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EFFECTS OF PLOUGHING AND MULCHING ON SOIL AND ORGANIC MATTER LOSSES AFTER A WILDFIRE IN CENTRAL PORTUGAL

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ABSTRACT. *Forest wildfires typically increase runoff and associated soil and organic matter losses. Both ploughing and mulching with forest residues have been applied in recently burnt areas in Portugal to mitigate these effects in soil erosion, but their effectiveness has never been compared directly. To this end, soil and organic matter losses by water after a wildfire were studied in two eucalypt plantations in central Portugal that had been affected by the same wildfire (August 2015). One of the sites was instrumented with six erosion plots (2 m by 8 m), divided over two blocks with one treatment per block: control (doing nothing) and ploughing to 0.2 m depth with a tracked excavator. The other site was instrumented with nine erosion plots, divided over three blocks with three treatments in each block: control (doing nothing) and mulching with forest logging residues at reduced (2.6 Mg ha^{-1}) and standard application rates (8 Mg ha^{-1}). Mulching was performed one month after the wildfire, whereas ploughing took place one year after the wildfire. For this study, soil and organic matter losses were monitored at 12 occasions from July 2016 to May 2017, roughly coinciding with the second post-fire year. Over this relatively dry period sediment losses at the control plots of both ploughed and mulched sites averaged 1.6 and 0.6 Mg ha^{-1} respectively. The corresponding losses of the ploughed plots were 19% lower, whereas those of the mulched plots were 67 and 93% lower at the reduced and standard mulch rates, respectively. The organic matter content of the eroded sediments was 22% in the unploughed plots, and ploughing reduced this figure in half, which could be explained by the inversion of the topsoil horizons by the excavator. Mulching at the standard application rate seemed to produce a clear enrichment in organic matter content compared to mulching at the reduced rate as well as doing nothing (25 vs. 16 and 14%). The two main findings of this research were that i) erosion rates exceeded the 1 Mg ha^{-1} tolerable soil loss during the second post-fire year, indicating that mitigation measures have to be implemented, ii) ploughing was clearly less suited for mitigating post-fire erosion than mulching with forest logging residues, even at application rates as low as that typically used in operational post-fire emergency stabilization with straw mulching.*

Efecto del labrado y del acolchado en las pérdidas de suelo y materia orgánica después de los incendios en el centro de Portugal

RESUMEN. *Los incendios forestales suelen incrementar la escorrentía superficial, la erosión del suelo y de la materia orgánica asociada. Técnicas como el labrado o el acolchado de restos forestales han sido realizadas en Portugal para mitigar estos efectos, pero sus efectividades no han sido nunca comparadas directamente. En este estudio se analiza la efectividad de estas técnicas en el control de la erosión hídrica y de las pérdidas de materia orgánica en dos plantaciones de eucalipto quemadas por el mismo incendio en Agosto de 2015 en el Centro de Portugal. En una ladera se instalaron seis parcelas de 2 m x 8 m, divididas en dos bloques con un tratamiento por bloque: control (sin intervención) y labrado del suelo a 20 cm de profundidad con una retroexcavadora. En la otra ladera se instalaron nueve parcelas en tres bloques, con tres tratamientos por bloque: control (sin intervención), acolchado (mulching) con restos forestales triturados aplicados a una tasa reducida (2.6 Mg ha*$^{-1}$*) y otra estándar (8.0 Mg ha*$^{-1}$*). El acolchado fue aplicado un mes después del incendio, mientras que el labrado ocurrió once meses después del incendio. La erosión del suelo fue monitorizada entre Julio 2016 y Mayo 2017, coincidiendo con el segundo año post-incendio. La erosión del suelo para este periodo relativamente seco fue de 1.6 y 0.6 Mg ha*$^{-1}$*, respectivamente para las parcelas control de las laderas labrada y acolchada. La erosión de suelo en las parcelas labradas fue un 19% menor que la erosión en las parcelas sin labrar, mientras que la erosión en las parcelas con acolchado a tasas reducida y estándar fue, respectivamente, un 67 y 93% menor que la erosión medida en las parcelas sin acolchado. El contenido de materia orgánica en los sedimentos fue de un 22% en el caso de las parcelas sin labrar. En el caso de las parcelas labradas esta cantidad se redujo a la mitad, lo que puede ser atribuido a la inversión de los horizontes edáficos por acción del labrado. El acolchado con tasa de aplicación estándar parece inducir un claro enriquecimiento en el contenido de materia orgánica de los sedimentos, especialmente si lo comparamos con la tasa reducida y con las parcelas sin acolchado (25 vs. 16 y 14%). Se concluye que: i) las pérdidas de suelo excedieron el umbral tolerable de 1 Mg ha*$^{-1}$* durante el segundo año después del incendio, lo que indica que hay que tomar medidas de mitigación de la erosión, ii) el labrado fue claramente menos efectivo para mitigar la erosión post-incendio que el acolchado de residuos forestales, incluso a tasas de aplicación tan bajas como las utilizadas típicamente en operaciones post-incendio con acolchados de paja.*

Key words: Ploughing, mulching, soil erosion, organic matter, wildfires.

