt and maritime pine plantations in Portugal, the country's two most widespread and fire-prone forest types (Hosseini et al., 2016; Shakesby et al., 1993; Vieira et al., 2016). Increased runoff and erosion rates following wildfires are generally attributed to (partial) consumption of the vegetation and litter layer as well as to heating-induced changes in soil properties determining soil's infiltration capacity and/or erodibility, including soil water repellency and aggregate stability (Cerdà and Doerr, 2005; Malvar et al., 2013; Mataix-Solera et al., 2011; Shakesby, 2011).

A range of measures has been tested for their effectiveness to mitigate post-fire runoff and erosion (Bautista et al., 1996; Fernández et al., 2011; Robichaud et al., 2008, 2013; Wagenbrenner et al., 2006). Robichaud et al. (2010) and Vega et al. (2013) made exhaustive reviews of the results of such tests, to inform post-fire land management in the USA and Galicia, respectively. Both reviews concluded that mulching, or the application of a layer of organic residues, is the most effective measure to reduce post-fire erosion, especially under intense rainfall events, typically using straw due to its wide availability, low costs and easy-of-handling. In Portugal, several field experiments have been carried out in recent years to test the effectiveness of mulching to reduce post-fire erosion (Hosseini et al., 2017a; Prats et al., 2012, 2016b). The two experiment in eucalypt plantations, however, opted for using eucalypt logging residues, firstly because of the limited availability of straw (Prats et al., 2012, 2014b, 2016b). These studies showed that mulching with eucalypt logging residues was highly effective, reducing post-fire erosion rates during the initial stages of the window-of-disturbance with 85% or more across a wide range of plot scales (0.25–100 m^2). However, the tested application rates were in the order of 10 Mg ha-1 or, in other words, considerably higher than the 2–3 Mg $ha^{-}1$ of straw mulch that are typically applied in operational post-fire land management in both the USA (Robichaud et al., 2010) and Galicia (Vega et al., 2013), casting doubt on the feasibility and economic viability of using eucalypt logging residues for large-scale mulching in operational post-fire land management settings.

The overarching aim of this study was therefore to provide further insights into the suitability of mulching with forest logging residues as a post-fire soil conservation measure, focusing on the role of mulch application rate. The first specific research questions was if two contrasting rates of applying eucalypt logging residues mulch immediately after wildfire would be effective measures to increase protective litter cover - i.e. the soil property that is directly targeted by mulching - over the fire-induced window-of-disturbance and, in this specific case, over the first post-fire year. These two rates were a “standard” rate of 8.0 Mg ha^{-1}, similar to that applied in prior field experiments in the study region, and a “reduced” rate of 2.6 Mg ha^{-1}.The second question was if these two mulching rates would impact other soil properties than litter cover that could potentially influence post-fire soil erosion by water and associated organic matter losses, in particular other ground cover categories and topsoil moisture content. The third question was if the “reduced” mulch application rate as effective to mitigate post-fire sediment losses as the “standard” rate, while the fourth question was if post-fire organic matter losses would be affected similarly by the two contrasting mulch application rates as sediment losses.

2. Case study area and monitoring site

This study was carried out in the Vale de Colmeias burnt area located in the Miranda do Corvo municipality of the Coimbra District in north-central Portugal. The wildfire started on 8 August 2015 and ended the next day, affecting a total area of 715 ha of mainly forest stands (96%) and, in particular, *Eucalyptus globulus* Labill. plantations (ICNF, 2017). According to EFFIS (2015), the study area as a whole was predominantly burnt at moderate or high severity. The climate of the area is Mediterranean with oceanic influence and can be classified as humid meso-thermal (Csb, according to the Köppen classification), with prolonged dry and warm summers (DRA-Centro, 1998). Long-term mean annual temperature and average annual rainfall at the nearest meteorological station (Carapinhal, located at approximately 12 km) were 12 °C and 851 mm (SNIRH, 2016).

Within the burnt area, a privately-owned *Eucalyptus globulus* Labill. plantation on a steep (27°), ENE facing slope was selected as study site. Two important reasons to select this particular plantation were that: (i) the trees were planted in regular lines running in downslope direction, thereby allowing to avoid the possibly confounding impacts of tree stems on overland flow retention and sediment deposition, especially at the lower parts of the erosion plots; (ii) the tree stems were still relatively thin as the plantation was 2–3 years into the second rotation cycle, thereby minimizing the chances that salvage logging would take place during the monitoring period and lead to disturbance of the plots (the impacts of salvage logging on erosion were studied in the same burnt area by Malvar et al. (2017). Fire severity at the actual study site was classified as high by EFFIS (2015) but field observations during early September 2015 suggested a moderate vegetation as well as soil burn severity. The former was indicated by partial combustion of the tree crowns and an average Twig Diameter Index of 0.4 (see Maia et al., 2012; based on measurements of 3–5 shrubs nearest to nine equidistance points along a transect running from the bottom to the top of the plantation), while the latter was indicated by complete combustion of the litter layer and the predominantly black color of the ash layer (see Shakesby and Doerr, 2006). The terrain between the planting lines where the plots were installed was smooth, lacking any obvious microtopographic features. The soil at the study site was described in the field through two full soil profiles that were cleared at the side of the trail at the bottom of the plantation and that were complemented by three validation profiles that were dug up some 10 m upslope. All five profiles were classified as epileptic Umbrisols (IUSS, 2014), comprising a thin (< 5 mm thick) layer of predominantly black ash and charred plant material, Ah1 and Ah2 horizons to a depth of 35–40 cm, and a C horizon of partly weathered pre-Ordovician schists of the Hesperic Massif (Pereira and Fitzpatrick, 1995). The two Ah layers had a dark brown color (7.5YR 3/4 in dry and 7.5YR 3/3 in wet), a loamy field texture, and a moderately fine blocky sub-angular to a fine granular structure. The samples collected from the two Ah layers of the full soil profiles had a pH (in 1:5 v/v Milli-Q water suspension, following ISO 10390:2005) ranging from 4.6 to 4.8, and an organic matter content varying from 15 to 18% (loss-on-ignition-method (Pribyl, 2010), using 2 g of soil without stones or recognizable plant parts in a muffle furnace at 550 °C for 4 h). These values agreed well with the results obtained for nine additional soil samples that were collected at 0–5 cm depth next to each of the plots in September 2015, with minimum–median–maximum values of 4.6–4.7–4.8 for pH and 15.3–16.1–18.2% for organic matter content.

