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Effects of forest residue mulching on organic matter and nutrient exports after wildfire in North-Central Portugal

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ABSTRACT

The quick implementation of emergency stabilization measures is vital for minimizing post-fire soil erosion and the associated fertility loss. Mulching has proven to be highly effective in minimizing post-fire soil erosion, however few studies have investigated its impacts on organic matter (OM) and nutrient mobilization from burned forest areas. This study evaluates the effectiveness of forest residue mulching at reducing OM, N and P losses within the sediments after a moderate-severity wildfire over a period of 5 years (Ermida, North-central Portugal). Untreated and mulched plots of ca. 100 m^2 were bounded with geotextile fabric and sediments were collected from silt fences after a total of 29 periods.

During the first five years after the fire, the accumulated OM, N and P exportations in the untreated plots were, respectively, 199, 5.2 and 0.38 g m^{-2}; and mulch significantly reduced these figures in, respectively, 91 %, 94 % and 95 % ($p < 0.05$). The overall OM content in the sediments of the untreated plots (45 %) was not different from the OM content of the mulched plots (34 %, $p = 0.16$). However, the N (8.9 g kg^{-1}) and P_{av} contents (0.62 g kg^{-1}) in the untreated plots were significantly higher than the N (5.6 g kg^{-1}; $p < 0.05$) and P_{av} contents (0.36 g kg^{-1}; $p < 0.05$) in the mulched plots. This effect was especially noticeable in the first year after fire. OM and TN contents in the sediments were highly variable throughout the study period, whereas P_{av} contents declined sharply in the first post-fire rainfall events, maintaining low values afterwards. The main factors driving nutrient exports were ash and litter cover, whereas no significant relationship was observed for OM exports. The present work has shown that forest residues application can be a sustainable strategy for the conservation of soil carbon and nutrients in fire-affected areas.

1. Introduction

Forest fires have become a common phenomenon over the past decades, having great environmental impacts worldwide (Ferreira et al., 2015; Turco et al., 2019; Santín et al., 2019; Wagenbrenner et al., 2006). Fires alter the physical, chemical and biological properties of soils, being known for enhancing soil erosion and the associated carbon and nutrient losses (Certini, 2005; Gómez-Rey et al., 2013). As the frequency of wildfires is not foreseen to decrease substantially in the next decades (Prats et al., 2012), it is of the utmost importance to evaluate the impacts of fires on soil and water resources. Finding management solutions that are able to effectively mitigate these impacts is key, not only during the first months after fire (Cerdà and Lasanta, 2005; Ferreira et al., 2005; Gómez-Rey et al., 2013; Vega et al., 2005), but also during the full period of the window of disturbance, which can last up to 14 years in some areas (Rhoades et al., 2019).

Post-fire treatments have been applied by land managers, especially after high severity wildfires, to minimize runoff and soil erosion (MacDonald and Larsen, 2009; Prats et al., 2014b). Various field experiments have shown mulching to be the most effective treatment at reducing post-fire runoff and soil erosion at hillslope scale (Bautista et al., 1996; Fernández et al., 2011; Miles et al., 1989; Prats et al., 2012; Prats et al., 2016a, 2016b, 2016c; Vega et al., 2014; Wagenbrenner et al., 2006). Post-fire mulching consists of spreading, as evenly as possible, a given type of plant material over the soil surface. To be effective at reducing soil loss, a minimum ground cover of 60–70 % should be achieved (Robichaud et al., 2010), resulting in application rates of 2–3 Mg ha^{-1} in the case of the straw mulch (Fernández et al., 2011; Fer-

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nández-Fernández et al., 2020), 3 Mg ha^{-1} in the case of hydromulch (Prats et al., 2016a) and 2.6–10 Mg ha^{-1} in the case of forest residue mulches (Prats et al., 2016b, 2016c). Over the last years, there has been an increasing interest in the application of mulches derived from forest residues in North-Central Portugal, namely eucalypt chopped bark mulch or eucalypt logging slash mulch (Prats et al., 2012, 2016b, 2016c). This type of mulch has several advantages: i) is available in the burned areas; ii) are less susceptible to removal by wind; iii) decay at slower rates than straw mulch, and iv) do not introduce invasive weeds (Prats et al., 2014a). In Portugal, the application of forest residue mulches have proven to be effective in reducing runoff volumes by 50 % and soil erosion by 90 % in burned areas, when the application coverage is approximately 70 % of ground cover (Ferreira et al., 2015; Keizer et al., 2018; Prats et al., 2014a).

Despite the high effectiveness of mulching in reducing soil erosion, few studies have assessed the effects of this type of treatment on soils, in particular on soil OM and nutrient contents (e.g. De la Rosa et al., 2019; Fernández-Fernández and González-Prieto, 2020; Fernández-Fernández et al., 2022; Francos et al., 2018; Lucas-Borja et al., 2021; Machado et al., 2022), which are known to be key for the productivity of forest ecosystems (Field et al., 2003; Otero et al., 2015). In Mediterranean forests, where P is typically the limiting nutrient for plant growth (Ferreira et al., 2016a; Hosseini et al., 2017; Machado et al., 2022; Otero et al., 2015), this topic becomes even more relevant. Mulch constitutes an additional source of OM and nutrients to the soil, being expected to improve its fertility (Francos et al., 2018; Lucas-Borja et al., 2021; Machado et al., 2022). However, the environmental changes induced by mulch (e.g. in moisture conditions; Prats et al., 2012) can influence the dynamics of soil organic matter and the nutrient cycles (Gómez-Rey et al., 2013; Lucas-Borja et al., 2021), as well as soil microbial activity (Fontúrbel et al., 2012; Barreiro et al., 2016). The type of mulch applied largely influences its effects on soils due to differences in the degradation rates (Barreiro et al., 2016). Post-fire straw mulch, for example, have been reported to increase soil C and N contents (Díaz-Raviña et al., 2012; Gómez-Rey et al., 2013) but only 4 to 5 years after its application (De la Rosa et al., 2019; Fernández-Fernández and González-Prieto, 2020). Therefore, the effects of other mulch materials with higher C:N ratios, like eucalypt bark strands, could take even longer to be perceived as they typically have lower degradation rates (Barreiro et al., 2016). The addition of mulch can induce a priming effect of soil OM, but under field conditions this effect can be difficult to identify due to a complex interplay of biotic and abiotic factors (Jurgensen et al., 2020).

