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Impacts of barley (*Hordeum vulgare* L.) straw mulch on post-fire soil erosion and ground vegetation recovery in a strawberry tree (*Arbutus unedo* L.) stand

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ABSTRACT

Rural fires are now a major societal concern across the world, especially where fire regimes have (apparently) intensified in terms of burnt area, intensity and recurrency. Among the indirect fire effects, fire-enhanced runoff and erosion have been an important focus of post-fire land and water management, in particular through emergency stabilization of hillslopes using a range of erosion mitigation measures. The most widely applied and – scientifically tested – measure is that of mulching with agricultural straw, in spite of concerns of introducing exogenous organic material and especially seeds of non-native higher plant species, including the straw species it- or themselves. So far, field studies in the present study region of north-central Portugal have preferred using endogenous forest residues but these studies concerned forest types for which such residues are easily available. The latter, however, is not the case for strawberry tree stands, so that straw mulch was selected in this study as a cheaper alternative to eucalypt or pine residues. This - apparently, first – post-fire erosion mitigation study in a strawberry tree (*Arbutus unedo* L.) stand aimed to compare post-fire sediment and organic matter losses as well as ground vegetation recovery without and with applying barley (*Hordeum vulgare* L.) straw mulch at a low rate of 2 Mg ha^{-1}. The experimental set-up involved a randomized block design with a total of six geotextile-bounded erosion plots of 2 m by 5 m that were organized in three blocks, were installed and mulched roughly one month after the 17-October-2017 M-fire in inland Central Portugal, and monitored at 12 irregular intervals during the first two post-fire years. The principal findings were that: (i) especially the specific sediment losses without mulching over the first post-fire year were notably higher than those reported by the prior field studies in the region, in eucalypt and maritime pine plantations; and that the - low - mulching rate: (ii) was extremely effective in reducing these first-post-fire-year losses; but (iii) did not result in changes in the cover or floristic composition of the ground vegetation cover that were noteworthy and longer-lived than the first post-fire year.

1. Introduction

Rural fires have become an important societal concern in many regions across the world because of (perceived) trends in burnt area, fire intensity and/or recurrence frequency, on the one hand, and, the other, the impacts of especially large and intensive fires on human health and socio-ecological systems (Pausas et al., 2008; Pereira et al., 2022; IPCC, 2022). These concerns are typically aggravated by observed and/or

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projected increases in frequency and intensity of climate and weather extremes, including fire weather (Turco et al., 2018; Dupuy et al., 2020; IPCC, 2022). In the case of Portugal, the burnt area (log-transformed) did tend to increase between 1980 and 2017 but not in a significant manner, while the burnt area of 2017 did set a new national record with over 500,000 ha (Turco et al., 2019). In 2017, Portugal's burnt area also set the record across southern European countries, being thrice as high as that of the second-ranked country Spain (San-Miguel-Ayanz et al., 2018).

After rural fires have been extinguished, an important concern of land and water managers of sloping landscapes often becomes the on-slope risks of soil (fertility) losses and the resulting off-slope risks of flooding, damages to hydraulic and road infrastructures, silting-up of reservoirs and/or contamination of surface water bodies (Robichaud et al., 2010; Vega et al., 2013b; Neris et al., 2021). Strong to extreme hydrological and erosion responses have been documented in and downstream of burnt areas worldwide (Shakesby, 2011; Moody et al., 2013), including through very illustrative videos in more recent years. Such fire-enhanced responses during the so-called window-of-disturbance are typically attributed to the (partial) combustion of vegetation and litter layer in combination with heating-induced changes to key topsoil properties such as infiltration capacity, water repellency, aggregate stability and resistance to shear stress (Larsen et al., 2009; Mataix-Solera et al., 2011; Shakesby, 2011; Moody et al., 2013; Santín and Doerr, 2016). The degree and duration of this enhancement depend strongly on the impacts of the fire on vegetation, litter layer and topsoil, or, in other words, on their respective burn severities (Robichaud et al., 2007; Vega et al., 2013a; Vieira et al., 2015; Parente et al., 2022; Fernández, 2023). In the present study region of north-central Portugal, fire-enhanced erosion response is typically short-lived, with soil (fertility) losses tending to decrease markedly after the first post-fire year, especially when accounting for rainfall variability (Prats et al., 2016a, 2016b; Vieira et al., 2016, 2018; Keizer et al., 2018; Lopes et al., 2020; Serpa et al., 2020).

The concerns about the on- and off-slope risks of fire-enhanced runoff-erosion responses have led to the field testing of a wide range of mitigation measures, especially on hillslopes as the principal runoff-erosion source and especially in the USA and the north-western region of Spain, Galicia (Robichaud et al., 2010; Vega et al., 2013b; Prats et al., 2014a, 2014b; Girona-García et al., 2021). In a nutshell, the recent meta-analysis of Girona-García et al. (2021) revealed that: (i) only two of their four major types of measures significantly reduced post-fire runoff (i.e. cover and barriers as opposed to seeding and chemical); (ii) all four of them significantly reduced post-fire erosion; (iii) the significant types did not differ significantly between them in their effectiveness in reducing runoff or erosion; (iv) straw mulch was significantly more effective in reducing erosion than hydromulch and, at least marginally so, than barriers and seeding but not than wood mulch. Worth referring is the much larger number of erosion observations in Girona-García et al. (2021) regarding straw mulch (72) than the other mulch materials (33/44) as well as the other three main types (11–38), possibly reflecting that straw has been preferred for mulching in operational post-fire emergency stabilization in the USA and Galicia. In the present study region, however, none of the prior post-fire erosion mitigation studies (Shakesby et al., 1996; Prats et al., 2012, 2014b, 2016a, 2016b, 2019; Keizer et al., 2018; Lopes et al., 2020) has tested straw mulch, arguably in the first place because of its reduced availability. The second reason concerns the precautionary principle of avoiding the introduction of exogenous materials in forest ecosystems, especially because of the concerns raised about the introduction with the straw of the straw species itself and/or other, ruderal and non-native higher plant species (Kruse et al., 2004; Santana et al., 2014; Fernández et al., 2016). While endogenous organic residues, in particular logging residues, are widely available for post-fire mulching in the exotic tree plantations of eucalypt that are current dominating the landscape in most of north-central Portugal, the same is not true for native-tree woodlands such as the region's maritime pine or strawberry tree stands. As such, this study preferred straw over eucalypt logging residues as exogenous material for mulching in a recently burnt strawberry tree stand. Worth stressing is still that the strawberry tree stand was selected for this study for two specific reasons. First, the above-mentioned prior studies in the region concerned either eucalypt or maritime pine plantations, and, second, strawberry tree plantations are increasingly viewed as an economically-viable land use to foster integrated fire management of fire-prone landscapes, not only in Portugal but across its Mediterranean distribution range (Gomes et al., 2019; Florestas.pt, 2023; REN, 2023). Strawberry tree stands were estimated to occupy roughly 20,000 ha across continental Portugal in 2022 (Florestas.pt, 2023).