Palabras clave: Labrado, acolchado, erosión, materia orgánica, incendios.

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1. Introduction

The effects of wildfires on vegetation and litter combustion and on soil properties have been exhaustively studied (Shakesby and Doerr, 2006; Shakesby, 2011; Francos *et al.,* 2016). Effects on hydrological and geomorphologic processes often include an increase in runoff rates, soil erosion and organic matter losses, with the consequent loss of biomass productivity and decline on short- to medium-term soil biodiversity (Badia and Marti, 2000; Cairney and Bastias, 2007).

Outside of the burned area other effects can happen, namely an increase of floods risk and downstream water bodies pollution (Cerdà and Doerr, 2008; Shakesby, 2011). In addition to the direct and indirect effects of wildfires, forest management practices can also increase runoff and soil erosion in burned areas (Shakesby *et al.,* 1996; Malvar *et al.,* 2016), thus highlighting the need for application of effective post-fire erosion mitigation measures. Ploughing is a traditional forest management practice that is usually performed on each 30 to 40 years with the aim of uproots old stumps, replanting or seedling (Shakesby *et al.,* 1996; Padilha *et al*., 2017). Some studies referred some advantages in its application, such as reducing competition with other plant species and improving accessibilities to the plantation areas (Robichaud *et al.,* 2000; Malvar *et al.,* 2016). Ploughing has been considered as an effective technique to reduce compaction resulting from the forestry heavy machinery (Robichaud *et al.,* 2000), since it increases the macropores volume, surface roughness and water infiltration capacity (Shakesby, 2011; Malvar *et al.,* 2016). However, when applied at larger scales or in areas with slopes higher than 15º, it can potentially increase soil losses (Robichaud *et al.,* 2000).

The application of organic materials such as mulches has been widely used in the USA as a post-fire soil erosion mitigation measure. Mulching promotes surface soil cover, reduces the direct impact of raindrops and creates obstacles to overland flow and detachment of soil particles (Robichaud *et al.,* 2013), thus increasing infiltration rates (Badia and Marti, 2000; Jourgholami and Abari, 2017). Both straw and forest residue mulches are able to reduce post-fire soil erosion in 80-90%, at application rates of 2 to 8 Mg ha^{-1} (Prats *et al.,* 2012, 2016; Fernández and Vega, 2014; Fernández *et al.,* 2016). So far, mulching has been rarely applied in Portugal as a post-fire soil erosion mitigation measure, due to the lack of knowledge on one hand, and on the other to the high application costs. The cost of a standard application of 8 Mg ha^{-1} of forest residue mulch, considering the machinery, manpower and availability of the organic material, was somehow expensive, as estimates are about 500-1000 € ha^{-1} (Prats *et al.,* 2012, 2014a). But on the other side, the costs of forest ploughing are far more expensive than mulching, and studies carried out in Portugal showed that ploughing can increase the soil erosion rates of burned areas from around 5 Mg ha^{-1} by year (Prats *et al.,* 2012, 2016) to ten times higher figures (Ferreira *et al.,* 1997; Martins *et al.,* 2013). There is a need to decrease the costs of mulching to do it a more feasible post-fire management tool, and at the same time, there is a need to assess how effective is ploughing as compared to mulching.

The aim of the present work was to compare the effects of two different post-fire management measures, namely ploughing and mulching with forest residues, to mitigate soil and organic matter losses. Specifically this work intended to: i) compare soil and organic matter losses in ploughed and unploughed plots in the second year after a wildfire; ii) compare soil and organic matter losses in mulched plots using two mulch application rates in the second year after wildfire; and iii) assess the most determinant factor in soil loss among time since fire, rainfall characteristics and soil cover.