The effect of mulching on post-fire OM and nutrient losses is another major research gap (Gómez-Rey et al., 2013). In fact, the overall knowledge on post-fire OM (e.g. Faria et al., 2015; Gómez-Rey et al., 2013; Lopes et al., 2020) and nutrient mobilization (e.g., Ferreira et al., 2016a, 2016b; Gómez-Rey et al., 2013; Hosseini et al., 2017; Santos et al., 2015; Serpa et al., 2020; Thomas et al., 1999, 2000a, 2000b; Walsh et al., 1992) in burned Mediterranean forests is rather limited. The few existing studies have, however, hinted that OM and nutrients are more likely to be preferentially mobilized associated to ash and soil particles than to runoff waters (Ferreira et al., 2016a, 2016b; Serpa et al., 2020). Most of these studies have focused on the short-term effects of fires (6 months to 1 year; Fernández-Fernández et al., 2016; Ferreira et al., 2016a, 2016b; Gómez-Rey et al., 2013) rather than on the medium (2–5 years; Faria et al., 2015; Hosseini et al., 2017; Serpa et al., 2020; Thomas et al., 1999, 2000a, 2000b; Walsh et al., 1992) to long-term (> 5 years; Santos et al., 2015) effects, which is crucial for realistically assessing the risk of soil fertility loss and water contamination after fire. So far, only one study have found a reduction effect of post-fire mulching on OM and nutrient losses by erosion (Gómez-Rey et al., 2013), however this work was carried out in an area affected by an experimental fire rather than a wildfire. They stated that straw mulch providing a soil cover of 60 % strongly reduced OM, N and P exports from the burned area during the first post-fire year (Gómez-Rey et al., 2013). Other study carried out in Portuguese wildfires (Thomas et al., 2000b) also reported that even a low litter cover (9 %) resulting from post-fire logging practices in the second post-fire year, was able to reduce N exports by almost 50 %. Based on these findings, it is expected that any treatment reducing erosion will also reduce OM and nutrient exports (Caon et al., 2014), but it is not clear how these treatments will influence the OM and nutrient contents in eroded sediments.

The main objective of this research was to evaluate the effects of forest residue mulch application on OM, N and P exportations and contents in the eroded sediments from a burned eucalypt hillslope in North-Central Portugal. The specific objectives of this research were to: i) study the temporal evolution of OM, N and P exportations from untreated and mulched plots over a 5-year period after a wildfire; ii) assess the key factors explaining the variability of OM, N and P exports and contents in the sediments, iii) assess the impacts of C, N and P losses by erosion as compared to the forest soil C, N and P stocks. This study is a follow-up of the work of Prats et al. (2016c), which evaluated the effectiveness of forest residue mulch in reducing runoff and soil erosion at the same study area. According to the previous research, mulch considerably reduced soil erosion in 90 % (from 616 to 56 g m^{-2}) and SOM losses in 93 % (from 247 to 17 g m^{-2}) in the 5 years after the wildfire, while increasing the thickness of the O layer, on average, by 1.2 cm.

2. Material and methods

2.1. Study area

The study site was located near the Ermida hamlet, in the Sever do Vouga municipality, north-central Portugal (40°45′05″ N, 80°21′18″ W). The wildfire affected an area of 295 ha, between 26 and 28 of July 2010 (ICNF (Instituto de Conservação da Natureza e das Florestas), 2010). Eucalyptus (*Eucalyptus globulus* Labill.) plantations were predominant in the area before the fire, but there was also some spare Maritime Pine (*Pine pinaster* Ait.) plantations and Cork Oak (*Quercus suber* L.) trees. Vegetation cover was dominated by *Ulex europaeus* L., *Pterospartum tridentatum* (L.) Willk., *Quercus robur* L., *Arbutus unedo* L., *Phillyrea angustifolia* L., *Pteridium aquilinum* (L.) Kuhn, *Simethis mattiazzii* (Vand.) Sacc. and *Scilla monophyllos* Link.

The climate in the area is classified as humid mesothermal (Csb in Köppen classification), with well-defined summers and winters and a dry season occurring in summer. The mean annual temperature is 14.9 °C, and the mean monthly temperatures ranges from 9.0 °C in January to 21.1 °C in July, regarding the period of 1990–2010 at the nearest weather station of Castelo Burgães (40°51′16″N, 8°22′55″W; 306 m a.s.l.; SNIRH (Sistema Nacional de Informação de Recursos Hídricos), 2022). In terms of annual rainfall, the average at the nearest rainfall station of Ribeiradio (40°44′39″N, 8°18′05″W; 228 m a.s.l.; SNIRH (Sistema Nacional de Informação de Recursos Hídricos), 2022) for the same period, was 1609 mm, varying between 960 mm and 2530 mm.

The study area is located in the Hesperian Massif, the major morpho-structural unit in the emerged territory of Portugal (Ferreira de Brum, 1978). The area presents mainly pre-Ordovician schists and greywackes, including also Hercynian granites at several locations (Ferreira de Brum, 1978). The slope that was selected for this study was steep (25°), had 40 m of length and a southwest aspect (40°44′05″N, 8°21′18″W, 200 m a.s.l.). Soil profiles revealed that soils were mainly sandy-loam Humic Cambisols at the base of the slope, and Umbric leptosols near the top of the slope (IUSS Working group WRB, 2015). The overall fire severity on the slope was classified as moderate, but gray and white ashes were found in some spots at the base of the slope, which are indicative of moderate to high fire severity. Further details about the study area can be found in Prats et al. (2014a, 2016b, 2016c).

2.2. Experimental set-up

On 20 August 2010, 6 sediment fence (SF) plots of 4 m wide by 25 m long were installed, having been delimited by geotextile fabric. On 15 September 2010, three randomly selected SF plots were treated with 10–15 cm width by 2–5 cm long eucalyptus bark and twig fibers from chopped logging residues at an application rate of 13.6 Mg ha^{-1}; enough to assure a soil cover of 80 % (Fig. 1). The other three SF plots were left untreated (Prats et al., 2016c). The mulch was purchased from a company handling such residues for biomass energy plants, having an average OM content of 88 % (determined by loss-on-ignition at 550 °C, 4 h; in Prats et al., 2016c), and a TC and TN of, respectively, 439 and 4 g kg^{-1} (determined by a flash 2000 elemental analyzer; in De la Rosa et al., 2019). Two totalizer and 1 tipping-bucket rainfall gauges were used to monitor rainfall amount and maximum rainfall intensity in 30 min (I_{30}).