3. Materials and methods

3.1. Experimental design and treatments

Almost one month after the fire (07 September 2015), a total of nine erosion plots were installed at the bottom part of the plantation (for reasons of easy access from the forest track immediately below), and, as referred earlier, in between the tree planting lines. The plots were divided over three blocks and, within each block, the three plots were randomly assigned one of the three treatments, i.e. mulching at the standard and reduced rates of 8.0 and 2.3 Mg ha-1 and doing nothing (control). Each plot was approximately 2 m wide and 8 m long, was bounded by geotextile held upright by wooden stakes and, at the bottom of the plot, by steel re-bars, and was protected against upslope run-on by trenches. Each plot was instrumented at its upper part with one or two soil moisture probes (EC-5, Decagon Devices), installed at 2.5 cm depth and recording at 5 min intervals, whereas the study site was instrumented with two totalizer rainfall gauges (in-house design) and two tipping-bucket rainfall gauges (ARG100, Campbell Scientific) linked to an event data logger (HOBO Pendant Event Data Logger, ONSET).

On 15 September 2015, before the occurrence of any rainfall following the wildfire, the six randomly selected plots were mulched with chopped eucalypt logging slash residues (mainly composed of bark shreds, twigs and leaves) which were purchased at a cost of 30 € per Mg as they are being used in biomass energy plants. Before application, the residues were sieved at 30 and then 4 cm mesh width to exclude the largest as well as the smallest fractions, as the former may induce a high variability in application rate and the latter are expectedly least effective in reducing soil erosion (Foltz and Wagenbrenner, 2010). Mulching was done by applying the sieved residues homogeneously across the plots at two contrasting rates, i.e. a "standard" rate of 8.0 Mg ha^{-1} similar to that found to be extremely effective in earlier field studies in the region (Prats et al., 2012, 2014b, 2016a) and a "reduced rate" of 2.6 Mg ha^{-1} that was found to be highly effective under laboratory conditions of simulated rainfall and run-on (Prats et al., 2017). Fig. 1 illustrates the aspect of the two mulching rates shortly after their application.

3.2. Field data and sample collection

Between 15 September 2015 and 31 August 2016, the eroded sediments deposited on the geotextile at the bottom of the plots were collected at generally 1- to 2-weekly intervals, depending also on the occurrence of rainfall. Larger stones and recognizable plant parts (twigs, leaves etc.) on top of as well as mixed within the deposited sediment were removed as much as possible, first in the field and later in the laboratory, for being considered to have originated from other transport processes than overland flow (gravity, wind, leaf fall). During each field trip, also the volume of rainfall in the totalizer gauges was measured. The ground cover within the plots was monitored at roughly monthly intervals by taking near-vertical photographs from breast height at three fixed locations in each plot (at one, two and three quarters of the plot length).

3.3. Laboratory analyses

After careful inspection and removal of stones and recognizable plant parts, the collected sediments were quantified by determining their dry mass content through oven-drying at 105 °C for 24 h (APHA, 2005). Subsequently, the sediments' organic matter content was determined using the loss-on-ignition method (Pribyl, 2010), using 2 g of soil placed in a muffle furnace at 550 °C for 4 h.

3.4. Data analyses

The readings of the soil moisture probes were corrected for probe-specific deviations based on their readings for four fluids with a wide range of dielectric permittivity. The standardized readings were then converted into plot-wise median values per monitoring period and month. The ground cover pictures were analyzed by drawing a 1-m^2 grid of 10 cm by 10 cm over them, and then visually classifying the cover at the 100 intersection nodes into one the following six categories: stones; bare soil; ashes and charcoal (further referred to as "ash"); litter (including the applied logging slash residues); moss; higher plants. The plot-wise average values for each cover category were then converted into monitoring period-wise and monthly values, through simple linear interpolation of the values from the preceding and succeeding dates of photography.

The impact of the treatments on sediment and organic matter losses, monthly ground cover values, and monthly topsoil moisture contents were tested for overall statistical significance by means of linear mixed-effects models with plot-wise repeated measurements structures, using treatment as fixed factor, and blocks and plots as random factors. Sediment and organic matter losses were log-transformed to meet the assumptions of normality (Shapiro-Wilk test) and homoscedasticity (Levene's test) of the model residuals. In case the overall treatment effect was significant, the values of the dependent variable were tested for significant differences between the three treatment for each individual time step (month), by means of Tukey's HSD. All statistical analyses were done in SPSS v.20.

In the case of the linear mixed-effects models for sediment and organic matter losses, ante-dependence first-order structures were selected as the most appropriate covariance structures, based on the lowest −2 log restricted likelihood statistics proposed by Littell et al.

Fig. 1. Illustration of the "reduced" (right plot: 2.6 Mg ha^{-1}) and "standard" (left plot: 8.0 Mg ha^{-1}) application rates of sieved eucalypt logging residues mulch, shortly after mulching in September 2015. Note that the 2 m by 8 m plots are located in between the eucalypt planting lines.