2. Material and methods

2.1. Study area

The study was conducted at Semide parish, Miranda do Corvo municipality (40º 9.977' N, 8º 19.506' O, Fig. 1), located in central Portugal, coinciding with a part of the Ceira river basin. This area was affected by a wildfire that started on 9th August 2015, and that resulted in a burned area of approximately 719 ha (ICNF, 2015). This area was previously dominated by forest use, namely by eucalypt stands. For the implementation of the measures under study, two representative hillslopes were selected, distancing about 2 km from each other and presenting similar slope and aspect (slope angle ranging 20-27º and aspect NNE-ENE, see Table 1). The severity of the wildfire was similar in both slopes, presenting a complete combustion of the litter layer and predominantly black ashes, thus suggesting a moderate severity according to Shakesby and Doerr (2006). The climate of the area is Mediterranean with oceanic influence (Köppen climatic classification: Csb). The average annual temperature and precipitation in the last 22 years according to the information at the nearest meteorological station of the Environmental Portuguese Agency at Carapinhal, located 12 km apart were 12ºC and 851 mm, respectively. The parent material of the study area was pre-Ordovician schist of the Hesperic Massif (Pereira and Fitzpatrick, 1995) and the soils were classified as acidic loamy Epileptic umbrisol (IUSS-WBR, 2014), with high organic matter content, around 13% in both study sites (Table 1).

2.2. Experimental setup

About one month after a wildfire, the mulching experiment was implemented in a hillslope (Fig. 1), according to the experimental design presented in Keizer *et al.,* (2018). Nine erosion plots (8 x 2 m) were installed and divided over three blocks to study two mulching application rates: reduced (2.6 Mg ha^{-1}) and standard (8.0 Mg ha^{-1}). In each block two plots received the two mulch treatments randomly, remaining one plot unmulched for control purposes (Fig. 1). Before mulch application, the residues were sieved at 4 cm mesh width to exclude the expectedly least effective mulch fraction in reducing soil erosion (Prats *et al.,* 2017). Eleven months after a wildfire (on July 2016)

Table 1. Treatments, soils and hillslopes characteristics (standard deviation between brackets).

	Ploughed hillslope		Mulched hillslope		
	Unploughed (control)	Ploughed	Unmulched (control)	Low mulch	High mulch
Treatments characteristics					
Ploughing depth (cm)	0	20	-	-	-
Mulch application rate (Mg ha^{-1})	-	-	-	2.6	8.0
Nº plots by treatment (n)	3	3	3	3	3
Soils and hillslopes characteristics					
Fire severity	Moderate		Moderate		
Slope aspect (º)	N80E		N70E		
Plots steepness (º)	20(5)		27(2)		
Bulk density (g cm^{-3})	0.76(0.10)	0.83(0.14)	0.90(0.11)		
Stone content (g cm^{-3})	0.32(0.09)	0.28(0.07)	0.42(0.09)		
Organic matter content (%)	13.10(1.79)	12.52(2.42)	13.8(2.70)		
Plot projected area (m^2)	14.37	15.09	15.12	15.11	15.16

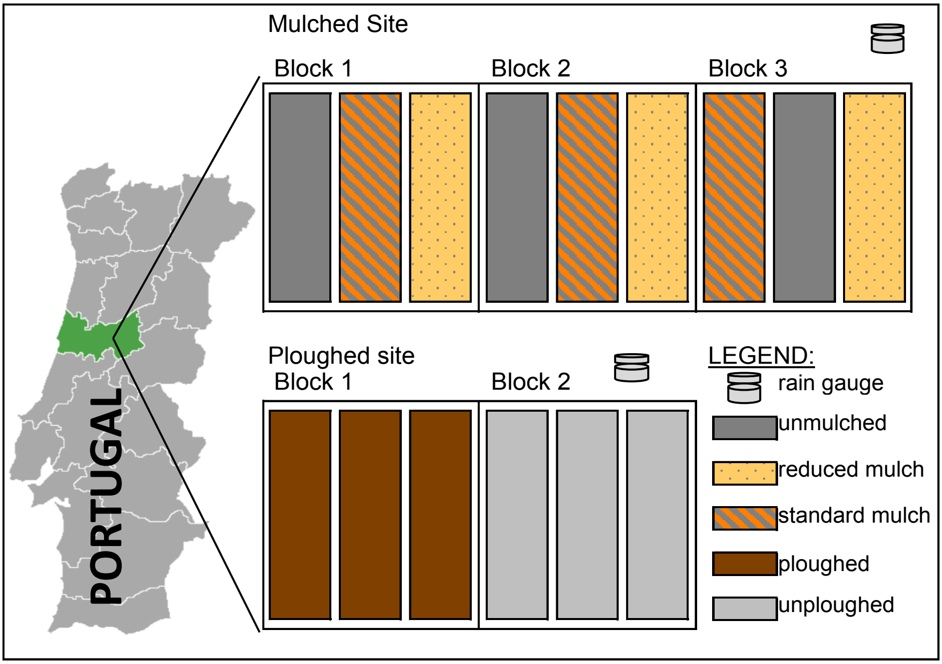

Figure 1. Geographical location of the study area and experimental design of the erosion plots.