2.3. Field sampling and laboratory analyses

Sediments generated by water erosion and accumulated at the bottom of the SF plots were collected at 28 occasions over a period of five years (from 15 October 2010 to 8 June 2015): 12 in the first year after fire, 10 in the second year, 4 in the third year and 1 in the fourth and fifth years. Additionally, the very first event of year 1 (on 28 August 2010), which was a wind event without rainfall was also monitored. Rainfall volumes were cumulated to the SF emptying dates, so the volumes for years 4 and 5 were higher than the ones for year 1 and 2. After sediment collection, all samples were air dried and then sieved at 2 mm. The < 2 mm sediment fraction was analyzed for OM, TN and P_{av}. The OM content of eroded sediments was determined by the loss on ignition at 550 °C for 4 h, as described by Botelho da Costa (2004). The presence of carbonates was assessed by applying drops of 1 M HCl to the samples. Since none of the samples revealed any signs of effervescence, the measured OM content was assumed to be the total OM. The carbon (C) contents were calculated based on their OM contents by applying the van Bemmelen factor (C content = OM content/1.724; Pribyl, 2010). Total nitrogen (TN), i.e. ammonium plus organic nitrogen, was determined by the Kjeldahl method (Bremner, 1979) using a FOSS Kjeltec™ 8100 apparatus. P_{av} was determined by the Bray method (Bray and Kurtz, 1945), using a mixture of ammonium fluoride (0.03 M) and hydrochloric acid (0.025 M) as extractant. The extracted P was analyzed spectrophotometrically as orthophosphate by the molybdenum blue method (APHA, 1998). Soil C, N and P stocks were calculated as follows: Soil (C, N and P) content × Bulk density × (1−⟩2 mm fraction) (Table 1).

2.4. Data analysis and calculations

The OM, TN and P_{av} exports (g m^{-2}), as well as their contents in eroded sediments (g kg^{-1}) and C:N, C:P and N:P ratios were used as dependent variables in mixed models, having the mulch treatment as the fixed factor (untreated/mulched) and plot as the random factor. The subject of the repeated measurements were the plots, with days-since-fire as the time factor. Normality of the residuals of the model and homogeneity of variances was checked with Shapiro-Wilk and Brown-Forsythe tests, respectively (SAS Institute Inc., 2008). Data on OM and nutrient exports/contents were fourth-root transformed to meet the assumptions of normality in the model residuals and of homoscedasticity of variances. The Tuckey-Kramer method (Kramer, 1956) was applied to perform multiple comparisons between periods and treatments. A Pearson correlation analysis was used to infer the key factors influencing OM, TN and P_{av} exports and contents considering 8 independent variables: rainfall amount, maximum rainfall intensity in 30 min (I30), stones, litter, vegetation, ash and bare soil cover percent as well as soil moisture.

3. Results

3.1. Organic matter and nutrient exports with eroded sediments

The total amount of OM and nutrients exported during the 5 years after fire was significantly higher in the untreated as compared to the mulched plots (Table 2). Over this time, mulch application led to an overall reduction of OM (199 vs. 11 g m^{-2}), TN (5.22 vs. 0.3 g m^{-2}) and P_{av} losses (0.38 vs. 0.02 g m^{-2}) of respectively 91 %, 94 % and 95 %.

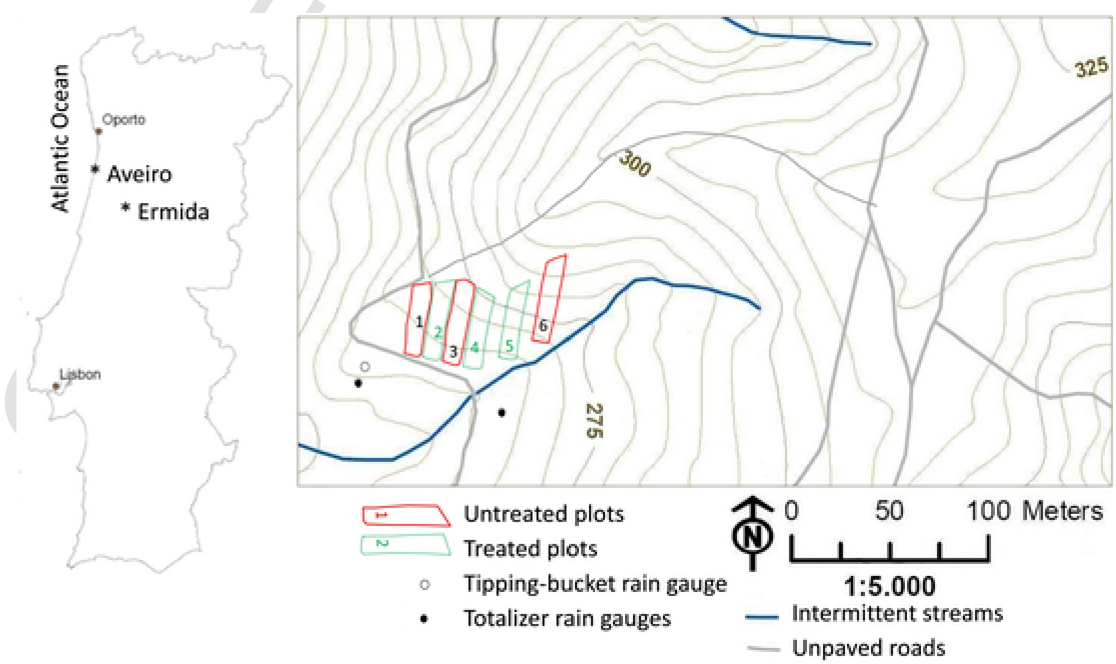

Fig. 1. Location of the Ermida study area (Aveiro district, Sever do Vouga municipality, North-Central Portugal) highlighting the rainfall gauges and experimental plots.

Table 1
Soil properties immediately after the wildfire (Year 0), including the composition of the ash blown by wind into the sediment fence plots in August 2010 and the soil contents of total carbon (TC), Total N (TN) and available P (P_{av}; Serpa et al., 2020) as well as soil properties at the end of the 5th year after fire (June 2015) in the upper 10 cm of the topsoil in the control and mulched plots (de la Rosa et al., 2019).

Topsoil properties	Untreated	Mulched
Year 0		
Wind-blowed ash & charcoal (Aug 2010)		
Dry loss/OM loss (g m^{-2})	3.0/1.1	2.0/1.8
OM content (%)	46.8	70.1
TC content (g kg^{-1})	271	407
TN content (g kg^{-1})	10.7	12.5
P_{av} content (g kg^{-1})	1.44	1.36
Topsoil properties		
O layer depth (cm; Sept 2010)	0	
Bulk density (0–5 cm; g cm^{-3})	1.12	
Stones >2 mm (0–5 cm; %)	54	
TC content (0–5 cm; g kg^{-1})	104	
TN content (0–5 cm; g kg^{-1})	0.70	
P_{av} content (0–5 cm; g kg^{-1})	0.16	
Year 5		
Topsoil properties		
O layer depth (cm; June 2015)	2.2	3.3
TC content (0–5 cm; g kg^{-1})	195	305
TC content (5–10 cm; g kg^{-1})	88	93
TN content (0–5 cm; g kg^{-1})	22	24
TN content (5–10 cm; g kg^{-1})	3	4

The mulch effect was particularly noticeable in the first three years after fire (Table 2; Fig. 2). The mulched plots showed significant reductions in annual OM exports during years 1, 2, and 3 (respectively 97, 93 and 61 %), TN exports during years 1 and 2 (respectively 98 and 91 %) and P_{av} exports during years 1, 2, and 3 (respectively 98, 92 and 75 %; Table 2). Time-since fire had a significant effect on OM and nutrient exports (Fig. 2). The highest OM and nutrient losses occurred at the beginning of post-fire year 1, however peaks in exports were also observed in post-fire year 2 and 4, more evidently for OM (Fig. 2). Noteworthy is the fact that these were also the years in which the treatment effect was significant for a higher number of periods: 18, 13 and 11 for OM, N and P losses, respectively (Fig. 2).