(2006). This implies that the variance among observations changed over time. Ante-dependence first-order structures allow the time step between observations to vary (Littell et al., 2006; Shek and Ma, 2011) or, in the present context, allow to first analyse the full, 1- to 2-weekly data set of sediment and organic matter losses and, thereby, add to the robustness of the analyses at the monthly time step. The forward selection procedure of the significant covariates of 1- to 2-weekly sediment and organic matter losses considered the following seven variables (and their interactions with treatment): maximum rainfall intensity over 30 min (I30), median soil moisture content, and average cover of stones, bare soil, ash and charcoal, and higher plants. Average moss cover was excluded for having tested positively for collinearity. The best fitting models were then re-applied to the monthly sediment and organic matter losses, which resulted in very similar albeit slightly worse test statistics.

4. Results

4.1. Treatment effectiveness in terms of targeted variable: litter cover

The application of mulch in September 2015 produced significant differences in litter cover between all three treatments, ranging from an average of 2% in the untreated plots to 50% and 79% in the plots mulched at reduced and standard rates, respectively (Fig. 2). The differences between the untreated and mulched plots continued to be significant till the end of this study, while those between the two application rates stopped being significant in May 2016. Even so, the difference in average litter cover between the two mulching treatments never dropped below 10%.

Both mulching treatments revealed a clear temporal pattern in average litter cover, decreasing gradually from its application in September 2015 till May–June 2016 and then again increasing somewhat, especially from June to July 2016 with roughly 10%. This decrease in average litter cover with time was noticeably faster in the case of the standard application rate than of the reduced rate, with roughly −4 vs. –2% per month between September 2015 and June 2016. The increase in litter cover after June 2016 was not unique to the mulched plots but was also observed in the untreated plots, probably reflecting leaf shedding from the resprouting eucalypts bordering the erosion plots.

4.2. Treatment impacts on non-targeted variables: other soil cover types and soil moisture content

Besides litter cover, also stone cover and bare soil cover revealed a significant treatment effect over the entire study period (F: 59.4 and 45.3, respectively). Immediately afterwards, in September 2015, mulching lowered the average bare soil cover from 37% in the untreated plots to 23 and 9% in the plots mulched at reduced and standard rate, respectively, and the average stone cover from 21 to 13 and 7%, respectively (Fig. 3). Over the subsequent months, average bare soil cover tended to decrease somewhat in the plots without mulching (minimum: 24%) as well as in the plots with reduced mulching (minimum: 15%), while it remained basically the same in the plots with standard mulching. Average stone cover equally lacked conspicuous variation with time, independent of treatment. By contrast, average higher-plant cover followed a marked temporal pattern that was similar for all treatments, increasing gradually till a maximum in June 2016 and then decreasing again somewhat, possibly as a result of the die-back of annual plant species. There were some hints that mulching hampered vegetation recovery. First, the maximum higher-plant cover – mainly composed of *Agrostis curtisii* Kerguélen, *Pterospartum tridentatum* (L.)Willk, *Ulex spec.* and *Erica spec.* - was higher in the untreated plots than in the mulched plots (52 vs. 38–42%); second, the maximum moss cover was higher in the untreated plots than in the plots with reduced mulching and, especially, in the plots with standard mulching (5 vs. 3 vs. 1%).

Topsoil volumetric moisture content was significantly impacted by treatment over the study period as a whole (F: 65.1). Also, average moisture content was significantly higher in the plots with standard mulching than in the plots without mulching in all but the last three - summer - months of the study period (Fig. 4). These significant differences typically corresponded to a difference in volumetric soil moisture content of 3–4%. By contrast, significant differences between reduced and no mulching were entirely lacking, while significant differences between the two mulch application rates were limited to three months falling in two distinct periods (September 2015 and April–May 2016). Nonetheless, there was a consistent pattern for average soil moisture content to increase from untreated to reduced to standard mulching in all study months. Average monthly values were, in median, 3% and 1% higher in the plots with standard and reduced mulching, respectively, than in the untreated plots.

4.3. Treatment effectiveness in terms of the principal soil threat: soil erosion by water

Mulching had a significant overall impact on sediment losses over the study period, while I30 and topsoil moisture content were covariates with a significant, positive effect and higher vegetation cover with a significant, negative effect (Table 1). The significant interaction of I30

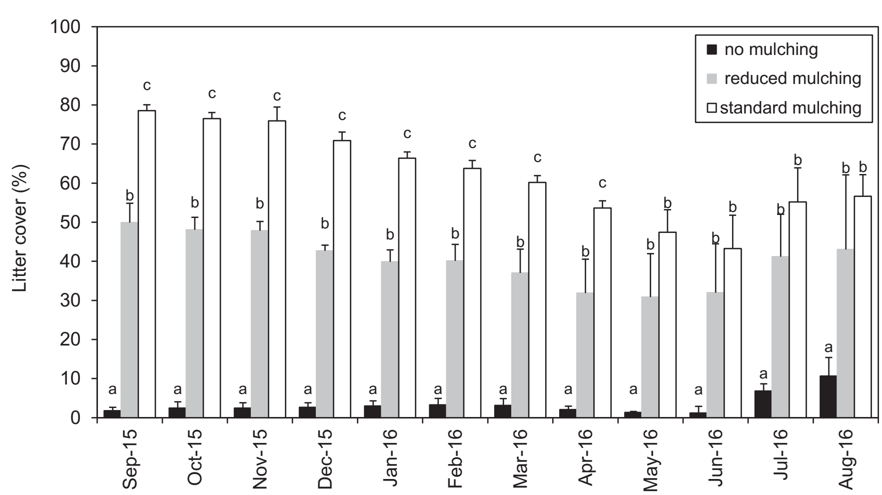

Fig. 2. Average monthly litter cover for three post-fire measures in an august-2015 burnt Portuguese eucalypt plantation. The letters a, b and c indicate statistically significant differences between plots without and with mulching at reduced and standard application rate.