The main aim of this study was to improve the knowledge of post-fire erosion and its mitigation through mulching, in particular by selecting a woodland type that, to the best of our knowledge, was not studied before and by selecting a mulch material that was not studied before in the study region of north-central Portugal. The specific objectives were to: (i) quantify the post-fire sediment and organic matter losses over the first two post-fire years; (ii) assess the effectiveness of straw mulching at a reduced application rate in reducing post-fire sediment and organic matter losses; (iii) determine the impacts of straw mulching on the recovery of the ground vegetation in terms of aerial cover and floristic composition.

2. Material and methods

2.1. Study site

The study was conducted near the village of São Pedro de Alva (40°18′5.06"N; 8° 9'57.82"W), which pertains to the municipality of Penacova in the Coimbra District of north-central Portugal. The study site was burnt by a mega-wildfire that started on 17th October 2017 and affected 54.407 ha of rural lands covered mainly by shrubland and forest plantations of eucalypt (*Eucalyptus globulus* Labill.), maritime pine (*Pinus pinaster* Aiton) (San-Miguel-Ayanz et al., 2018). As referred earlier, a strawberry tree (*Arbutus unedo* L.) stand was selected for this study for two reasons. First, strawberry tree plantations are increasingly viewed as a less fire-prone but, at the same time, highly fire-resilient and economically-viable alternative for eucalypt and pine plantations and, hence, as an important land-use option for integrated fire management at the landscape scale (Vasques et al., 2013; Gomes et al., 2019; Florestas.pt, 2023). The main product of strawberry trees are its fruits, which are traditionally used for alcoholic beverages but more recently also for direct consumption. The second reason was that, to the best of our knowledge, no prior study has quantified post-fire erosion rates in strawberry tree stands. This specific strawberry tree stand was selected as the land owner was interested in post-fire erosion and its mitigation, including in the context of land-use certification, and fully supported the study, in terms of authorization, providing information and avoiding disturbance to the experiment. The stand covered an area of roughly 50 m by 50 m - reflecting the typical small-scale nature of forest properties in the region - on a steep (21–23°) NW-facing slope (Fig. 1). The strawberry trees occurred with a highly irregular spatial pattern, at a density of 850 trees/ha, were roughly 40 years old, and attained heights of up to 4 m. In phytosociological terms, the study site pertains to the association of *Phillyreo angustifoliae-Arbutetum unedonis*, which constitutes the first stage in the substitution of the cork oak forest association of *Sanguisorbo agrimonioidis -Quercetum suberis* (Aguiar, 2021).

The climate of the area is Mediterranean humid meso-thermal, with prolonged warm dry summers, corresponding to the Köppen–Geiger class Csb (Kottek et al., 2006). The long-term, 30-year average annual air temperature and precipitation at the nearest meteorological station (Alagoa, located at approximately 5 km) were 14.1C and 1022 mm, respectively (SNIRH, 2023).

The soil at the study site was classified as Umbric Leptosol (IUSS, 2015), developed from pre-Ordovician schists, based on two soil profiles

Fig. 1. Photographs of the study site and of the one of the three pairs of plots on the day of mulch application (21st November 2017).

that were excavated halfway the upper and lower halves of the study site. Both profiles comprised an Ah horizon of approximately 15 cm over a C horizon of schist. The soil texture of the Ah horizon was determined in the field (Vos et al., 2016) as sandy loam to loamy sand, while its color was classified as 7.5YR 4/3 according to the Munsell color chart.

2.2. Experimental set-up and treatment

The study site was instrumented with a total of six bounded erosion plots of 5 m by 2 m, using geotextile to bound the plots to avoid run-on and sediment influxes. The six plots were organized in three blocks that were located approximately halfway the upper, middle and lower sections of the study site, avoiding the presence of strawberry trees within or immediately next to the plots and, thereby, disturbance due to their foreseen pruning. Each block consisted of a pair of adjacent plots, as illustrated in Figure1. In addition, the study site was instrumented with one automatic rainfall gauge (ECRN-100 from Decagon devices, linked to an ONSET event data logger (HOBO Pendant Event Data Logger)) and one in-house totalizer rainfall gauge, for the purpose of validating the automatic records.

Site instrumentation was completed roughly one month after the fire, on the 20th of November 2017. During this period, some 50 mm of rainfall had been recorded at the above-mentioned, nearest meteorological station of Alagoa, but no major soil erosion features were visible at the study site, including ash mobilization. The next day, one plot per block was randomly selected and treated by manually applying straw mulch of barley (*Hordeum vulgare* L.) that was provided by the land owner. The mulch was applied in a homogeneous manner across the plots at a rate of 2 Mg ha^{-1}. This application rate was selected for being at the lower end of the straw mulch application rates used in operational post-fire emergency stabilization and, hence, representing a less costly and more cost-effective option, also in comparison with applying wood mulches (Girona-García et al., 2021, 2023).

2.3. Field data and sample collection, and laboratory analyses

Before mulching, vegetation and soil burn severities were determined visually for each erosion plot. Vegetation burn severity was consistently high in the sense that only twigs and branches of the shrubs (and of the surrounding strawberry trees) remained and no ground vegetation was left. Soil burn severity was consistently moderate in the sense that no litter layer remained, the ash layer was predominantly black, and that the topsoil structure and color were not visibly altered.

On the day of installing the erosion plots, the ash layer next to each erosion plot was collected in a plot of 25 cm by 25 cm, located halfway the length of the erosion plot. Afterwards, the topsoil at 0–2 and 2–7 cm depth was sampled using two bulk density cores with a diameter of 84 mm and a height of 20 and 50 mm. All samples were sieved manually at a mesh width of 2 mm, and then analyzed for their dry mass (APHA, 1998). The loads of ash and char (> 2 mm) particles were, on average, 563 and 37 g m^{-2}, with standard deviations of 105 and 33 g m^{-2}, respectively. The upper 7 cm of the topsoil had an average and standard deviation of bulk density of 0.88 and 0.11 g m-3, and of stoniness of 37 and 8% (*w*/w).