3.2. Organic matter and nutrient contents in eroded sediments

Unlike exports, no significant differences in the concentration of OM in the sediments were found between mulched and untreated plots, over the 5-year monitoring period (Table 3). TN and P_{av} contents, on the other hand, were significantly higher in untreated than mulched plots, for the total monitoring period of 5 years but only for the first year following fire (Table 3).

Time-since-fire had a significant effect on the OM ($F = 4.37$; $p < 0.01$), TN ($F = 18.4$; $p < 0.05$) and P_{av} ($F = 37.5$; $p < 0.05$) contents of eroded sediments, in both mulched and untreated plots. In general, the highest peak in OM and nutrient contents, in both treatments, was observed in the first read-out, which corresponded to a wind erosion event. In the subsequent rainfall events, the temporal patterns differed between treatments, but only for TN and P_{av} contents (Fig. 3). In the mulched plots, a sharp decrease in sediment OM contents was observed in the first five runoff events, but from that point onwards no clear pattern was identifiable. In the untreated plots, on the other hand, sediment OM contents exhibited a consistent decrease in the first two post-fire years, but afterwards there was a slow increase in concentrations until the end of the monitoring period. A sharp decrease in the sediments' TN contents were observed in the mulched plots during the first post-fire runoff events, but a slow recovery was observed afterwards. Conversely, in the untreated plots, the TN contents of sediments showed a major peak in the first rainfall events, which was followed by a decrease until the end of year 3, and then a slight increase towards the end of the monitoring period. In what concerns to P contents, a similar pattern was observed in the mulched and untreated plots, consisting of a sharp decrease in the first post-fire rainfall events, with low values being maintained till the end of the study period (Fig. 3). Despite these variations in OM and nutrient contents, the variations in C:N, C:P and N:P ratios did not differ due to the treatment (Table S1).

3.3. Factors influencing OM and nutrient exports and contents in eroded sediments

No significant relationship was found between rainfall amount and OM and nutrient exports or contents in eroded sediments (Table S2). Conversely, rainfall intensity was positively correlated with OM, N and P exports ($0.29 < r < 0.31$, $n = 168$, $p < 0.001$, as well as with the P contents in eroded sediments ($r = 0.26$; $p < 0.001$). The percentage of litter cover on the soil surface was inversely correlated with OM, N and P exports ($-0.38 < r < -0.33$, $p < 0.001$) as well as concentrations ($-0.32 < r < -0.26$, $p < 0.001$). The ash cover had a direct correlation with OM and nutrient exports ($0.47 < r < 0.43$; $p < 0.001$) and concentrations ($0.35 < r < 0.48$; $p < 0.001$). In what concerns the percentage of stones, a positive correlation was found with OM, N and P exports ($0.30 < r < 0.34$; $p < 0.001$). Bare soil and vegetation cover, on the other hand, showed no significant correlations with the dependent variables. Soil moisture showed negative correlations, but they were only significant in the case of TN and P_{av} contents ($-0.26 < r < -0.23$; $p < 0.01$).

The results of the Pearson correlation analysis also showed that OM, N and P exports were strongly correlated to each other ($0.98 < r < 0.96$; $p < 0.001$). On the other side, the contents of OM,

Table 2
Mean (± standard deviation) total and annual soil, organic matter (OM), total nitrogen (TN) and available phosphorus (P_{av}) losses in the 5 years following fire. Year or treatment values followed by different letters within a variable indicate significant differences ($p < 0.05$) between post-fire years (1 to 5 and total) and/or treatments (untreated or mulched). Additionally, mulch values were highlighted in bold if significantly different from the corresponding untreated values within the same variable and/or year.

Post-fire year	Soil loss (g m^{-2})		OM loss (g OM m^{-2})		TN loss (g N m^{-2})		P_{av} loss (g P m^{-2})	
	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched
1	462 ± 280^{a}	**19 ± 4^{def}**	157 ± 66^{a}	**4 ± 2^{def}**	4.33 ± 2.13^{a}	**0.10 ± 0.05^{d}**	0.324 ± 0.193^{a}	**0.008 ± 0.003^{cde}**
2	92 ± 46^{b}	**8 ± 4^{g}**	27 ± 11^{b}	**2 ± 1^{g}**	0.58 ± 0.21^{b}	**0.05 ± 0.04^{d}**	0.036 ± 0.014^{b}	**0.003 ± 0.003^{e}**
3	28 ± 11^{cd}	**11 ± 3^{efg}**	6 ± 3^{d}	**1 ± 0^{efg}**	0.14 ± 0.06^{cd}	0.04 ± 0.01^{d}	0.008 ± 0.004^{cd}	**0.002 ± 0.001^{e}**
4	25 ± 20^{cde}	11 ± 8^{efg}	7 ± 5de	2 ± 1^{efg}	0.14 ± 0.1^{cd}	0.06 ± 0.04^{d}	0.013 ± 0.012^{cd}	0.003 ± 0.003^{de}
5	9 ± 5^{fg}	7 ± 3^{g}	2 ± 1^{fg}	1 ± 1^{g}	0.04 ± 0.02^{d}	0.05 ± 0.03^{d}	0.002 ± 0.002^{e}	0.003 ± 0.002^{e}
Total	616 ± 347^{a}	**55 ± 13^{bc}**	199 ± 74^{a}	**11 ± 3^{c}**	5.22 ± 2.33^{a}	**0.3 ± 0.06^{bc}**	0.383 ± 0.22^{a}	**0.019 ± 0.004^{bc}**