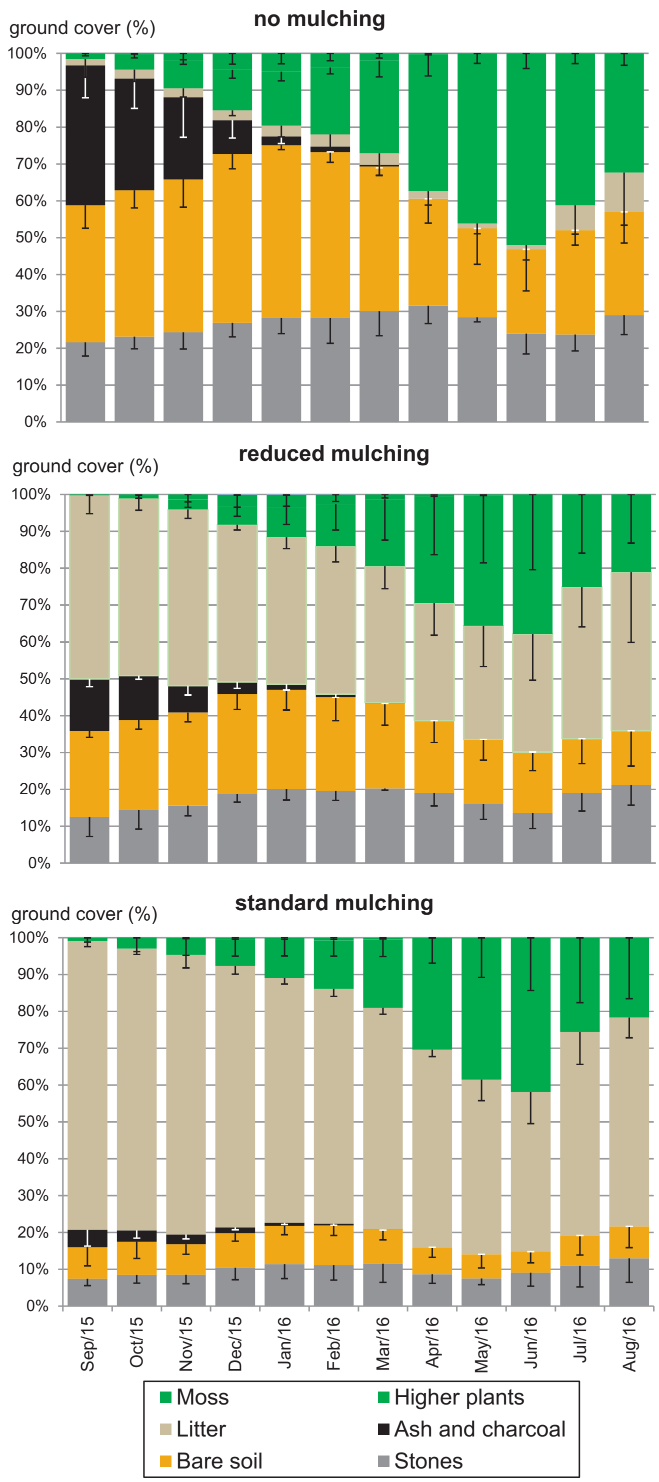

Fig. 3. Average monthly values of the six identified ground cover categories for three treatments (untreated vs. euclaypt logging residues mulching at reduced vs. standard rate) in an August-2015 burnt Portuguese eucalypt plantation.

and treatment indicated that the effect of I30 on sediment losses was not the same for the three treatments, indicating distinct erosion responses for the treatments. In fact, average sediment losses over the first year following the wildfire differed substantially between the three treatments, ranging from 8.0 Mg ha^{-1} for the untreated plots, to 1.1. Mg ha^{-1} for the plots mulched at the reduced application rate, and to 0.3 Mg ha^{-1} for the plots mulched at the standard rate. Hence, the overall effectiveness of mulching to reduce the first-post-fire-year sediment losses was only 10% lower for the reduced than standard rate (86 vs. 96%). Worth noting is that the study year was relatively wet, with a total rainfall of 1295 mm, i.e. some 50% above the long-term mean at the nearest weather station of Carapinhal.

The average monthly sediment losses suggested that the role of mulching (rate) was consistent over the first post-fire year, with values decreasing systematically from untreated to reduced to standard mulching (Fig. 5). The differences between standard and no mulching were also significant for all ten study months with rainfall, while the differences between reduced and no mulching were significant for the initial eight months. The differences between the two mulch application rates were significant in six out of ten cases (i.e. the ten months with rainfall), apparently with some tendency to occur later on in the study (January–May 2016). Average monthly sediment losses peaked in January 2016 for all three treatments, when monthly rainfall first exceeded 100 mm following the wildfire and, at the same time, maximum rainfall intensity first exceeded 20 mm h^{-1} (Fig. 4). This peak value was clearly more pronounced in the case of the untreated plots than in the case of the mulched plots, amounting to 39 as opposed to 22% of the total sediment losses over the study period.

In line with the abovementioned tendency in significant differences in monthly sediment losses between the two mulching rates, the monthly treatment effectiveness of the reduced mulching rate seemed to decline gradually after January 2016, whereas that of the standard mulching rate remained by and large constant till May 2016 (Fig. 6). The initial effectiveness of both mulching rates during September 2015 stood out as relatively low compared to the effectiveness during the ensuing autumn and (early) winter months (77–80 vs. 88–98%).

4.4. Treatment impacts in terms of the secondary soil threat: organic matter losses

Organic matter losses over the entire study period amounted, on average, to 1.7, 0.2 and 0.1 Mg ha^{-1} for the plots without and with reduced and standard mulching, respectively. Hence, organic matter constituted a noticeably similar, substantial fraction of the overall sediment losses for all three treatments (20–22%). Also, the effectiveness of the two mulching rates to reduce organic matter losses over the first post-fire year was basically the same as their effectiveness to reduce sediment losses, i.e. 87 and 96%.