The eroded sediments were collected at a total of 12 occasions between the 21st of November 2015 and the 9th of October 2017, with a greater frequency during the first post-fire year (n = 8, till the 2nd of August 2016) than the second post-fire year (n = 4) for two reasons. First, the second post-fire year was a relatively dry year, with approximately 55% of the above-mentioned long-term average rainfall at the Alagoa station. Second, the erosion rates observed during the first measurement occasion of the second post-fire year (30th of November 2018) were low. The collected sediments were weighted in the field and brought to the laboratory for determining their dry mass (APHA, 1998) as well as their organic matter content (loss-on ignition method at 550 °C for, 4 h (Pribyl, 2010)).

The ground cover within each plot was estimated at six of the erosion measurement occasions, four of which during the first post-fire year. To this end, near-vertical pictures were taken of two fixed 1 m by 1 m quadrats in each plot, located at the bottom and top of the plots' outer boundaries. The photographs were overlaid virtually by a grid of 10 equidistant rows as well as columns, and the cover category identified visually for each of the 100 row-column intersections. The following six main cover categories were distinguished: stones (>5 mm), bare soil, ash layer (including charcoal particles), straw mulch and vegetation. The vegetation class was further divided into the following sub-categories: living vegetation (including mosses), dead vegetation and litter (mainly dead leaves from the strawberry trees. The cover results per plot were then obtained by averaging the frequencies of each grid and converting them into percentages. The same methodology was used to determine the plots' plant species composition at all six occasions. Furthermore, a vegetation relevee was made at the end of the study period, estimating the vertically-projected aerial cover into classes of 5% but subdividing the lowest class in <1% and 1–5%. The relevee and quadrat-based estimates were compared to rescale the quadrat-based results from the five prior occasions. Finally, the identified vascular plant taxa were divided into two groups with contrasting post-fire regeneration strategies (Keeley, 1986; Moreira et al., 2012; Maia et al., 2012), i.e. resprouters (*Eucalyptus globulus* Labill., *Pteridium aquilinum* (L.) Kuhn, *Quercus suber* L., *Ulex europaeus* L./*Genista triacanthos* Brot.), and seeders (*Cistus psilosepalus* Sweet, *Hordeum vulgare* L.).

2.4. Data analysis

The role of mulching and time-since-fire in post-fire soil erosion and vegetation cover was tested by means of linear mixed-effects repeated-measures modelling (Littell et al., 2006), using the plots as random factor, the restricted maximum likelihood criterion to select the variance components or autoregressive variance-covariance structures, and the Tukey–Kramer method (Kramer, 1956) for post-hoc testing. The erosion modelling was done for the annual figures over the first and second post-fire years as well as for the figures of the 11 individual measurement occasions. In the latter case, a stepwise forward-selection procedure was carried out to include possible significant covariates among the variables of rainfall (total, maximum 30-min intensity), ground cover classes (mulch, ash, stone and bare soil), and vegetation cover classes (total, resprouters, and seeders and mosses together (because their separate values lacked expression)). The vegetation cover modelling concerned all three aforesaid variables but was limited to the 11 individual measurement occasions and did not consider covariates. Initial modelling results revealed noticeable heteroscedasticity in the residual erosion values as well as the residual cover values but this could largely be overcome through fourth-root transformations.

Multiple regression modelling was carried out to quantify how well the spatiotemporal variation in post-fire erosion across the 11 measurement occasions could be predicted by potentially explanatory, independent variables. The independent variables included here were related to rainfall (total and maximum 30-min intensity (I30)), ground cover (mulch, ash, stone, and bare soil), and vegetation cover (total, resprouters, and seeders and mosses together). The modelling combined the REG stepwise forward-selection procedure (Littell et al., 2006) with the collinearity test (Belsley et al., 1980) to select the minimum set of explanatory variables that each individually explained a significant fraction of the (cumulative) variation, and, at the same time, did not exceed a threshold value of 20 for the condition index. The zero erosion values were excluded from the analysis.

All the statistical analyses were carried out using SAS Institute Inc. (2016), and involved an α of 0.05.

3. Results

3.1. Annual rainfall and erosion

Total precipitation at the study site was almost twice as high over the first post-fire year than over the second post-fire year, amounting to 1059 and 569 mm, respectively. The former value was very similar to the above-mentioned long-time average at the Alagoa station. Likewise, the average sediment losses without mulching were much higher over the first than second post-fire year, even 45 times higher with 7.3 Mg ha^{-1} as opposed to 0.16 Mg ha^{-1}(Fig. 2). By contrast, the average sediment losses with mulching did not differ significantly between the two periods, in spite they were nine times higher over the first than second post-fire year (0.7 Mg ha^{-1}vs. 0.08 Mg ha^{-1}). Perhaps worth special reference is that some straw was eroded during the first post-fire year, even if the average amount was just 0.03 Mg ha^{-1} or, in other words, <2% of the application rate (Fig. 2).

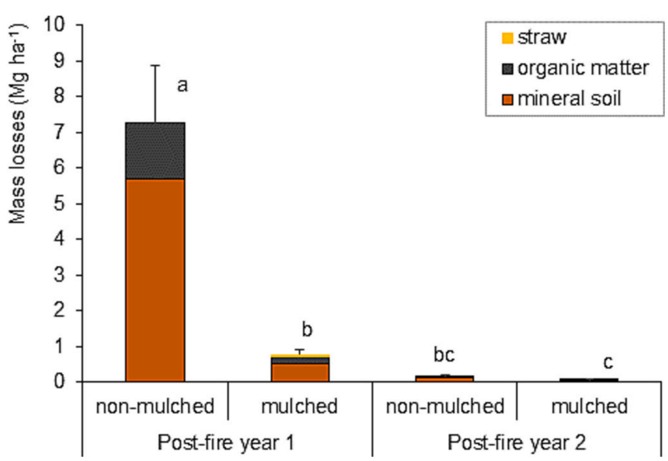

Fig. 2. Average sediment losses from the non-mulched and mulched plots over the first and second post-fire years, also showing their three fractions of mineral soil, organic matter and straw. The error bars represent the standard deviations of the sediment losses, while different letters indicate significant differences in sediment losses.

The above-mentioned differences in average sediments losses corresponded to an effectiveness of the mulching to reduce sediment losses by 90 and 50% over the first and second post-fire year, respectively. However, this reduction in sediment losses was only statistically significant in the case of the first post-fire year and not in the case of the second post-fire year. The specific rates of annual sediment losses per mm of rainfall revealed the same statistical results. The only significant differences were those between the rate of the non-mulched plots over the first post-fire year and the other three rates (6.9 vs. 0.1–0.7 kg ha^{-1} mm^{-1}).