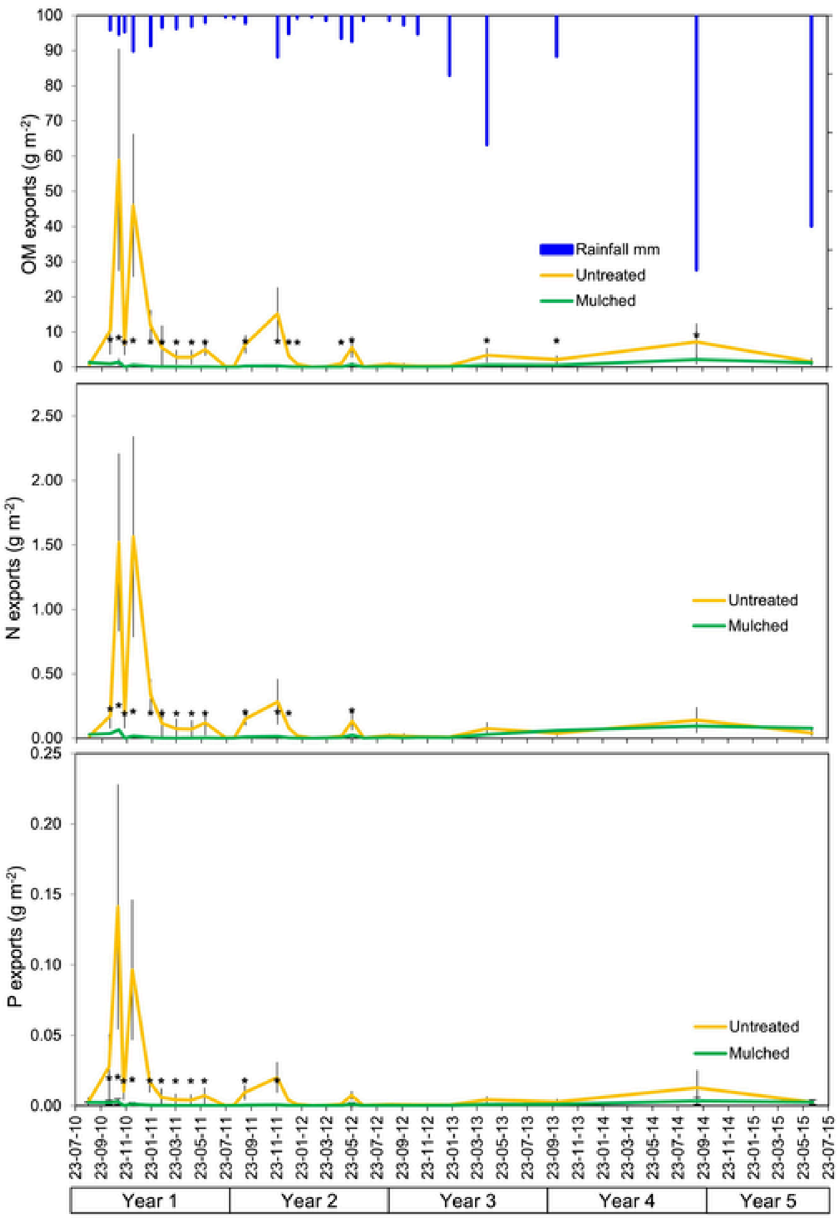

Fig. 2. Rainfall amount, organic matter (OM exports), total nitrogen (TN exports) and available phosphorus exportations (P_{av} exports) within the eroded sediments, for the 29 periods of the 5 years following fire. Asterisks indicate periods in which the differences between untreated and mulched plots are statistically different at $p < 0.05$.

Table 3
Sediment fraction lower than <2 mm (%), corresponding organic matter (OM, %), Total nitrogen (TN; g kg^{-1}) and available phosphorus (P_{av}; g kg^{-1}). Year or treatment values followed by different letters within a variable are significantly different ($p < 0.05$). Additionally, mulch values were highlighted in bold if significantly different from the corresponding untreated values within the same variable and/or year.

Post-fire year	<2 mm fraction (%)		OM (%)		TN (g kg^{-1})		P_{av} (g kg^{-1})	
	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched
1	82 ± 5^{a}	66 ± 7^{abcd}	47 ± 15^{a}	32 ± 10^{ab}	10.0 ± 0.7^{a}	**5.2 ± 0.7^{bc}**	0.72 ± 0.05^{a}	**0.41 ± 0.05^{b}**
2	77 ± 2^{abc}	67 ± 10^{abcd}	41 ± 13^{ab}	33 ± 3^{ab}	6.5 ± 0.9^{ba}	6.0 ± 0.9^{bc}	0.40 ± 0.05^{b}	0.36 ± 0.05^{b}
3	62 ± 9^{bcd}	**37 ± 7^{e}**	37 ± 13^{ab}	40 ± 15^{ab}	4.8 ± 0.8^{bc}	3.6 ± 0.8^{c}	0.29 ± 0.02^{bc}	0.22 ± 0.02^{c}
4	78 ± 5^{ab}	**60 ± 20^{cd}**	37 ± 9^{ab}	43 ± 25^{a}	5.9 ± 1.1^{bc}	5.9 ± 1.1^{bc}	0.45 ± 0.04^{b}	0.31 ± 0.04^{bc}
5	51 ± 11de	54 ± 20de	34 ± 9^{b}	30 ± 4^{b}	4.6 ± 2.1^{bc}	6.5 ± 2.1^{bac}	0.27 ± 0.09^{bc}	0.35 ± 0.09^{bc}
Total	79 ± 6^{a}	**61 ± 4b^{cd}**	45 ± 13^{ab}	34 ± 11^{ab}	8.9 ± 0.7^{a}	**5.6 ± 0.7^{bc}**	0.62 ± 0.02^{a}	**0.36 ± 0.02^{b}**