The organic matter content of the eroded sediments varied somewhat between the different months, with the range of average monthly values being smaller for the plots with reduced mulching (17–23%) than for the untreated plots (15–27%) and the plots with standard mulching (19–32%). Even so, average monthly organic matter losses were very strongly linearly correlated with average monthly sediment losses for each of the three treatments (Pearson's correlation coefficient: 0.98–0.99). Not surprisingly therefore, overall and monthly statistical test results for organic matter losses closely matched those for sediment losses (Table 1, Fig. 7) and monthly patterns in treatment effectiveness did so too (Fig. 8).

5. Discussion

5.1. Treatment effectiveness in terms of principal soil threat: soil erosion by water

The present results fitted in well with two principal findings of the precursor laboratory study by Prats et al. (2017). The authors found that an overall mulch cover of 50% was sufficient to reduce inter-rill erosion (as produced by their simulated rainfall runs) very substantially (with 94%) but, at the same time, that an overall mulch cover of 70% was clearly more effective, reducing inter-rill erosion with 99%. The differences in actual effectiveness figures between Prats et al. (2017) and this study (94 vs. 86% and 99 vs. 96%) could be regarded as surprisingly minor, given the major discrepancies in the two studies'

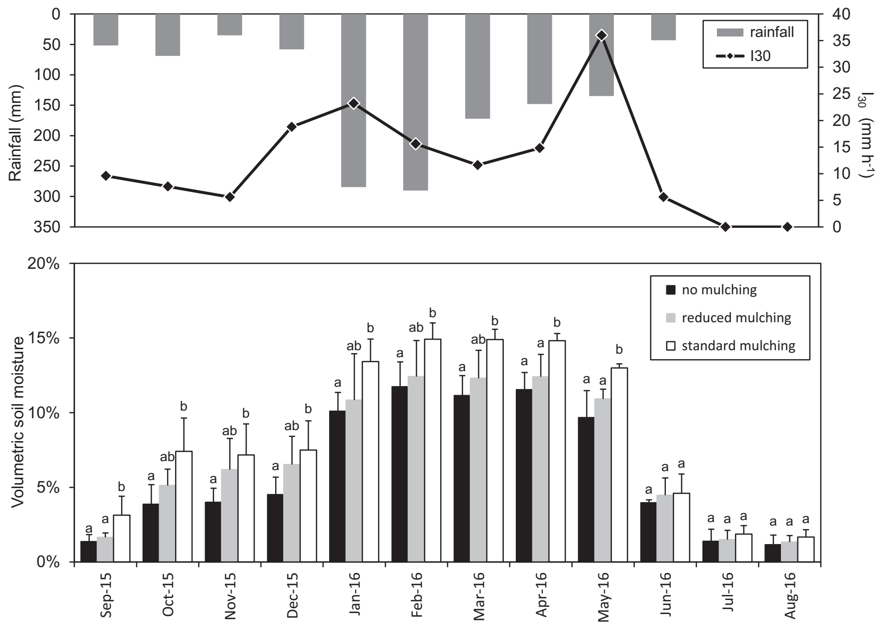

Fig. 4. Median monthly volumetric topsoil moisture contents for three post-fire measures in an august-2015 burnt Portuguese eucalypt plantation, as well as monthly rainfall totals and maximum 30-min rainfall intensities (I30). The letters a, b and c indicate statistically significant differences between plots without and with mulching at reduced and standard application rates.

Table 1
Linear mixed-effects modeling results of log-transformed monthly sediment and organic matter losses of three post-fire measures (doing nothing and forest residue mulching at reduced and standard application rate) during the first year following a wildfire in a Portuguese eucalypt plantation. Not listed are the covariates (rainfall total and stone, bare soil and ash cover) the covariate-treatment interactions that are not significant (ns) in both cases.

	Sediment losses (log (Mg ha^{-1}))			Organic matter losses (log (Mg ha^{-1}))		
	n	F-value	Estimate	n	F-value	Estimate
Intercept	1	660.2		1	1637.0	
Fixed factor						
Treatment	2	7.4		2	12.9	
Covariates						
I_{30}	1	291.4	0.05	1	292.3	0.04
Treatment *I_{30}	2	14.5		2	18.30	
Topsoil moisture content	1	10.0	1.60	1	ns	
Higher-vegetation cover	1	34.1	−0.01	1	30.80	−0.01
Treatment ∗ higher-veg. cover	2	ns		2	6.62	

experimental conditions as well-illustrated by the erosion rate of 250 Mg ha^{-1} of the control treatment (bare "soil") in Prats et al. (2017).