The organic matter (OM) losses from the non-mulched plots constituted a similar fraction of the sediment losses over the first post-fire year and over the second post-fire year, averaging 22 and 23%, respectively. By contrast, the OM losses from the mulched plots represented a clearly higher fraction of the sediment losses over the second than first post-fire year, amounting, on average, to 36 and 25%, respectively. Even so, the OM fractions of the annual sediment losses did not differ significantly with either post-fire year or (non-)mulching, or with their interaction.

3.2. Temporal variation in rainfall and erosion

Rainfall varied markedly over the first 11 erosion measurement occasions, ranging from 15 to 314 mm (Fig. 3). The highest rainfall amounts (>250 mm) were recorded during late winter-early spring of both 2018 and 2019. By contrast, maximum rainfall intensities over 30 min (I30) were comparable for all occasions, with 16.5 to 23.2 mm h^{-1}.

Sediment losses from the non-mulched plots also differed notably among the 11 erosion measurement occasions, with average values varying between 0 and 2.9 Mg ha^{-1} (Fig. 3). The latter value corresponded to a clear and significant peak in sediment losses. Compared to the losses of the preceding occasion and of the succeeding occasion, this peak could be explained better by differences in maximum rainfall intensity (23.2 vs. 17.2/18.5 mm h^{-1}) than in rainfall amount (93 vs. 43/173 mm). The sediment losses from the mulched plots revealed a concomitant significant but less pronounced peak. It averaged 0.3 Mg ha^{-1} as opposed to 0.1 Mg ha^{-1} for both the preceding and succeeding occasion.

The mixed-effects modelling revealed a significant interaction between mulching and time for all four - 4th root-transformed - soil erosion variables, on the one hand, and, on the other, that rainfall amount was a significant co-variate in the case of the absolute sediment and organic matter losses (Table 1). The implied lack of a significant overall effect of mulching across the 11 measurement occasions reflected small and contrasting differences in erosion rates during most of the second post-fire year. Fig. 3 illustrates this for the sediment losses, with the post-hoc tests revealing significantly higher losses from the non-mulched than mulched plots for the first eight occasions as well as the last one as opposed to significantly lower losses from the non-mulched than mulched plots for the ninth occasion, and no significant differences for the tenth occasion. The respective mulching-induced reductions in average sediment losses amounted to 85–99%, undetermined and 51%. These relative reductions were not only poorly related with rainfall amount and maximum intensity but also with sediment losses from the non-mulched plots, with Pearson's product-moment correlation coefficients being 0.21, −0.18 and 0.18, respectively.

The multiple linear regression results were similar for the - 4th-root transformed - sediment and organic matter losses (Table 2). In both cases, stone cover clearly was the principal explanatory variable, with

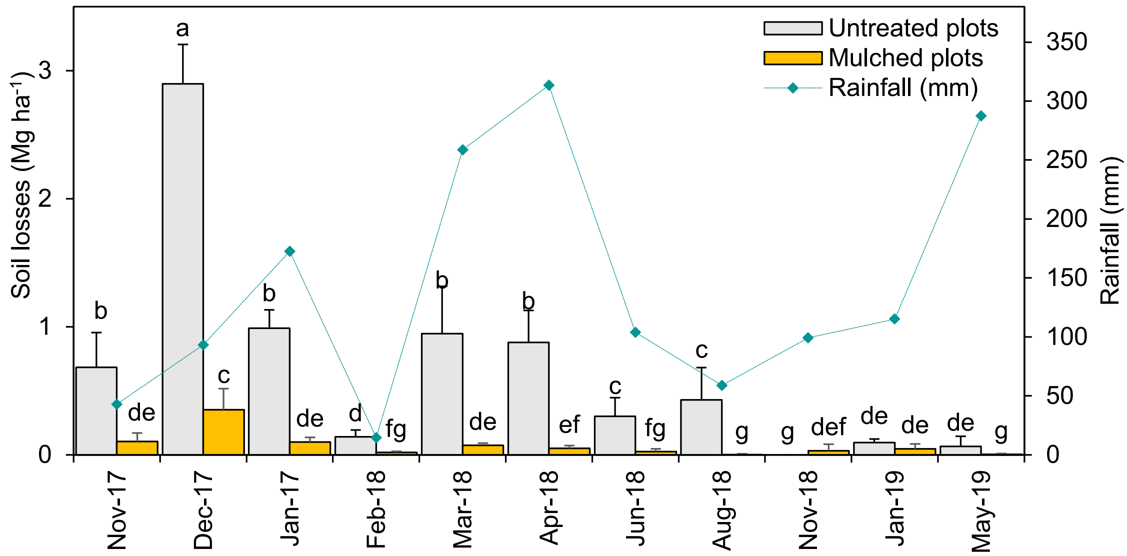

Fig. 3. Temporal patterns in total rainfall and average sediment losses (+ standard deviation) from the non-mulched and mulched plots during the first two post-fire years (but not showing the 12th measurement occasions, as all sediment losses were zero). Different letters indicate significant differences, at an α of 0.05, across treatments as well as measurement occasions.

Table 1
Summary of the mixed-effects modelling results for the four soil erosion variables during the first two post-fire years, following 4th-root transformation in all seven cases. Ndf and ddf stand for numerator and denominator degrees of freedom, respectively, while the underlined F-values are significant at α = 0.05.

	ndf	ddf	Sediment losses (Mg ha^{-1})	Organic matter losses (Mg ha^{-1})	Organic matter content (%)	Specific sediment losses (Mg ha^{-1} mm-rain)$^{-1}$
Fixed factors						
Mulching	1	4	84.4	48.6	12.6	72.5
Time	10	30	47.8	51.5	12.0	44.9
Mulching × time	9	30	8.9	11.8	6.3	5.8
Significant covariate(s)						
Total rain (mm)	1	30	5.6	5.3		

partial r^2's of 0.50–0.51 as opposed to 0.02–0.08 for the other three variables included in the models. Among the cover-related variables, mulch cover explained clearly less of the variability in both sediment and organic matter losses than ground vegetation cover and, in particular, the cover of seeders and mosses together, with the partial r^2's amounting to 0.3–0.4 and 0.7–0.8, respectively. The multiple regression results for the OM content were markedly different, not only in the sense that total vegetation cover was the principal explanatory variable but also that its partial r^2 was just 0.25.

3.3. Mulch, ash, stone and bare soil cover

The straw application was highly effective in the sense that the mulch cover of the treated plots averaged 90% immediately afterwards (Fig. 4). Mulch cover then gradually decreased at the subsequent measurement occasions till reaching roughly 10% in January 2019. This decrease reflected first and foremost vegetation recovery, as further detailed in the next section, with the vegetation increasing blocking the view of the underlying straw. A similar decrease was observed in the non-mulched plots, with the total cover of ash, stones and bare soil amounting, on average, to 99% in November 2017 and 4% almost two years later. While bare soil cover was of reduced importance in the non-mulched plots (roughly 5% during first post-fire year), the plots' ash and stone covers revealed distinct temporal patterns. Ash was the dominant cover type at the first measurement occasion, averaging 58%, but then decreased to 4% in April 2018. By contrast, the average stone cover increased from 38 to 59% over the same period, dropping off afterwards to 17, 11 and 4%, respectively, again reflecting vegetation recovery.