the ploughing operation was carried out in another hillslope 2 km apart from the mulched hillslope. Ploughing consisted on moving the soil with a backhoe to a maximum depth of 20 cm in an area of 500 m^2 (Fig. 2). Three erosion plots with the same size were installed over the ploughed area, and other three were installed in a contiguous unploughed area to act as controls (Fig. 1). Erosion plots were bounded by trenches and silt fence fabric to avoid run-on into the plots and allowing the retention of the eroded sediments at their base. Each hillslope was instrumented with one rain gauge consisting of automatic tipping bucket type.

Figure 2. Pictures of the ploughing (a) and mulching (b). Numbers at the bottom of a sediment fences indicates (1) untreated, (2) ploughed, (3) standard mulch at a high application rate of 8.0 Mg ha^{-1} and (4) reduced mulch plots at a low application rate of 2.6 Mg ha^{-1}.

2.3. Field measurements and sampling

Field sampling campaigns were carried out at approximately weekly intervals or at longer intervals when no rainfall occurred. A total of twelve data read-outs were considered in the scope of this study, between July 2016 and May 2017. Each sampling field campaign consisted in monitoring the erosion plots by collecting and weighing the total amount of sediments eroded and transported by water to the bottom fenced area of the plot (Fig. 2), for further quantification of sediment moisture and organic matter contents. In the laboratory, a representative subsample of 2-5 g was collected to a crucible and dried for 24 hours at 105 ºC to determine the moisture content (APHA, 2005), and then ignited for 4 hours at 550 ºC to quantify the organic matter content (Pribyl, 2010).

2.4. Data treatment and analysis

Rainfall data were registered through the tipping bucket principle recorded in the automatic rainfall gauges. The total amount of rainfall (mm) was lumped for each period between sampling campaigns in order to relate erosion to the total rainfall occurred. The maximum 30-minutes rainfall intensity (I30, mm h^{-1}) was also calculated for each period.

Ground cover was assessed in the erosion plots on four occasions during the study period, with intervals of approximately two months. Each ground cover observation was performed in a different season of the year, end of summer (31 August 2016), end of autumn (6 December 2016), winter (24 January 2017) and beginning of spring (14 March 2017). An individual picture was taken in the bottom, middle and top of each plot. For cover classification, one virtual grid (corresponding approximately to 1 m^2) was drawn over each picture containing one hundred intersection nodes for further evaluation of soil cover, based on assignment of one of five cover categories: bare soil, litter (including mulching and debris), plants, moss and stones. These soil surface components are major proxies in soil erosion assessment (Hueso-González *et al.,* 2017).

For each experiment, a two-way analysis of variance model was built with treatment and time since fire as main effects repeated in the sampling campaigns. Dependent variables were log-transformed to guarantee the assumptions of normality and homogeneity of variance. Post-hoc tests, based on the Tukey-Kramer, were performed to separate the means between treatments, with a significance level of $p \leq 0.05$. SPSS v.20 program was used for these analyses.

3. Results

3.1. Rainfall amounts and intensity

Between July 2016 and May 2017, the total amount of rainfall was 556 and 572 mm in the ploughed and mulched hillslopes, respectively. These values corresponded to about 68% of the total rainfall that occurred in that hydrological year (831 mm) and 66% of the annual mean recorded in 22 years in the meteorological station at Carapinhal. The highest rainfall amount was registered on 11th November 2016 at both hillslopes (92 and 107 mm for ploughing and mulching slopes, respectively). However, rainfall intensities were different between sites, with the highest intensities occurring in the ploughing site on October 2016 (32 and 36 mm h^{-1}), while in the mulching site occurred in November 2016 (21 mm h^{-1}) (Fig. 3).

