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# Post-fire soil water repellency under stones and forest residue mulch versus of bare soil

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**Abstract:** Soil water repellency (SWR) is commonly defined as a physical property of soil to resist wetting. Fire can induce, enhance, or reduce SWR and, consequently, lead to considerable changes in soil water infiltration and storage and increase soil erosion by water. The application of mulches to cover burned areas has been found to be an efficient emergency stabilization treatment. However, little is known about possible side effects on SWR, especially long-term effects. Under forests, SWR is known to be very heterogeneous, particularly in proximity to trees and shrubs, litter type and thickness, stones, cracks and roots. This study targeted the effects of post-fire mulching on SWR in a eucalypt plantation five years after a wildfire. The application of forest residue mulch did not significantly change SWR in bare soil patches or under stones, comparing the mulched and untreated plots. By contrast, SWR in the mulched plots was, significantly stronger under mulch than in bare soil. The same was true for both soil organic matter content (SOM) and soil moisture content (SMC), suggesting that SOM played a more important role than SMC. In turn, SWR under mulch was not significantly different from SWR under stone, while both SMC and SOM were significantly higher under mulch than stone. This could be explained by the differences in SMC overriding the effects of the differences SOM, or, alternatively, by possible differences in SOM quality, in particular of the "fresh" input from the mulch. Overall, the present results indicated that different mechanisms may drive SWR dynamics beneath mulch fragments, stones and bare soil patches. A better understanding of these mechanisms is important to improve the knowledge of post-fire overland flow generation and, thereby, to improve its prediction using hydrological models, especially during the early phases of the window-of-disturbance.

**Keywords:** Wildfire; Hydrophobicity; Mulching; Rock fragment; Stone lag.

## INTRODUCTION

Soil water repellency (SWR) is a physical property that is defined as the capacity of soil to resist wetting (Doerr et al., 2000) and can influence forest hydrological processes (Zavala et al., 2014). Presence of repellent soils has been reported to occur worldwide (DeBano, 2000) and can affect soil respiration (Urbanek and Doerr, 2017), infiltration and water storage (Doerr et al., 2006), surface runoff (Vieira et al., 2018), and soil erosion (Doerr et al., 2000).

The severity of SWR, i.e. how strongly water is repelled (Douglas et al., 2007), has been associated with variations in soil variables such as: texture (González-Pelayo et al., 2015); pH (Doerr et al., 2007); temperature (Cawson et al., 2016); moisture content (Whelan et al., 2015); organic matter content and type (Barton and Colmer, 2011); and soil beneath different vegetation types (Verheijen and Cammeraat, 2007). Among these variables, special importance has been given to a soil moisture content (SMC) threshold, which is commonly proposed to mark the transition zone from repellent to wettable conditions (Malvar et al., 2016a). Additionally, the presence of soil organic matter, including waxes, oils, and resins, can increase soil water repellency (SWR), thereby enhancing repellency as the organic matter content in soil increases (Doerr et al., 2007). However, the spatial and temporal occurrence and variability of SWR are still unclear.

Fire is recognised as an important factor for SWR dynamics and has been shown to induce, enhance, or reduce SWR, depending mostly on factors such as maximum fire temperature, fire duration, and vegetation type (Doerr et al., 2009; Malvar et al., 2016a). During the burning process, certain hydrophobic compounds from the vegetation may migrate into soil surface, inducing SWR (DeBano, 2000). Simultaneously, the distribution of fire temperatures, ranging from 200 to 900 °C, as well as the duration of burning, from a few minutes up to 30 minutes, will determine the resulting ash content. This surface ash may then leach into the soil after the first rainfall events, promoting SWR indirectly (Kutiel et al., 1995). However, if the temperatures reach higher values, the repellency might be destroyed (Zavala et al., 2014). Fire temperatures and duration vary considerably in space, indirectly leading to high heterogeneity of SWR within a slope (Cawson et al., 2016).

Portugal is one of the countries most affected by wildfires, especially in the last three decades when numbers and area of wildfires has increased considerably, with 100,000 ha $yr^{-1}$ of burnt area, which corresponds to 3% of the national forest area (Pereira et al., 2006). In the years following wildfire, increased runoff generation occurs along associated sediment losses (Malvar et al., 2016b; Vieira et al., 2016), which in turn can lead to major hazards such as flash floods (Lourenço and Rodrigues, 2015) and/or downstream water contamination (Silva et al., 2015).