3.4. Ground vegetation cover and composition

The application of barley straw had a noticeable impact on the floristic composition of the vegetation, in the sense that barley attained an average cover in the mulched plots of 6 and 18% in March and April 2018, respectively, as opposed to 0% in the non-mulched plots (Fig. 5). This peak in barley cover in April 2018, however, was not associated with a higher total vegetation cover, as it averaged 44% in both the

Table 2
Summary of the multiple linear regression models for the three soil erosion variables during the first two post-fire years, following 4th-root transformation in all three cases.

	Sediment losses (Mg ha^{-1})		Organic matter losses (Mg ha^{-1})		Organic matter content (%)		
Parameter	Estimate	r2	Estimate	r2	Parameter	Estimate	r2
Intercept	−0.482	–	−0.265	–	Intercept	2.140	–
Stone cover	0.005	0.50	0.004	0.51	Total vegetation cover	0.004	0.25
Seeder+mosses cover	−0.016	0.08	−0.010	0.07	Mulch cover	0.001	0.07
Mulch cover	−0.002	0.04	−0.002	0.04			
Total rain	0.0005	0.02	0.0003	0.03			

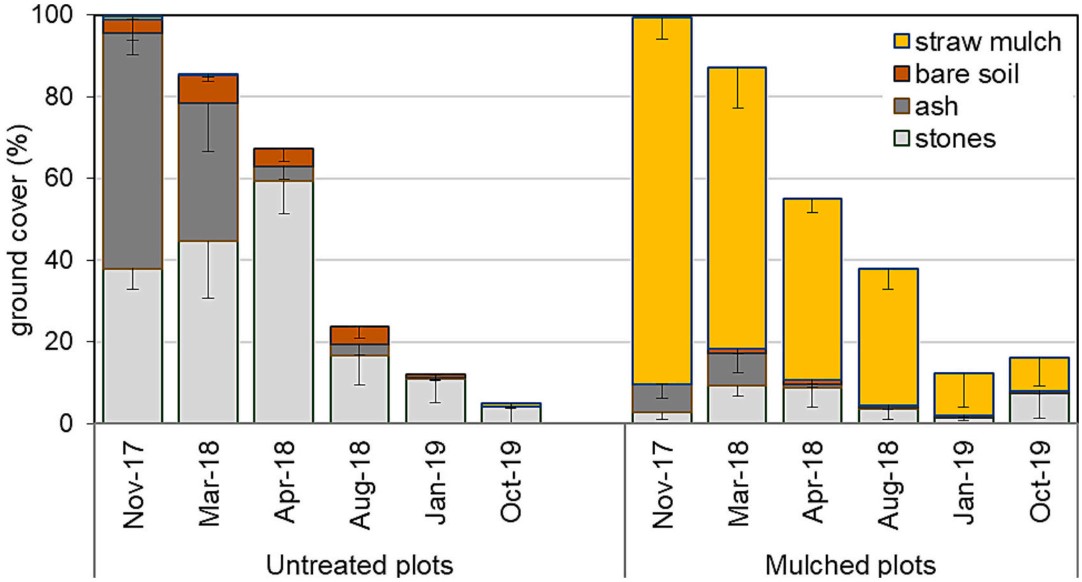

Fig. 4. Evolution of the mulch, ash, stone, bare soil covers in the non-mulched and mulched plots during the first two post-fire years, showing averages and - subtracted - standard deviations.

mulched and non-mulched plots. Even so, it did seem associated with a reduction in the cover of the moss *Funaria hygrometrica* Hedw., averaging 2 and 14% in the mulched and non-mulched plots, respectively. After April 2018, the mulched and non-mulched plots did not differ consistently or markedly in either their total vegetation cover or their floristic composition. Total vegetation cover attained 60–70% in August 2018, 10 months after the fire, and 80–90% in October 2019, 24 months after the fire. The floristic composition was poor throughout the study period, with 4–5 higher plant species, and was clearly dominated by the fern *Pteridium aquilinum* (L.) Kuhn.

The mixed-effects modelling of the - 4th root transformed - vegetation cover values revealed contrasting results for the total vegetation cover and the cover of the seeders and mosses together, on the one hand, and, on the other, the cover of the resprouters (Table 3). The two former variables revealed a significant interaction between mulching and time, while the latter variable revealed a significant overall effect of time. The temporal patterns in resprouter cover were straightforward, including in

Table 3
Summary of the mixed-effects modelling results for the three ground vegetation cover variables during the first two post-fire years, following 4th-root transformation in all three cases. Ndf and ddf stand for numerator and denominator degrees of freedom, respectively, while the underlined F-values are significant at α = 0.05.

	ndf	ddf	total vegetation cover	sum of seeders and mosses	resprouters
			(%)	(%)	(%)
Mulching	1	4	65.3	17.3	4.0
Time	11	44	1753.0	17.1	664.7
Mulching × time	11	44	131.0	2.6	0.6

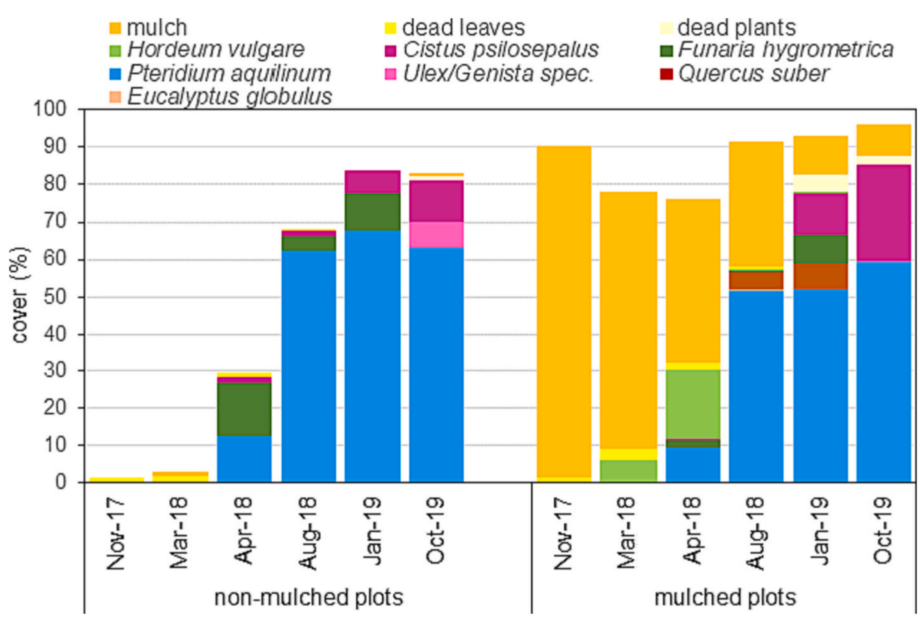

Fig. 5. Evolution of the average covers of the individual plant species as well as of dead leaves and mulch in the non-mulched and mulched plots during the first two post-fire years.