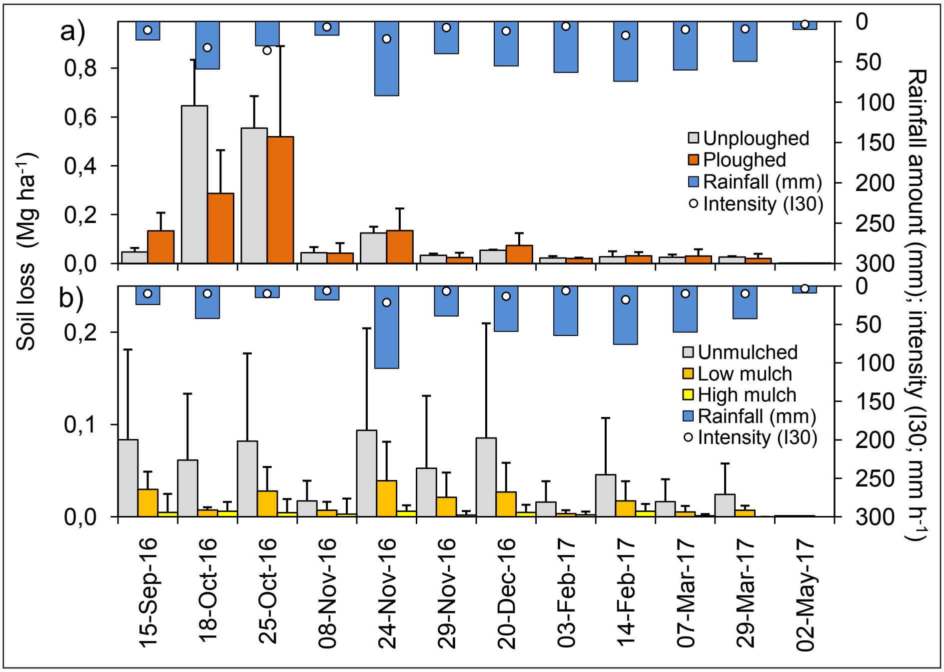

Figure 3. Soil losses (Mg ha^{-1}) for each one of the readouts in the ploughed (a) and mulched (b) hillslopes, corresponding rainfall amount (mm) and rainfall intensity (I30 max; mm h^{-1}). Error bars are standard deviation over the mean value.

3.2. Soil surface cover

In the first soil cover assessment (August 2016), bare soil and stones respectively covered 15 and 23% of the surface of the unploughed plots, while litter and vegetation reached to 30% (Fig. 4a). In turn, the ploughing treatment increased the surface of bare soil and stones to 20 and 50%, respectively, while also decreased vegetation and litter cover to 0 and 20%. Regarding the mulching experiment, untreated plots presented a surface cover consisting of 23% bare soil, 25% stones, 16% litter and 34% vegetation. The plots with the reduced mulch application rate presented lower bare soil (18%) and stones cover (38%), but a greater litter cover (38%), as a result of the mulch applied (Fig. 4b). The plots with the standard mulch treatment presented more litter cover (54%), which lasted for almost a year following application. After the first cover assessment, bare soil surface cover decreased to apparently stable values in both experiences.

3.3. Total soil losses and treatment effectiveness

Data collected from July 2016 to May 2017 showed soil losses higher than 1 Mg ha^{-1} in both unploughed and ploughed plots, while the unmulched plots reached half of this value (Table 2). Although the mineral fraction of the eroded soil was the same in both ploughed and unploughed plots, organic matter losses were greater in the unploughed