The present results also agreed well with the findings of prior field studies in the study region, which suggested that mulching with eucalypt logging residues at "standard" application rates of roughly 10 Mg ha^{-1} was highly effective in reducing enhanced erosion rates in eucalypt plantations during the initial stages of the fire-induced window-of-disturbance. Prats et al. (2012) found an 84% difference in post-fire sediment losses between untreated plots and plots mulched at 8.7 Mg ha^{-1}, with losses amounting to 5.4 and 0.7 Mg ha^{-1}, respectively, over an approximately 1 year period following mulching. Possibly, this somewhat lower effectiveness in Prats et al. (2012) was due to their somewhat lower litter cover immediately after mulching (70 vs. 79%) but also the later timing of their mulch application (four months after the fire) could have played a role. An effectiveness of "standard" mulching more similar to the present one was reported by Prats et al. (2016b). The authors found that micro-scale plots (c. 0.5 m2) mulched at 11 Mg ha^{-1} produced 93% less sediments over the first post-fire year than untreated micro-scale plots, while large-scale plots (roughly 100 m2) mulched at 14 Mg ha^{-1} produced 96% less sediments. Possibly, this – admittedly, small - difference in percent-wise effectiveness in Prats et al. (2016b) reflected the role of plot size (and associated decrease in erosion rate) rather than of mulch application rate, as the micro-scale plots had a higher litter cover immediately after mulching than the large-scale plots (87 vs. 77%) but, at the same time, produced roughly twice as much sediments without treatment (9.5 vs. 4.6 Mg ha^{-1}). The present rates of erosion reduction were furthermore in good agreement with those reported by the only other post-fire erosion mitigation studies that seemed to have tested the effectiveness of mulching with eucalypt logging residues, both in Galicia, north-west Spain (Fernández and Vega, 2014, 2016a). Fernández and Vega (2014) found that mulching at 3.5 Mg ha^{-1} reduced soil loss with 87%, while Fernández and Vega (2016a) reported that mulching at 11 Mg ha^{-1} reduced soil loss with 84%. Other types of tree-based mulches have also been tested for post-fire erosion mitigation, in particular wood chips (Kim et al., 2008; Fernández et al., 2011) and wood strands (Robichaud et al., 2013). Woodchips were reasonable effective in the case of Kim et al. (2018) but very poorly in the case of Fernández et al. (2011), reducing post-fire erosion rates with 51 and 6%, respectively, possibly due to the higher ground cover initially provided in the former than latter case (70 vs. 45%). Robichaud et al. (2013) found that wood strands providing an initial ground cover of 50–55% reduced sediment losses over the first post-fire year to a similar or greater extent than the reduced mulching rate studied here, depending on burnt area (79 and 96%, in the School and Hayman fore, respectively).

Worth highlighting in the present results was further that the reduced mulch application rate was sufficient to keep post-fire sediment losses during the first post-fire year within the bounds of the precautionary threshold value of tolerable hill slope soil erosion of 1 Mg ha^{-1} y^{-1} proposed by Verheijen et al. (2009, 2012). Although this figure will be averaged out with time-till-the-next-wildfire, a more ambitious target may still be recommendable to guarantee long-term sustainable forest productivity in the north-central Portuguese mountain ranges. Namely, the soils in the region are typically shallow (Malvar et al., 2013; Shakesby, 2011; Tavares-Wahren et al., 2016), recurrence intervals between wildfires are likely to shorten with climate change Cardoso Pereira et al., 2006; Nunes et al., 2018), and the impacts of recurrent fires on soil (fertility) continue poorly studied (Malkinson et al., 2011; Hosseini et al., 2016, 2017a, 2017b).

The prevalence of maximum rainfall intensity over rainfall total to explain post-fire sediment losses was in line with the results of prior

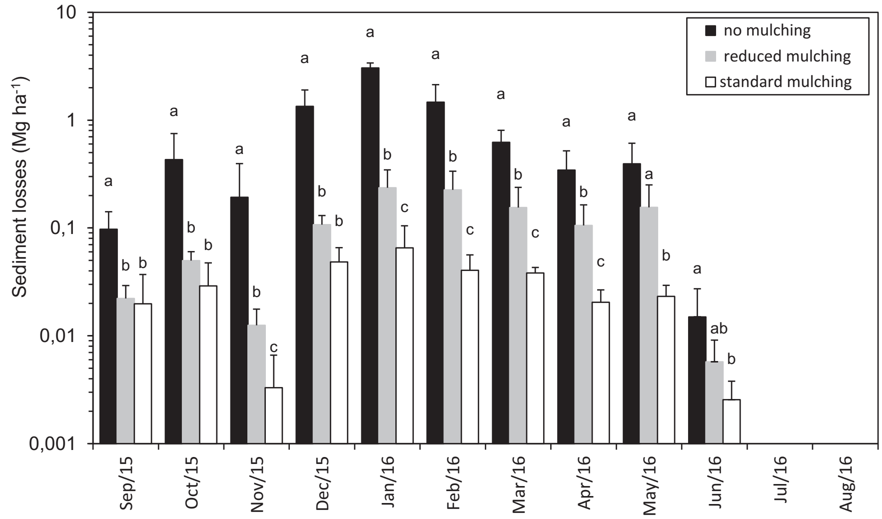

Fig. 5. Average monthly sediment losses for three post-fire measures in a Portuguese eucalypt plantation during the first year following a moderate-severity wildfire. The letters a, b and c indicate statistically significant differences between plots without and with mulching at reduced and standard application rates.

studies in recently burnt eucalypt plantations in north-central Portugal. In the case of Malvar et al. (2016), maximum rainfall intensity over 15 min (I15) was one of the significant covariates for sediment losses at the micro-plot scale over the first two years following wildfire, while rainfall total was for runoff amounts. The same applied, mutatis mutandis (maximum rainfall intensity over 30 min (I30) instead of I15), for the combined micro- and large-scale plot data in Prats et al. (2016b). Likewise, in the case of Prats et al. (2012) I30 explained a much larger fraction of the variance in sediment losses than rainfall total, while the opposite was true for runoff amounts.

5.2. Treatment impacts on the secondary soil threat: organic matter losses

The close agreement in the present study between the effectiveness of mulching to reduce organic matter losses as opposed to sediment losses was also observed in the two prior field experiments that tested "standard" application rates of eucalypt logging mulch in recently eucalypt plantations in north-central Portugal. In the case of Prats et al. (2012), organic matter losses were 88% lower in the mulched than untreated plots, whereas sediment losses were, as mentioned earlier, 84% lower. In the case of Prats et al. (2016b), the percent-wise difference in organic matter losses between mulched and untreated plots was exactly the same as the difference in sediment losses for the micro-scale plots (93%) and a mere 1% higher for the large-scale plots (97%). The present organic matter losses from the untreated plots closely matched those of the large-scale plots of Prats et al. (2016b: 1.9 Mg ha^{-1}). The same was true regarding Prats et al. (2012), especially when the losses from their second post-fire autumn in 2008 were ignored (1.9 as opposed to 2.6 Mg ha^{-1}).