terms of significant post-hoc differences, as the cover in March 2018 was significantly higher than the cover on the two preceding occasions and significantly lower than the cover on the three succeeding occasions (Fig. 6). The temporal patterns in combined seeder and moss cover were more intricate, with an initial peak in April 2018 that, as referred earlier, was due to barley in the mulched plots and *Funaria hygrometrica* Hedw. in the non-mulched plots. The role of mulching in the combined seeder and moss cover was significant on two occasions, in March 2018 and October 2019, in both cases with a higher cover in the mulched than non-mulched plots. These two significant differences were associated with barley and *Cistus psilosepalus* Sweet, respectively (see Fig. 5). The March-2018 difference in the combined seeder and moss cover was responsible for the only significant post-hoc difference in total vegetation cover.

4. Discussion

4.1. Post-fire sediment losses without mulching

The average sediment losses from the three non-mulched plots over the first post-fire year (7.3 Mg ha^{-1}) were clearly higher than the median values over any one post-fire year reported by Shakesby (2011) for plot-scale studies in the Mediterranean following not only moderate fire severity (2.1 Mg ha^{-1}), as observed here, but also high fire severity (3.7 Mg ha^{-1}). When comparing with the values reported for the study region of north-central Portugal for similarly-sized plots of 10 to 20 m^2 and, in the case of Prats et al. (2016a) 100 m^2 over the first post-fire year, the present value was somewhat smaller than the average value observed by Keizer et al. (2018: 8.0 Mg ha^{-1}) but noticeably higher than the average values observed by the other field studies. Namely, these other prior values were, in decreasing order: 5.6 Mg ha^{-1} (Prats et al., 2012: eucalypt stand); 5.1 Mg ha^{-1} (Malvar et al., 2017); 4.6 Mg ha^{-1} (Prats et al., 2016a); 3.0 Mg ha^{-1} (Prats et al., 2016b; NB: across plot scales); 2.0 Mg ha^{-1} (Ferreira et al., 1997; NB: single plot); 1.2 Mg ha^{-1} (Shakesby et al., 1996: eucalypt stand); 0.8 Mg ha-^{1} (Prats et al., 2012: pine stand). Worth referring is that, like here, these prior field studies all concerned (predominantly) moderate fire severity and soils derived from schist parent material. Furthermore, the lowest of these prior figures, for the pine stand in Prats et al. (2012), could be explained by spontaneous mulching through needle cast from scorched pine crowns, in agreement with Fernández et al. (2020).

Worth noting is that the above-mentioned region-wise comparison of absolute sediment losses involved pronounced differences in annual rainfall amounts, ranging from 450 mm (Ferreira et al., 1997) to 1684 mm (Prats et al., 2012). When compensating for these rainfall differences, the sediment loss rate reported here not only outranked that of Keizer et al. (2018) but also noticeably exceeded those of all other prior studies. The present specific sediment losses per mm of rainfall amounted to 6.9 kg ha^{-1} mm-rainfall^{-1} as opposed to 5.6 kg ha^{-1} mm-rainfall $^{-1}$ in Keizer et al. (2018) and, in decreasing order, 4.3 kg ha^{-1} mm-rainfall $^{-1}$ in Ferreira et al. (1997), 4.1 kg ha^{-1} mm-rainfall $^{-1}$ in Malvar et al. (2017), 3.4 kg ha^{-1} mm-rainfall $^{-1}$ in Prats et al. (2016b), 3.3 kg ha^{-1} mm-rainfall $^{-1}$ for the eucalypt stand in Prats et al. (2012), 3.1 kg ha^{-1} mm-rainfall $^{-1}$ in Prats et al. (2016a), 1.8 kg ha^{-1} mm-rainfall $^{-1}$ rainfall for the eucalypt stand in Shakesby et al. (1996) and 0.5 kg ha^{-1} mm-rainfall $^{-1}$ for the pine stand in Prats et al. (2012). A possible explanation for the comparatively high sediment losses in the present study over the first post-fire year resides in the recent land-use history of the study site. Namely, the irregular spatial distribution as well as the varying sizes of the strawberry trees suggested that the stand had resulted from selective thinning and not from planting, at least at the field scale, and, especially, the associated mechanised soil mobilization as is typical for the eucalypt and pine stands in the study region. Since ploughing for the establishment of monospecific tree plantations results in erosion rates that are even higher than those following wildfires (Shakesby, 2011), the present study site could “suffer” to a lesser extent from sediment-limited erosion than the eucalypt and pine sites of the other regional studies. Even so, the stone cover of the non-mulched plots was at least 60% in this study (i.e. maximum value observed in April 2018), while it was only half in, for example, Keizer et al. (2018). Therefore, the stone cover of the non-mulched was possibly of less importance in limiting the initial post-fire sediment losses than argued by Shakesby et al. (1994). The multiple regression results did in fact indicate that stone cover could best explain a substantial part of the temporal and mulching-related variation in sediment losses but in the sense that sediment losses increased with increasing stone cover.