The application of mulch from various materials to reduce the risk of soil erosion in burned areas has been observed as an efficient stabilization treatment to minimize the fire effects on soils (Robichaud et al., 2010). In Portugal, several pilot studies have addressed the spatial and temporal effectiveness of forest residue mulch application after wildfires in reducing runoff generation and sediment transport (Prats et al., 2012; 2014; 2016a; 2016b). However, besides the benefits of reducing runoff and erosion, little is known about possible side-effects (Fér et al., 2022). For example, Puga et al. (2017) report that mulching application following wildfire did not have any impact on ground-dwelling arthropods community. De la Rosa et al. (2019) concluded that mulching indirectly contributed to the preservation of topsoil pyrogenic C. mulch may even protect the soil for many years without affecting understory vegetation (Jonas et al., 2019).

But it is unknown how mulching affects SWR, especially in the long term. Prats et al. (2016c) reported SWR reduction after the application of hydro-mulch, but the mixture contained surfactants known to reduce SWR. Conversely, in another study, no effect on SWR was observed after application of forest residue mulch (Prats et al., 2016a).

Most SWR field studies measure repellency in homogeneous bare ground patches and often overlook spatial heterogeneity in the topsoil. Few studies address factors such as proximity to shrub/trees (Keizer et al., 2005), the effects of plant litter (Verheijen and Cammeraat, 2007), cracks and roots (Urbanek et al., 2015) and stones (García-Moreno et al., 2013; Gordillo-Rivero et al., 2014; Urbanek and Shakesby, 2009). Yet, forest soil water repellency is distributed very heterogeneously and many of these soil surface components affect runoff generation and sediment movements (Ferreira et al., 2008). Malvar et al. (2016a) found significant spatial variability in SWR over eucalypt plantations within a slope on half of the sampling days. Granged et al. (2011) reported an increase in runoff generation influenced by the heterogeneous wetting pattern of SWR under burned pines. This is an important factor for hydrological models, as reported by Vieira et al. (2018), where the runoff generation in soils with SWR is largely explained by SWR-related variables.

The objective of this study was to assess the impact of post-fire mulching on SWR in a eucalypt plantation five years (mid-term) following a wildfire. Specifically, the study aimed to monitor SWR in three different spatial conditions: Bare soil, beneath stones, and beneath mulch fragments. Additionally, the study explored the dynamics of SWR in relation to soil moisture content (SMC), soil organic matter (SOM) and the amounts of topsoil litter.

Post-fire mulching is currently being used globally to mitigate erosion by water, yet its indirect effects on SWR remain largely unknown. With similar importance, topsoil stones are often overlooked in hydrological studies. A better comprehension of these two soil surface phenomena is crucial for enhancing our understanding of runoff generation in forested plantations and may contribute to improving hydrological modelling.

## MATERIAL AND METHODS

### Study area and sites

In 2010, the FIRECNUTS project installed a study site in the vicinity of Sever do Vouga municipality, located in north-central Portugal. The aim was to assess the effectiveness of forest residue mulch, specifically chopped eucalypt bark mulch in reducing post-fire runoff and soil erosion (Prats et al., 2014; 2016a; 2016b). The site was selected following a wildfire in July 2010, which consumed 295 ha of planted forests, primarily consisting of *Eucalyptus globulus* and *Pinus pinaster*. Within four weeks after the fire, six plots measuring 4 m × 25 m each (ranging from 83 to 131 m$^2$) were defined in a randomised design on a steep southeast-facing slope (25°) within a eucalypt plantation. Three plots were treated with chopped eucalypt bark mulch, which included remnants of wood fragments, applied at a rate of 14 Mg ha$^{-1}$, to ensure more than 60% of topsoil cover (Robichaud et al., 2010), while three plots were left untreated as controls.

The region is situated within the Hespheric Massif, a major physiographic unit in the region as described by Ferreira, (1978). The predominant parent material comprises pre-Ordovician schists and greywackes. Soil profiles indicate that soils range from sandy-loam Humic Cambisols at the base of the slope and Umbric Leptosols near the top of the slope. The climate is classified as humid mesothermal (Csb, Köppen classification), characterized by moderately dry summers (DRA-centro, 1998). Annual mean temperature has been recorded at 14.9°C (last 20 years, based on data from the nearest weather station; Bouça 40°51'16" N, 8°22'55" W; SNIRH, 2016). Similarly, the mean annual rainfall over the same period stands at 1609 mm (based on data from the nearest rainfall station; Ribeiradio 40°44'39" N, 8°18'05" W; SNIRH, 2016).