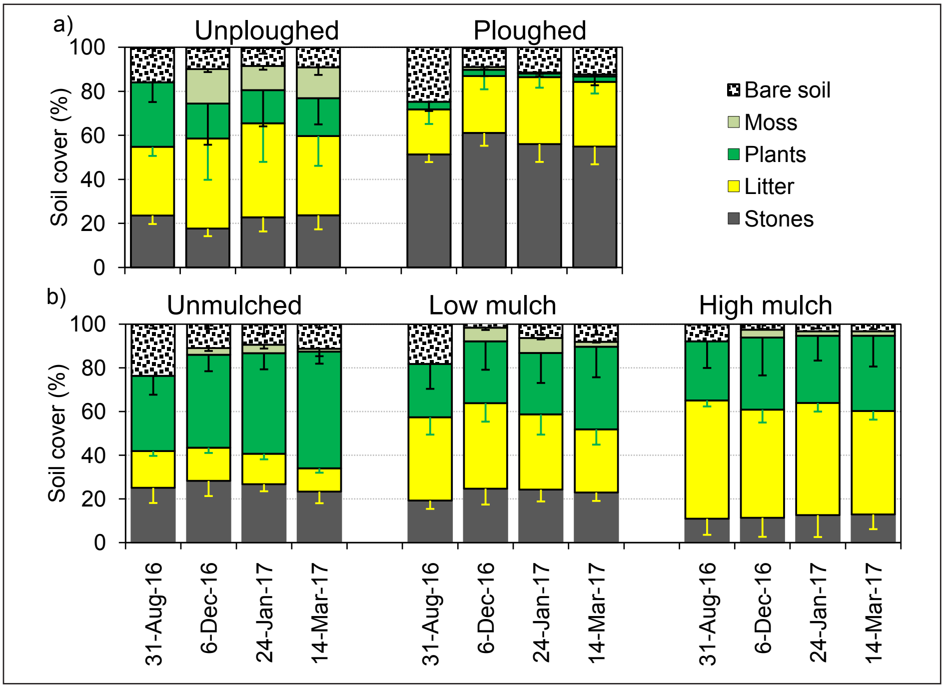

Figure 4. Soil cover (%) for each one of the treatments on the ploughed (a) and mulched (b) hillslopes. Error bars are standard deviation over the mean value.

plots (average organic matter contents of 22 and 11%, respectively). Mitigation of soil erosion due to ploughing was ineffective regarding both total soil loss and mineral fraction (F-value=0.1, Table 3). On the other hand, ploughing allowed a significant reduction in 61% of the organic matter lost (F-value=24.6, Table 3).

*Table 2. Total, mineral, soil organic matter losses (standard deviation between brackets) and treatment effectiveness expressed as: Effectiveness (%) =100-((treated/ control)*100). Treatments followed by different letters are statistically different (p<0.05).*

	Ploughed hillslope		Mulched hillslope		
Treatments	Unploughed	Ploughed	*Unmulched*	*Low mulch*	*High mulch*
Soil losses (Mg ha^{-1})					
Mineral fraction	1.25 (0.22)a	1.18 (0.73)a	0.50 (0.81)a	0.16 (0.16)b	0.03 (0.01)b
Organic fraction	0.36 (0.04)a	0.14 (0.08)b	0.08 (0.08)a	0.03 (0.03)b	0.01 (0.00)b
Total	1.61 (0.25)a	1.32 (0.81)a	0.58 (0.74)a	0.19 (0.19)b	0.04 (0.01)b
Treatment effectiveness (%)					
Mineral fraction		6		68	94
Organic fraction		61		62	90
Total		18		67	93

Table 3. Results of the two-way analysis of variance for total soil loss and organic matter (o.m.) losses. Log_{10}: Logarithm base 10.

Treatment	Source	Log_{10} (total losses)		Log_{10} (o.m. losses)	
		F	*p*	F	*p*
Ploughing	Interception	1330.3	<0.001	3533.6	<0.001
	Treatment	0.1	0.805	24.6	<0.001
	Time	16.1	<0.001	20.8	<0.001
	Treat*Time	0.8	0.612	0.9	0.503
Mulching	Interception	1441.9	<0.001	3380.3	<0.001
	Treatment	18.9	<0.001	20.0	<0.001
	Time	1.4	0.173	1.7	0.106
	Treat*Time	0.2	0.999	0.4	0.979

In the mulched hillslope, total soil losses observed in the reduced mulch plots were 5-fold of those observed in the standard mulch plots. The mineral fraction on the eroded sediments was three to sixteen times lower (and significantly lower for both reduced and standard mulch treatments, respectively) than that observed in the unmulched plots. The organic fraction of the eroded soil was higher in the mulched plots (16 and 25% of the total eroded sediments for reduced and standard mulch plots, respectively) than in the unmulched plots (14%). Mitigation of soil erosion (both mineral and organic fraction) due to mulch was systematically more effective with the standard mulch rate (90% of the erosion in the untreated plots) rather than with the reduced mulch treatment (60% of the erosion in the untreated plots).

3.4. Soil loss temporal patterns

In the ploughing experiment, soil losses were more pronounced in the two sampling campaigns corresponding to the highest rainfall intensities. These periods represented 70-60% of the total soil loss in both unploughed and ploughed plots (Fig. 3a). In fact, the time factor had a significant effect on soil and organic matter losses (F-values of 16 and 20, Table 3).

In the mulching experiment, soil losses were systematically higher in the unmulched plots when compared to the mulched ones. The lowest soil losses were directly related with the higher mulch application rates. Soil losses were relatively constant throughout the monitoring period in all treatments studied, as reflected by the low F-values (1.4 and 1.7, Table 3) of time effect for the mulched site, while treatment factor was always significant. The effect of time was reflected by the fact that the campaigns where the losses reached the highest values matched with the higher rainfall intensities, such as the campaigns performed at 24 November 2016 (107 mm; 21.2 mm h^{-1}) and 14 February 2017 (76 mm; 17.7 mm ha^{-1}; Fig. 3b).