In spite of the above, the organic matter contents of the eroded sediments reported here (20–22%) were markedly lower than those reported by the two Prats et al. (2012, 2016b) studies over the first 1–1.5 years following wildfire. This was most conspicuous for the untreated plots, with average values ranging from 41% (Prats et al., 2016b: large-scale plots), to 46% (Prats et al., 2012) and 56% (Prats et al., 2016b: micro-scale plots). For untreated micro-scale plots, Malvar et al. (2016) reported an intermediate organic matter content of approximately 50% that appeared to vary little with time over the first two years following wildfire. A typical range of 40–55% was also suggested by Prats et al. (2016b), based on their revision of the – very few – existing studies with data on the organic matter content of sediment eroded following wildfire or prescribed burning. The comparatively low organic matter contents in the untreated plots of this study could be due to the limited ash load of the thin O horizon immediately after the fire, possibly reflecting reduced pre-fire fuel loads as a result of understory vegetation management in between the eucalypt planting rows and/or a previous fire in 2000. Such a limited ash load could also explain why the eroded sediments of the untreated and mulched plots of this study had basically the same organic matter content, especially also since the organic matter content of the topsoil was of the same order of magnitude (15–18%). By contrast, the untreated plots of Prats et al. (2012) revealed a marked enrichment of the eroded sediments in organic matter content compared to the mulched plots (46 vs. 23%). To a lesser extent, the same was true the large-scale plots of Prats et al. (2016b: 41 vs. 23%), while the opposite applied to the micro-scale plots of Prats et al. (2016b: 56 vs. 62%). This contrasting finding at the micro-plot scale could reflect a more complete export of the ash layer due to the shorter transport distance to the plot outlet.

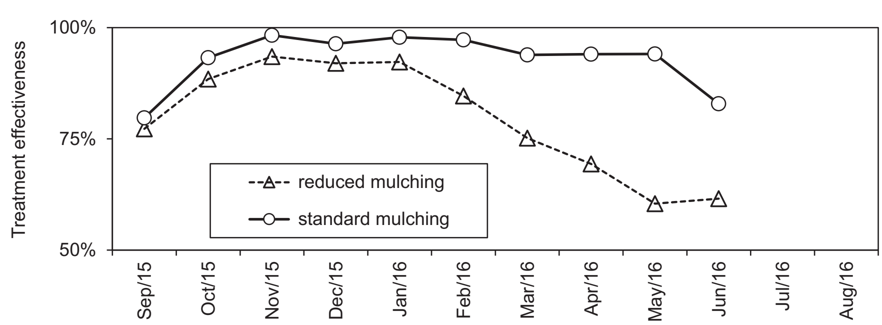

Fig. 6. Effectiveness of two contrasting application rates of eucalypt logging residues mulch to reduce average monthly sediment losses in a Portuguese eucalypt plantation during the first year following a moderate-severity wildfire.

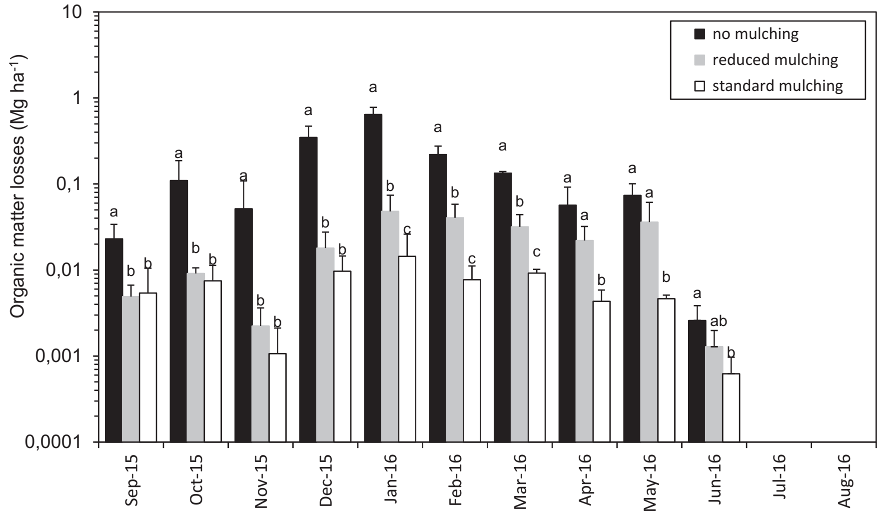

Fig. 7. Average monthly organic matter losses for three post-fire measures in a Portuguese eucalypt plantation during the first year following a moderate-severity wildfire. The letters a, b and c indicate statistically significant differences between plots without and with mulching at reduced and standard application rates.

The present finding that post-fire organic matter losses, like sediment losses, were better explained by rainfall intensities than by rainfall totals fitted in with the results obtained by Malvar et al. (2016), apparently the only study that had explicitly addressed this topic so far.