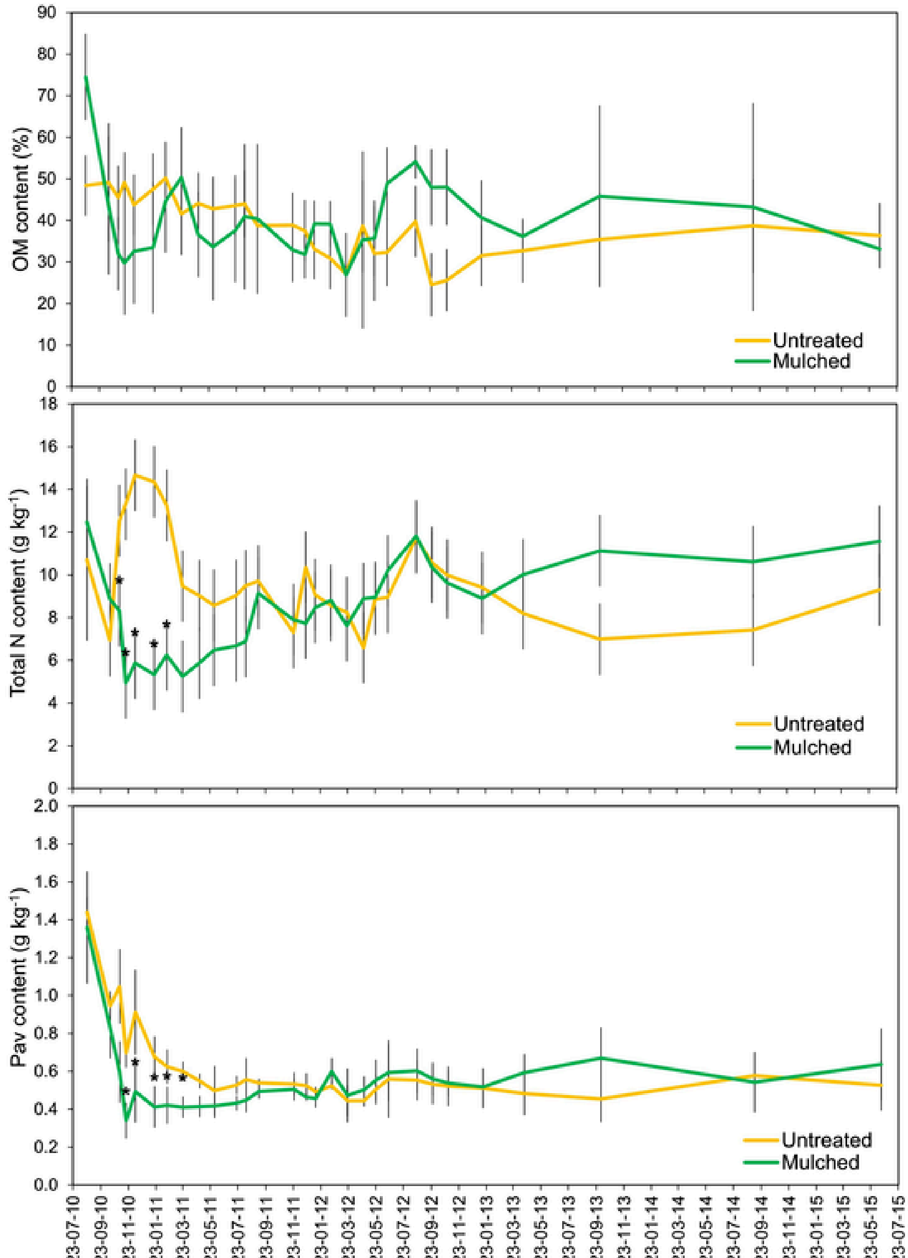

Fig. 3. Organic matter (OM content), total nitrogen (Total N content) and available phosphorus content (Pav content) in the eroded sediments, for the 29 periods of the 5 years following fire. Asterisks indicate periods in which the differences between untreated and mulched plots are statistically different at $p < 0.05$.

N and P were also correlated, but in a lesser extent than the exports ($0.63 < r < 0.59$; $p < 0.001$).

4. Discussion

4.1. Organic matter, N and P exports with eroded sediments

Eucalypt chopped-bark mulch substantially reduced OM, N and P exports in the sediments in the study area (Table 2; Fig. 2), as would be expected since this type of mulch has been reported to have high effectiveness in reducing post-fire soil erosion (Prats et al., 2016b, 2016c). By providing a protective soil cover, mulch reduces the erosive potential of rain, thereby preventing ash and soil losses as well as the associated OM and nutrient losses (Bodí et al., 2014; Caon et al., 2014; Thomas et al., 1999). The mulch effect was particularly noticeable in the first two years following fire, which coincided with the bulk of the erosion response (Table 2) as also found by other authors (Pierson et al., 2019), highlighting the importance of a timely application of erosion mitigation treatments in recently burned areas. During this period, the existence of the mulch layer seems to have prevented N and P mobilization during high intensity rainfall events (Fig. 2; Table S2), which are typically the most erosive events (Prats et al., 2016c).

The first-year exportations of C, N and P from our mulched plots (respectively 2.3; 0.1 and 0.008 g m^{-2}, Table 2) were lower when compared to the work of Gómez-Rey et al. (2013), which evaluated the impacts of straw mulch on post-fire C, N and P exports during the first post-fire year (respectively 10; 0.8 and 0.001 g m^{-2}) from a moderate severity experimental fire in a gorse shrubland area in Galicia (NW Spain) (Table 4). The two-year exportations of C from our mulched plots (3.4 g m^{-2}) was also lower than the study of Fernández (2022) who monitored C exports from straw mulched plots during 2 post-fire years (6 g m^{-2}; Table 4). These findings suggest that eucalypt chopped-

Table 4

Compilation of field studies into the effects of mulch-based treatments in the burned soil C, N and P stocks, exportations within the sediments and loss ratios for untreated and mulched plots reported by different authors. Loss ratios were calculated as the exportations (g m^{-2}) divided by the stocks (g m^{-2}) in the upper 2 cm of the mineral topsoil. Abbreviations are: nr. Sites: number of sites, SB. Severity: Soil burn severity (M: moderate; H: High; MH: moderate to high), na: not assessed.

Sources	n° sites	SB. Severity	Period (years)	Plot size (m^2)	Burned mineral soil stocks at 0–2 cm depth (g m^{-2})			Exportations within the sediments (g m^{-2})						Loss ratios (exportation/soil stocks; %)					
								Untreated plots			Mulched plots			Untreated plots			Mulched plots		
					C	N	P	C	N	P	C	N	P	C	N	P	C	N	P
This study	1	MH	5	100	1026.4	6.9	1.53	115.5	5.2	0.380	6.2	0.3	0.019	11.3	75.4	24.8	0.6	4.3	1.2
Gomez-Rey et al. (2013)	1	M	1	300	2171.2	72.4	0.05	102.8	7.6	0.009	10.0	0.8	0.001	4.7	10.5	16.8	0.5	1.1	1.7
Santos (2014)	3	MH	2	0.28	1073.5	53.8	0.19	119.5	1.7	0.216	na	na	na	11.1	3.2	115.8	na	na	na
Serpa et al. (2020)	2	M	2	0.28	1589.6	6.4	1.42	na	1.5	0.525	na	na	na	na	23.6	37.1	na	na	na
Ferreira et al. (2016a, b; 2017)	3	M	1	0.28	1068.3	6.6	11.84	na	0.8	0.417	na	na	na	na	11.6	3.5	na	na	na
Faria et al. (2015)	1	M	2	130	1115.2	67.3	na	33.8	1.9	na	na	na	na	3.0	2.8	na	na	na	na
Fernandez (2022)	1	H	2	80	1085.6	na	na	109.0	na	na	6.0	na	na	10.0	na	na	0.6	na	na
Pierson et al. (2019)	4	H	4	150.5	522.5	29.0	na	69.2	3.3	na	59.8	3.0	na	13.3	11.2	na	11.4	10.2	na
Abney et al. (2019)	3	H	0.3	100	553.8	30.8	na	2.0	0.1	na	na	na	na	0.4	0.3	na	na	na	na