4. Discussion

4.1. Ploughing impact on soil erosion

The first three campaigns revealed the highest values of soil and organic matter losses, with more impact observed in the unploughed plots. In the first campaign, soil loss was higher in the ploughed plots, although these losses were not very pronounced (Fig. 3a). This fact could be due to the loss of soil structure through ploughing, which might have result in easy mobilization of the soil particles after small amounts of rainfall (Robichaud *et al.,* 2000). Other studies have stated a close relation between rainfall intensity and erosion; especially in areas presenting a high bare soil cover (Prats *et al.,* 2012, 2014b; Malvar *et al.,* 2016; Hueso-González *et al.,* 2017). In the second and third campaigns, soil losses were higher, summing up to 74 and 61% of the total soil loss monitored in both unploughed and ploughed treatments. These figures were above the tolerable limit for soil erosion of 1 Mg $ha^{-1}year^{-1}$ (Verheijen *et al.,* 2009), both for the study period (Table 2) and also if calculated for the entire second year (2.3-1.8 Mg ha^{-1} $year^{-1}$, respectively for each treatment). Studies performed by Shakesby *et al.* (1996) and Ferreira *et al.* (1997) showed much higher soil losses in ploughed plots (51 Mg ha^{-1} $year^{-1}$), which hardly could be related with a higher depth of the soil mobilization during the ploughing operations, or a longer monitoring period. Higher rainfall intensity or lower stone content in the soil are more likely to explain these striking differences. The increase of the micro-topography attained with ploughing often promotes runoff infiltration and sediments impoundment, and ultimately prevents soil erosion (Robichaud *et al.,* 2000). However, in this study there were no marked differences between soil losses observed in ploughed and unploughed plots. In addition, the surface exposure of stones and roots due to the soil mobilization process, which could have acted as sinks to promote infiltration (Shakesby, 2011; De Figueiredo *et al*., 2012), apparently did not produced any effect. Ploughing has led to higher soil loss when compared control (unploughed) in smaller plots (De Figueiredo *et al.,* 2012; Martins *et al.,* 2013) and with more aggressive ploughing operations (Shakesby *et al.,* 1996; Ferreira *et al.,* 1997). On other hand, these latter authors refer that, at a basin scale, ploughing effects may not be perceived at a short-medium term due to the higher deposition capacity of the sediments generated within the basin itself. At long term (c.a. 20 year after ploughing), Malvar *et al.* (2016) showed that soils may reach an exhaustion point. In other words, soils do not have an infinite capacity to be eroded, and the erosion rates may ultimately decrease and become smaller than in unploughed areas due to soil exhaustion, especially in very poor and stony soils (Shakesby, 2011). The amount of organic matter that was lost with the sediments in the ploughed plots was 50% less than in the control plots. It is expected that ploughed soils will have less organic material available in the surface to be transported due the mobilization process and incorporation of organic material in depth (Ferreira *et al.,* 1997). However, these positive results on preserving organic matter must be interpreted with caution. For instance, Polyakov and Lal (2008) recorded greater organic matter losses in recently ploughed soils, and attributed it not only to water erosion (that removed 44% of the organic carbon within the soil up to 1 m depth), but also to the organic matter mineralization (estimated to be up to 14% of the re-deposited and not eroded sediments). In the agricultural scope, new NTM technologies (acronym for "no till management") such as mulch-based cropping systems have been successfully used to improve the quality of conventionally ploughed soils, and have shown excellent capacities to recover ploughing-degraded soils. Neto *et al*. (2010) showed that 12 years of management with NTM approaches on soils degraded due to the continuous effect of conventional ploughing for 23 years, have improved soil properties (increase carbon fixation and productivity, decrease bulk density, etc.) to pre-disturbance levels.