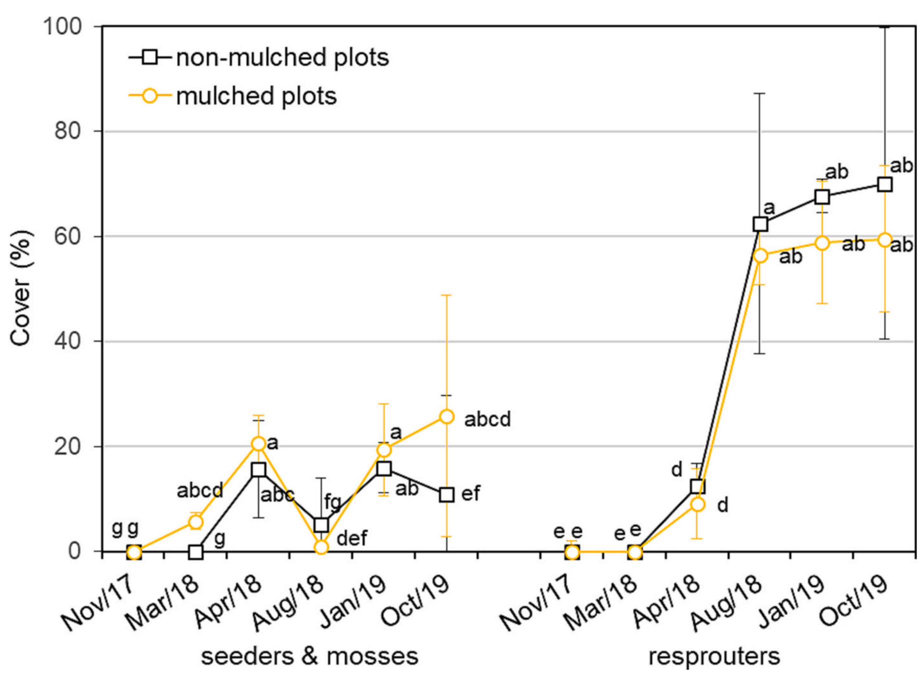

Fig. 6. Temporal patters in the cover (average and standard deviation) of the seeders and mosses together as well as of the resprouters in the mulched and non-mulched plots during the first two post-fire years. Different letters indicate significant post-hoc differences for each cover category separately.

Possibly, however, the cause-effect relationship was in the opposite direction, with surface stones being uncovered by wash-off of the wildfire ash. Nonetheless, it is worth stressing that the methodology applied here to estimate ground cover inherently implied that stone cover was dependent on (changes in) the overlying cover categories, not only of ash but also of vegetation in the case of the non-mulched plots. In the initial forward-selection step in the regression modelling of sediment losses, ash cover was also identified as the second-best explanatory variable after stone cover, and only explained slightly less of the variation than stone cover, with a partial r^2 of 0.45 as opposed to 0.50.

The average sediment losses from the non-mulched plots decreased very drastically from the first to the second post-fire year, with 98% to 0.16 Mg ha^{-1}. This could only be explained to a small extent by the reduced rainfall over the second year, since the concomitant decrease in specific sediment losses amounted to 96% (6.9 to 0.3 kg ha^{-1} mm-rainfall^{-1}). Unlike the specific sediment losses over the first post-fire year, those over the second post-fire year were relatively small in comparison to the ones reported by the prior field studies in the region. In increasing order, Prats et al. (2016a) reported 0.8 kg ha^{-1} mm-rainfall^{-1} over the second post-fire year, Lopes et al. (Lopes et al., 2020: second post-fire year of Keizer et al. (2018)) 0.9 kg ha^{-1} mm-rainfall^{-1}, Shakesby et al. (1996) 1.3 kg ha^{-1} mm-rainfall^{-1} for their pine stand, Prats et al. (2016b) 2.5 kg ha^{-1} mm-rainfall^{-1}, and Shakesby et al. (1996) 3.3 kg ha^{-1} mm-rainfall^{-1} for their eucalypt stand. The latter case stood out in the sense that it was the only one in which the specific losses over the second year even exceeded those over the first post-fire year, and notably so with roughly 80%. Shakesby et al. (1996) also referred the exceptional nature of their increase, against the literature at the time, and attributed it in part to the higher frequency of intense daily and hourly rainfall during the second than first post-fire year. Unfortunately, however, the almost complete lack of field studies at (sub-) hourly or even event-wise resolution continues to seriously hamper a better understanding of post-fire runoff and erosion processes at the plot scale. Even so, the above-mentioned regional specific losses over the second post-fire year could indicate a broad relationship with annual rainfall. Namely, the lowest losses of 0.3 kg ha^{-1} mm^{-1} rainfall coincided with the lowest rainfall amounts of 550–600 mm y^{-1}, the intermediate losses of 0.8–1.3 kg ha^{-1} mm^{-1} rainfall with intermediate rainfall amounts of 900–1200 mm y^{-1}, and the highest losses of 2.5–3.3 kg ha^{-1} mm^{-1} rainfall with the highest rainfall amounts of 1450–1500 mm y^{-1}. Nonetheless, the intermediate losses of 0.9 kg ha^{-1} mm^{-1} rainfall in Lopes et al. (2020) were produced by just 572 mm.

4.2. The effectiveness of straw mulching to reduce post-fire soil erosion

The observed mulch-induced reduction in sediment losses of 90% over the first post-fire year closely matched the global meta-analysis results of Girona-García et al. (2021). In particular, the present effect size of −2.34 was close to the mean effect size of −2.16 for the middle of the three classes of straw application rates identified by Girona-García et al. (2021), ranging from 201 to 250 g of straw per m^2. This 90% reduction observed here also agreed well with the reductions reported by the prior post-fire erosion mitigation studies in region that involved losses exceeding 1 Mg ha^{-1} y^{-1} (i.e. ignoring the pine stand in Prats et al. (2012)). The reductions of these prior studies ranged from 83% (Prats et al., 2016b) to 86% (Prats et al., 2012: eucalypt stand; Keizer et al., 2018: reduced application rate) and 96% (Prats et al., 2016a; Keizer et al., 2018: standard application rate). Worth referring is that these prior results concerned either hydromulch (Prats et al., 2016b) or forest residue mulch at much higher application rates than in this study (8–14 vs. 2 Mg ha^{-1}), with the exception of the reduced application rate in Keizer et al. (2018: 2.6 Mg ha^{-1}).

The present reduction in sediment losses of 50% over the second post-fire year was relatively small, not only compared to the first post-fire year but also compared to the findings of Girona-García et al. (2021). The effect size of −0.69 observed here was towards the lower end of the 95% confidence interval for the lowest class – and not, as referred before, the middle class - of straw application rates distinguished by Girona-García et al. (2021: ≤2 Mg ha^{-1}). Likewise, it was towards the lower end of the 95% confidence interval for the second post-fire year in Girona-García et al. (2021). Furthermore, the present effectiveness over the second post-fire year was low compared to that reported by the prior studies in the region. In decreasing order, Lopes et al. (Lopes et al., 2020: standard application rate), Prats et al. (2016a, 2016b) and Lopes et al. (Lopes et al., 2020: reduced application rate) reported mulch-induced reductions in sediment losses over the second post-fire year of 93%, 92%, 83% and 67%, respectively. The present, low effectiveness could be explained by the low specific sediment losses in the present study compared to these prior studies in the region, as referred earlier (0.3 vs. 0.8–2.5 kg ha^{-1} mm-rain^{-1}). The differences in sediment losses between the mulched and non-mulched plots were also notably inconsistent across the measurement periods of the second post-fire year in the present study, while they were perfectly consistent in the study of Lopes et al. (2020).