bark mulch might be more effective than straw mulch at reducing C and N mobilization due to its higher effectiveness in reducing soil erosion (Girona-García et al., 2021). Still the 5-years C and N exportations of our research work (respectively 6.2 and 0.3 g m^{-2}; Table 4) was lower than another work carried out in the western United States (Pierson et al., 2019) in hillslope plots (151 m^2) treated with wheat straw mulch for 4 years (respectively 59.8 and 3.0 g m^{-2}; Table 4). These differences can be attributed to the low performance of straw mulch under the extremely intense erosion events that happened in one of the four study sites, the Hayman wildfire (Pierson et al., 2019). Yet in the same study, wood strand mulch was a bit more effective in mitigating C (28 g m^{-2}) and N exportations (1.3 g m^{-2}), but they were still higher than the 5-years results of our study. The comparison of the few research of Table 4 is difficult due to the different analytical methods used to determine soil C, N and P contents. In the case of C, loss-on-ignition and the van Bemmelen factor (which is too low for most soils according to Pribyl, 2010) were used to calculate C contents (Santos, 2014; this study) and compared with combustion with elemental analyzers (Abney et al., 2019; Faria et al., 2015; Fernández, 2022; Gomez-Rey et al., 2013; Pierson et al., 2019;). In the case of N, both Kjedahl digestion (Ferreira et al., 2016b; Santos, 2014; Serpa et al., 2020) and elemental analyzers (Abney et al., 2019; de la Rosa et al. 2019; Faria et al., 2015; Gómez-Rey et al., 2013; Pierson et al., 2019;) were found to be equivalent, although N values were slightly higher using elemental analyzers (Jimenez and Ladha, 1993).

Especial care deserves the determination of P by different methods (Wolf and Baker, 1985), as the bulk of the Portuguese studies (Ferreira et al., 2016a; Santos, 2014; Serpa et al., 2020; this study) differed from the studies in Galicia (Fernández-Fernández et al., 2016; Gómez-Rey et al., 2013).

The C and nutrient exports from the untreated plots were also within the range of values reported for other burned hillslopes in the Iberian Peninsula and the United States (Table 4). The annual C exports of the first post-fire year of our study (91 g m^{-2}) were similar to those measured by Gómez-Rey et al. (2013) in an experimental fire (102.8 g m^{-2}; Table 4). Other studies reported similar C exportations for a period of two years (range of 34–119 g m^{-2} in Faria et al., 2015; Fernández, 2022 and Santos, 2014) as compared to our study during the first two years (106.7 g m^{-2}). Pierson et al., 2019 still reported lower C exportations for four years (69.2 g m^{-2} in) as compared to our study during four years (114.2 g m^{-2}). Despite the difficulties to compare the previous research, the first and most important factor explaining post-fire OM and nutrient exportations is fire severity (Abney et al., 2019; Pierson et al., 2019; Rhoades et al., 2019; Vega et al., 2013). The link between fire severity and C, N and P exports can be inferred from research assessing the effects of fire on soil C, N and P contents. The higher soil burn severities corresponded with lower C and associated nutrient contents in the topsoil (Vega et al., 2013), but with more erosive situations. Consequently, Rhoades et al. (2019) found that large catchments in the Hayman wildfire, unburned or burned at low and high severity, delivered each year, respectively, 0.012, 0.044 and 0.065 g N m^{-2}, although these figures were obtained 14 years after the fire.

Unlike C exports, the N exports in our study were almost 2 times lower (4.3 vs.7.7 g m^{-2}) than those of Gómez-Rey et al. (2013), which can be attributed to the presence of N-fixer plants such as gorse in the pre-fire vegetation. However, our N exports were 2–3 times higher compared to other 2-years studies in North-Central Portugal burned at a similar fire severity (1.9–1.5 g m^{-2}; Faria et al., 2015; Santos, 2014; Serpa et al., 2020; Table 4). Interestingly, our 4-years N exports (5.19 g m^{-2}) were also higher than those reported for pine forest burned at high severity in the western US (3.3 g m^{-2}; Pierson et al., 2019). Other authors working in North-Central Portugal (Ferreira et al., 2016a, 2016b; Serpa et al., 2020) have attributed the differences in post-fire nutrient losses to pre-fire vegetation (e.g. higher losses in eucalypt than pine stands) and slope aspect (e.g. higher losses in north-faced than south-faced slopes), however these links were only partially evident in our research.

Regarding P exports, Gómez-Rey et al. (2013) encountered values one order of magnitude lower than in our study (0.32 vs. 0.009 g m^{-2}; Table 4) likely due to the low P stocks in soils. It is surprising that P exportations found within North-Central Portugal burned areas (0.21–0.52 g m^{-2}; in Ferreira et al., 2016a; Serpa et al., 2020; Santos, 2014) were very similar to the ones of our study, despite these previous works estimated P_{av} losses in a very different way, by measuring runoff with microplots of 0.28 m^2, at different monitoring periods, and different eucalypt and pine plantations with different forest management (Table 4). Both the scale factor (lower exportations at increasing the plot size) and the monitoring methodology (small runoff microplots versus hillslope sediment fences) may have played a role. In fact, a detailed study (Lane et al., 2008) determined that P exportations at the catchment scale for the first 3 post-fire years were 0.16 g m^{-2}, indeed lower than most of the hillslope P exportations of Table 4. They also found that 86 % of P was exported in particulate form. As P is preferentially transported associated to sediment particles (Ferreira et al., 2016a; Serpa et al., 2020), the use of sediment fences, which capture mostly particulate fractions (Robichaud and Brown, 2002; Wilson et al., 2021) may be more effective at retaining P than runoff plots. On the other hand, runoff tanks have a limited storage capacity and other limitations associated to sample homogenization (Bagarello and Ferro, 1998).

The overall C, N and P exports measured in the untreated plots during the 5 years of monitoring were estimated to represent respectively, 11 %, 75 % and 25 % of the C, N and P stocks contained in the upper 2 cm of the topsoil (Table 4). Other researchers have measured C losses within the same range of 3–13 %, but the N and P losses varied in a much larger range (Table 4). In the mulched plots, C, N and P losses represented only a small fraction of the soil stocks, respectively 0.6, 0.1 and 1.2 %, which was in line with other studies in Galicia (Fernández, 2022; Gómez-Rey et al., 2013) but not in the USA, where straw mulch was not very effective (Pierson et al., 2019; Table 4). These findings highlight the importance of forest residue mulches for minimizing the risk of soil fertility loss in burned forests, especially in the Mediterranean, where P is the limiting nutrient for plant growth (Ferreira et al., 2016a; Hosseini et al., 2017; Machado et al., 2022; Otero et al., 2015).

4.2. Organic matter, N and P contents in eroded sediments

The wind event that occurred shortly after fire, deposited ash and charcoal particles rich in OM (and consequently C, N and P), on both untreated and mulched plots (Table 1). The C contents of the wind-blown sediments were within the range of values reported in other studies for the ash layer (227–345 g kg^{-1}; Campos et al., 2016; Gómez-Rey et al., 2013; Santín et al., 2018), but the N and P contents were about one order of magnitude higher (Santín et al., 2018; Serpa et al., 2020), which can explain the higher P exports found in the present study, especially during the first post-fire year (Table 4).