5.3. Overall discussion

The results of this study would seem to constitute an important argument for the further testing of mulching with eucalypt logging residues in eucalypt plantations, one of the predominant and, at the same time, most fire-prone forest types in Portugal (Cardoso Pereira et al., 2006; Moreira et al., 2009). Mulching with eucalypt logging residues at an application rate of around 3 Mg ha^{-1} would seem a suitable alternative to straw mulching in an operational setting, as straw is typically applied at rates of 2–3 Mg ha^{-1} for post-fire hillslope stabilization in the USA (Robichaud et al., 2010) as well as Galicia (Vega et al., 2013). Furthermore, the effectiveness of 2–3 Mg ha^{-1} of straw mulch has been found to vary considerably, not only between but also within burnt areas, with reductions in post-fire sediment losses typically exceeding 50% (Bautista et al., 1996: 50–95%; Wagenbrenner et al., 2006: > 95% over the second to fourth post-fire years; Fernández et al., 2011: 66%) but ranging from 5 to 98% in the case of Robichaud et al. (2013: the first post-fire year). Robichaud et al. (2013) attributed their instances of poor effectiveness to when a fast decline of the straw cover was accompanied by a poor recovery of the spontaneous vegetation. To overcome this potential limitation of straw mulching, Badía and Martí (2000) combined it with seeding but the increase in effectiveness compared to just seeding was somewhat limited (+4 and +16%), possibly because of the reduced application rate of 1 Mg ha^{-1}. Fernández and Vega (2016b) also found a low straw mulch application rate to be poorly effective, with 1.5 Mg ha^{-1} of straw reducing post-fire erosion by 38%. While straw mulching does not tend to have negative impacts on post-fire recovery of spontaneous or seeded vegetation (Badía and Martí, 2000; Wagenbrenner et al., 2006; Fernández et al., 2011), the present results suggested that the same may not be true for mulching with eucalypt logging residues. Although Fernández and Vega (2016a) did not find any such detrimental effects of eucalypt bark strand mulch on post-fire regeneration of the natural vegetation, further research would seem recommendable, also against the background of fuel load management.

In regions such as north-central Portugal, the main limitation to using straw for post-fire mulching is arguably its scarcity (even more so in drought years as 2017), while eucalypt logging residues are widely available and are being gathered and treated commercially for use in bioenergy plants (Prats et al., 2014a). Even so, large-scale application of eucalypt logging residue mulch would still seem to require detailed analysis of actual mulch availability as well as of a series of logistic challenges that have already been overcome in the case of straw mulching, both in the case of manual and aerial mulching. Also, acceptance and/or adoption of post-fire emergency stabilization measures and, in particular, mulching by private landowners and forest managers cannot be taken for granted, in part because of lack of familiarity with these measures. This was one of the key outcomes of the third stakeholder workshop in the RECARE case study in Portugal, with the lack of familiarity with these measures (including their logistical aspects) as well as their costs being appointed as main barriers.

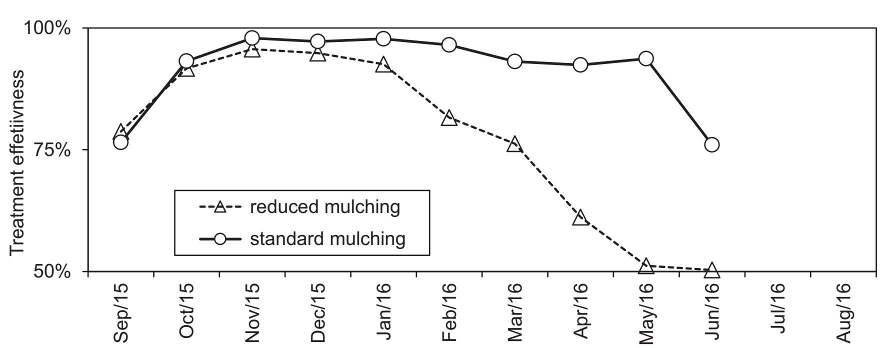

Fig. 8. Effectiveness of two contrasting forest residue mulch application rates to reduce average monthly organic matter losses in a Portuguese eucalypt plantation during the first year following a moderate-severity wildfire.

In the meantime, further research is recommended to test, under field conditions, if mulch application rates can be further optimized through spatially-explicit application schemes such as strips. The laboratory results of Prats et al. (2017) did indeed suggest that mulch strips could be highly effective, especially in the absence of (concentrated) run-on from upper slope parts or forest tracks. Mulch application in strips would definitely be greatly facilitated by the extensive forest track networks that are typical in eucalypt plantations in north-central Portugal.

6. Conclusions

The main conclusions of this study into the effects of two contrasting application rates of eucalypt logging residues mulch on soil erosion by water as well as on targeted and untargeted soil properties in a eucalypt plantation in north-central Portugal during the first year following a moderate-severity summer wildfire were the following:

- While mulching at a "standard" application rate of 8.0 Mg ha^{-1} was confirmed to be extremely effective in reducing overall sediment losses from 8.0 to 0.3 Mg ha^{-1} y^{-1}, mulching at a roughly 3-times lower rate was found to be highly effective too, reducing overall losses to 1.1 Mg ha^{-1} y^{-1} and significantly reducing monthly losses of the first eight and most rainy months after the wildfire;
- The effectiveness of both application rates to reduce organic matter losses by runoff closely matched their effectiveness to reduce sediment losses, with losses of 0.1 and 0.2 rather than 1.7 Mg ha^{-1} y^{-1}, in spite of the fact that the organic matter content of the eroded sediments was relatively low compared to that of prior field studies in the same region;
- Litter cover decreased gradually with time-since-mulching but more markedly so in the case of the standard than the reduced mulch application rate;
- The significant impact of mulching on sediment losses could in part be explained by its effects on topsoil moisture content.

Acknowledgements

This study was funded through the EU-FP7 project RECARE (grant no. 603498), with additional support by CESAM, through the strategic project UID/AMB/50017, funded by the FCT/MEC with co-funding by the FEDER, within the PT2020 Partnership Agreement and Compete 2020. JJK further wants to acknowledge his IF-FCT research grant (IF/01465/2015), and SPA and DCSV their FCT post-doctoral grants (SFRH/BPD/97851/2013 and SFRH/BPD/114898/2016, respectively). Finally, we would like to acknowledge the comments and suggestions by two anonymous reviewers and one of the guest-editors, as they have allowed us to markedly improve this manuscript.

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