4.2. Mulching impact on soil erosion

The observed soil loss during the second year in the mulching experiment was lower than that reported in Keizer *et al.,* (2018) during the first year in all the treatments under study (8, 1.1 and 0.3 Mg ha^{-1}, in the unmulched, reduced and standard mulch plots, respectively). This decline in soil loss is related, on one hand, with the increase of some surface components such as litter and vegetation layers (Hueso-Gonzalez *et al.,* 2017) and, on the other hand, with the decrease of material available to be transported and eroded, which reflected in an increase in the stoniness with disappearance of the bare soil layer. The same effect has been observed in control and treated plots in other research that monitored soil erosion throughout several post-fire years (Badia and Marti, 2000; Prats *et al.,* 2012, 2016; Malvar *et al*., 2016). However, examples exist where post-fire erosion did not decrease over time (Robichaud *et al*., 2013), and therefore the window of disturbance may last for several years. The organic matter content of the eroded sediments decreased from 21, 18 and 33% (observed during the first post-fire year (Keizer *et al.,* 2018) to 14, 16 and 25% during the second year, for the control, reduced and standard mulch treatments, respectively. This decline may be related to the wash-out of the superficial ashes that, for the same area, are mostly (87%) composed by organic matter (Prats *et al.,* 2017). The relative differences between treatments are related to the effect provided by mulch. During the second year, the unmulched plots showed the lowest organic matter content while the standard mulch plots showed the highest content. Therefore, mulch has possibly increased the organic matter content of the soil. Accordingly, mulch application was reported to produce an increase from 40 to 120% of organic matter in the top 2 cm of soil, depending on both the soil type and the mulch application rate (Prats *et al.,* 2016). Overall, the increasing in the soil organic matter has been pointed as the key factor for boosting productivity of soils and an effective way to increase soil carbon fixation (Polyakov and Lal, 2008; Neto *et al.,* 2010).

Regarding the mulch application rate, the standard mulch treatment resulted 27% more effective in mitigating the soil erosion as compared to the reduced mulch treatment for both the first (Keizer *et al.,* 2018) and second year after wildfire. The difference is mostly explained by the greater soil cover provided by the standard mulch treatment. Field studies in Portugal with such standard mulch rates (≥9 Mg ha^{-1} in Shakesby *et al.,* 1996; Prats *et al.,* 2012, 2016) resulted in treatment efficiencies similar to the ones achieved in this study. Regarding the reduced mulch application rate (2.6 Mg ha^{-1}, corresponding to one third of the material used in the standard mulch), our results are in agreement with laboratory studies performed with shredded forest residues (Prats *et* *al.,* 2017) and straw (Abrantes *et al.,* 2018). Lower application rates resulted in lower efficiencies, though thresholds of 2.6 Mg ha^{-1} for the shredded forest residue mulch and 1 Mg ha^{-1} for the straw provided a ground protective cover around 50%. The reduced mulch application rate was validated as efficient in reducing post-fire soil erosion in 86%, during the first year following the wildfire (Keizer *et al.,* 2018), and in 60% during the second year (this study). Litter cover on the soil surface decreased with time, from 48 and 77% immediately after application (for reduced and standard mulch treatments, respectively) to values of 35 and 51% at the end of the first year (Keizer *et al*., 2018) and 31 and 37% at the end of the second year (this study). Moreover, the amount of litter decreased less (13 and 4% in the first and second year, respectively) in the reduced mulch treatment than in the standard mulch rate (26 and 14% in the first and second year, respectively), which highlights conservative features of the reduced mulch application rate in preventing soil loss. Similar results were obtained by Fernandez *et al*. (2016) with the aerial application of straw, at rates of 2.5 - 3 Mg ha^{-1}, for the first and second year (25 and 40% reduction of litter cover, respectively). These results show that forest residue mulch is more resistant to decomposition than the straw mulch. However, it is also possible that the use of sieved mulch and the field patterns of vegetation growth and litter deposition are certainly influencing the decrease in litter cover.

5. Conclusion

Soil and organic matter losses after a wildfire were measured and compared on two hillslopes, one ploughed and the other treated with mulching. Ploughing did not reduce the total soil losses, despite showing a reduction in the organic material removed with the sediments. These results should be taken with caution, since studies performed in recently ploughed areas indicate that an important part of soil organic carbon may be lost due to mineralization to atmosphere, instead of water erosion. Even one year after wildfire, soil losses were higher than tolerable levels, so erosion control measures were relevant. The higher erosion rates were due to rainfall intensity, since two of the most intense events produced 70% of the total erosion.

The reduction in soil erosion by the two mulch treatments (60% and 90%, for the reduced and standard mulch rates, respectively) was very consistent, not only for the total losses in the second year after wildfire but also for organic matter losses. In addition to the previous conclusions, the reduced mulch application rate (2.6 Mg ha^{-1}) led to a cost-effective reduction, regarding the material and treatment application. Thus, the reduced mulch treatment is a preferential measure as compared to the no intervention, allowing soil conservation, promoting soil carbon fixation and benefitting stakeholders, not only in relation to the costs reduction, but also because it support long-term productivity and conservation of forested areas.

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