After the first post-fire rainfall event, mulch impacted the OM, N and P contents of eroded sediments differently (Fig. 3). The sediments' OM contents were not significantly affected by mulch, as reported in other burned areas treated with forest residue (Prats et al., 2012) or straw mulch (Fernández-Fernández and González-Prieto, 2020), likely due to the lack of mulch removal. However, they contrast with the findings of other research using wood strand mulch (Pierson et al. (2019), hydromulch (Prats et al., 2016a) or corn/wheat straw mulch (Prats et al., 2022) that reported significant increases in the OM content of sediments from the mulched plots. These discrepancies can be attributed primarily to the mulch degradation rates. Forest residue mulch tends to degrade slower than wood strand or straw mulch (Barreiro et al., 2016), so its effects on the OM content of soils, and consequently, on eroded sediments are expected to be perceived long after its application. In fact, it took four-five years for the forest residue mulch to degrade, which was reflected in the higher OM, N and P contents on the sediments of the mulched than untreated plots (Table 3).

Other factor that can influence the amount of OM in untreated plots is the proportion of char particles being eroded, which likely depends in a complex function of the amount of sediments, its coarse/fine fractions and time since wildfire. The OM content in the sediments of the control plots decayed slightly with each post-fire year (Table 3), likely an effect of the preferential removal of the light, particulate, larger than 2 mm and rich in OM char particles (Caon et al., 2014; Lane et al., 2008; Machado et al., 2022). In a similar way, the lower OM content in the mulched plots can be attributed to the lower washing of this particulate fraction, but also to the extremely low amounts of sediments being eroded, either fine or particulate, greatly amplifying the variation of OM contents, as happened in other mulch research studies (Gómez-Rey et al., 2013; Prats et al., 2012, 2016a, 2022). Interestingly, the more erosive periods, those eroding >25 g OM m^{-2} were not the ones with the higher OM contents (Fig. 4). In contrast to the previous statement, these events had the lowest proportion of large particles (i.e.; fine fraction in sediments higher than 60 %; Fig. 4).The importance of the different fractions of SOM was assessed by Campo et al. (2022) using sediment fences, and they determined that the free light fraction of the SOM

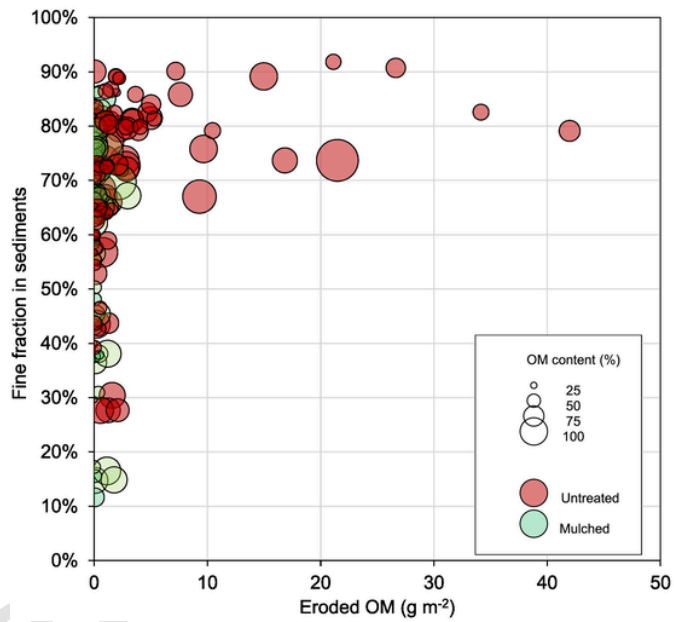

Fig. 4. Amount of eroded OM (g OM m^{-2}) versus percentage of the fine fraction (< 2 mm) in the sediments of each SF plot. Bubble size varies according to the OM content of the sediments.

decreased widely during the first post-fire year, while other fractions, such as the occluded light fraction and the heavy fractions varied in a lesser extent. They assessed the particle size of the sediments and found that the fine fraction constituted 68 % of the total sediments, very similar to the present study (Table 3).

Unlike for OM, mulch application had a significant reduction effect on the N and P contents of the sediments during the first post-fire year (Fig. 3). The existence of a protective mulch cover prevented the wash-off of the nutrient-enriched ash layer, and reduced the sediments' N and P contents as well as exportations, especially in the first post-fire rainfall events (Caon et al., 2014; Machado et al., 2022). This hypothesis seems to agree with the results of the correlation analyses, which revealed an inverse relation between the litter cover percent and the nutrients concentrations and exportations, but a strong direct relation with the ash cover percent (Table S2). Time-since fire had a significant effect on the nutrient contents of eroded sediments (Table 3), but the temporal patterns differed between treatments, even if only for N. In the untreated plots, there was a peak in N contents during the first rainfall events likely due to the wash-off of the ash layer, but as this layer became exhausted the amount of N in sediments progressively decreased (Table 3). In the mulched plots, on the other hand, the existence of a protective ground cover prevented the erosion of the ash cover, thereby decreasing the N contents until the third year. However, as it was reported before, when the mulch started to degrade it increased the N and P contents of the sediments from the 4th year onwards. Unlike OM and N, the P contents followed the same temporal pattern in treated and untreated plots, decreasing sharply in the first post-fire rainfall events, which can be attributed to the was-off of the easily-erodible, particulate ash and char layer (Lane et al., 2008; Ferreira et al., 2016a; Serpa et al., 2020).

5. Conclusions

The main conclusions of this research were the following:

- The forest residue mulch reduced the exportations of OM, C, TN and P up to 90 % compared to the untreated plots, highlighting the importance of a protective soil cover for minimizing the on- and off-site impacts of forest fires.

- The existence of a mulch layer over the soil prevented the wash-off of the easily erodible nutrient-enriched ash layer, thereby reducing the N and P contents of eroded sediments (by 37 % to 47 %), especially during the first post-fire year that typically coincides with the critical period of the post-fire window of disturbance.
- Mulch application can help reduce post-fire soil fertility loss and promote ecosystem regeneration, since the exports of P, which is commonly the limiting nutrient for plant productivity in Mediterranean forests, represented only 1.2 % of the soil P stocks in the mulched plots, whereas in the untreated plots it represented 25 %.

To allow for a better understanding of fire and post-fire erosion mitigation treatments on soil fertility across Mediterranean environments, it is recommended that future studies measure the C, N and P pools in nearby unburned areas to determine the original forest floor conditions. The measurement of ash loads is also crucial since the ash/charcoal constitutes the major source of C, N and P immediately after the wildfire. Some standardization of the methods being used to estimate the soil C, N and P stocks is also fundamental to allow a comparison between research carried out in fire-affected areas.

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CRediT authorship contribution statement

S.A. Prats : Conceptualization, Methodology, Resources, Investigation, Visualization, Data curation, Writing – original draft. **D. Serpa :** Methodology, Resources, Writing – review & editing. **L. Santos :** Methodology, Resources, Writing – review & editing. **J.J. Keizer :** Investigation, Visualization, Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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