The reduced importance of not only mulch cover but also rainfall in explaining the sediment losses across all plots and across the entire study period was perhaps somewhat surprising. First, the mixed-effects modelling revealed significant differences between the mulched and non-mulched plots for nine out of the 11 measurement occasions, on the one hand, and, on the other, a significant role of rainfall amount as co-variate. Second, the various multiple regression models in Prats et al. (2012) all had rainfall intensity or amount as principal explanatory variable and all but one had litter cover as secondary but still quite relevant explanatory variable, with partial r^2's ranging from 0.37 to 0.55 and from 0.21 to 0.28, respectively. By contrast, the global multiple regression model in Prats et al. (2016b) was more in line with the present one, at least in the sense that rainfall was of reduced importance compared to a cover-related variable (r^2 of 0.02 vs. 0.55). This cover-related variable in Prats et al. (2016b), however, was the total protective cover - i.e. the sum of mulch, litter and vegetation cover – and this was associated with a negative regression coefficient as opposed to stone cover here. Although such composite cover variables were not included in the present study, stone cover was by and large complementary to the total cover of straw mulch and vegetation from April 2018 onwards, when ash cover had dropped to negligible values. Possibly, the reduced importance of rainfall in this study and Prats et al. (2016b) compared to Prats et al. (2012) was related with their longer durations, in combination with a decrease in specific sediment losses per mm of rainfall with time-since-fire. The present study and Prats et al. (2016b) covered the first two post-fire years, while Prats et al. (2012) concerned the first post-fire year and the second post-fire autumn.

4.3. The effects of straw mulch on vegetation recovery

The most obvious impact of the mulching on the post-fire vegetation composition was the introduction of barley in the mulched plots, arguably through viable seeds mixed with the straw. This impact, however, was short-lived, as barley was no longer present in the mulched plots from August 2018 onwards and, being an annual species, was apparently unable to produce seeds that could germinate during the second post-fire year. At the same time, this impact seemed contained in space, as barley was not observed in any of the non-mulched plots, in spite they bordered the mulched plots. Similar results were reported by the other two post-fire mulching studies in the Iberian Peninsula that applied barley straw and determined floristic composition (Badia and Clara Marti, 2000; Fernández et al., 2016). Badia and Clara Marti (2000) reported an average cover of barley of 9 and 14% for two contrasting soil types at the end of the first post fire year and of 1% at the end of the second post-fire year, i.e. very similar to 14 and 0% reported here. Fernández et al. (2016) found higher densities of barley than oat and wheat (10 vs. 3 vs. 0 seedlings per m^2) one year after applying a mixture of barley, oat and wheat straw. The findings in Fernández and Vega (2014) and Díaz-

Raviña et al. (2018) likewise suggested that mulching with wheat straw did not lead to the introduction of wheat, implying some advantage of using wheat straw over barley straw for post-fire erosion mitigation in the Iberian Peninsula or at least its more humid regions.

The present results did not support the concerns expressed by, for example, Kruse et al. (2004) and Fernández and Vega (2014), about the introduction with mulch of other non-native and especially invasive plant species. Likewise, Fernández et al. (2016) found no evidence for the presence of non-native species following post-fire mulching with a mix of barley, oat and wheat straw (other than, as referred earlier, barley and oat). Apparently, the same was true in the above-mentioned studies of Fernández and Vega (2014) and Díaz-Raviña et al. (2018), both involving post-fire wheat-straw mulching.

The native plant species composition at the present study site was also not notably affected by the mulching during the first two post-fire years. This lack of a short-term effect was in line with the findings of Fernández et al. (2016) for the first post-fire year following barley straw mulching, and of Fernández and Vega (2014) for the first two post-fire years following wheat straw mulching. Nonetheless, mulching was found here to significantly affect the cover of one of the native species, i.e. the seeder *Cistus psilosepalus* Sweet. This effect was only observed at the end of the study period, so that its duration beyond the second post-fire year remained uncertain.

The total ground vegetation cover was not significantly affected by the present mulch application either, except on one occasion in March 2018 due to the comparatively early emergence of the barley introduced with the mulch. Among the post-fire straw mulching studies in the Iberian Peninsula, Fernández et al. (2011) and Vega et al. (2014) equally reported no effects, while Fernández and Vega (2014), Fernández et al. (2016) and Lucas-Borja et al. (2019: non-logged plots) found mulching to favour vegetation cover recovery. Intermediate results were presented by Fernández and Vega (2016) and Díaz-Raviña et al. (2018), in the sense that mulching only enhanced vegetation cover during the initial parts of their studies, i.e. the first year out of three and the first eight months out of 12, respectively.

5. Conclusions

The main conclusions of this study into soil erosion and vegetation recovery in a strawberry tree stand in north-central Portugal during the first two years following a moderate severity wildfire and the effects thereupon of applying of barley straw mulch at a low rate of 2 Mg ha^{-1} were as follows:

- the average sediment losses without mulching were much higher during the first post-fire than second year, not only in absolute numbers but also relative to the annual rainfall amounts, and these first-post-fire year losses were also high compared to the prior studies in the study region;
- notwithstanding the low application rate, mulching significantly and strongly reduced the sediment losses over the first post-fire year from, on average, 7.3 to 0.7 Mg ha−1 y−1, and consistently so throughout this first year, but not the sediment losses over and throughout the second post-fire year;
- the temporal patterns in sediment as well as organic matter losses across the mulched and non-mulched were clearly better explained by stone cover than by ground vegetation cover and, to a greater extent still, mulch cover;
- The mulching did not lead to the introduction of other non-native plant species than barley, while barley attained a reduced maximum cover (on average, 18%) and did not carry over to the second post-fire year;
- The mulching did not significantly affect the recovery of the total ground vegetation cover, except on one occasion during early spring of the first post-fire year that involved reduced cover values (<10%) that were due to barley.

CRediT authorship contribution statement

O. González-Pelayo: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **S.A. Prats:** Data curation, Investigation, Methodology, Software, Writing – review & editing. **Vieira AMD:** Writing – review & editing. **Vieira DCS:** Data curation, Investigation, Methodology, Writing – review & editing. **P. Maia:** Data curation, Investigation, Methodology, Writing – review & editing. **J.J. Keizer:** Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

For the purpose of submit a research article to the Ecological Engineering journal, I declare that the information provided is accurate to the best of my knowledge.

Name of investigator: Oscar González Pelayo, PhD.

Name of Institution: University of Aveiro.

Data availability

The authors do not have permission to share data.

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