The present study was conducted in the original plots (Prats et al., 2014) five years after their installation (June 2015). A general description from the site indicated that the eucalypts trees had reached hights ranging from 9 to 14 m, while the shrub vegetation within the plantation (mainly composed of *Ulex europaeus* and *Pterospartum tridentatum*) ranged from 1.5 to 2.0 m in height.

### Field measurements

On June 25$^{th}$ 2015, twelve sampling grids measuring 1 m$^2$ were selected inside the existent plots (Prats et al., 2014), resulting in six sampling grids for both the mulch treatment and the control.

### Ground cover

Ground cover was recorded at each intersection of a 1 m × 1 m square grid, delineated by 10 equidistant rows intersecting with 10 equidistant columns, totalling 100 intersections. Six categories were documented: bare soil, stones (including rock outcrops), char, litter, mulch and vegetation (lower than 50 cm in height). After removing all above-ground vegetation and litter (excluding the remnants of mulch), the grid was repositioned in the same location, and new ground cover categories were documented.

### Soil surface water repellency

After recording the ground cover, soil surface SWR measurements were conducted within each of the 12 sampling areas (1m$^2$) using the molarity of an ethanol droplet (MED) test (Doerr, 1998). These measurements were taken *in situ*, comprising four tests on bare soil patches and four tests beneath surface stones (after carefully removing the stones). Within the mulched areas, SWR was also measured under four mulch fragments. Three drops of ethanol with increasing concentrations were applied to the soil surface, and the ethanol concentration at which all tree drops infiltrated within 5 seconds was recorded. This indirect measurement of soil surface tension defined the strength of SWR. SWR was expressed as one of 10 intensity classes (Malvar et al., 2016a): 0, very wettable (0%); class 1 and class 2, wettable (1% and 3%, respectively); class 3, slightly water-repellent (5%); class 4, moderately water-repellent (8.5%); class 5, strongly water-repellent (13%); class 6 and class 7, very strongly water-repellent (18% and 24% respectively); and class 8 and class 9, extremely water-repellent (36% and more than 36%, respectively). These intensity classes therefore constitute an interval measurement scale.

One cm away from each SWR measurement, soil samples were collected to a depth of one cm (ca. 1 g) and placed into zip bags for determination of gravimetric soil moisture content and organic matter content (totalling 120 measurements). All remaining mulch was removed and collected for dry biomass determination (at 105 °C for 24h). Gravimetric soil moisture content (SMC) was determined by drying samples at 105 °C for 24 h, while soil organic matter (SOM) content was determined by loss on ignition at 550 °C for 4 h (Botelho da Costa, 2004).

### Data analysis

Statistical analyses were performed using the SigmaPlot 11.0 software package (Systat Software, Inc., 2012). To test differences in mean values of ground cover (i.e., litter, vegetation, bare soil, stones, char and mulch remains) between untreated and mulched areas, a parametric t-test was performed because all cover values were normally distributed and showed equal variance.

Because the MED classes are not measured on a scale with a constant unit, all statistical tests carried out were non-parametric. A multiple comparison analysis was performed using pair-wise two-sample Mann–Whitney U-tests (MWU-t). The paired-site comparison focused on differences between untreated vs. mulched areas. Within treatments, pair coverage comparison was focused on differences between bare soil vs. stones; bare soil vs. mulch; and stones vs. mulch.

The Spearman rank correlation coefficient was used to explore the relationship between SWR median MED classes and auxiliary variables, i.e., median SMC, median SOM and dry litter. A significance level of 0.05 was used for all statistical tests.

## RESULTS

### Ground cover

The soil surface (Table 1) was largely covered by litter, with no significant differences ($P = 0.122$) observed between untreated and treated sampling points (62% and 74%, respectively). Vegetation cover was not significantly different ($P = 0.699$), despite being the double in untreated areas (21%) compared to mulched areas (12%). Topsoil bare patches and stones covered less than 10% and 5% respectively in both untreated and mulched areas. The quantity of litter was 31% greater in untreated areas ($P = 0.024$), with 405 g m$^{-2}$ compared to 278 g m$^{-2}$ of dry biomass in mulched areas. Mean vegetation dry weight was consistent across both treatments. Charred material was 3.5 g m$^{-2}$ in untreated areas, doubling to 6.9 g m$^{-2}$ in treated areas, yet the difference was not significantly different between treatments ($P = 0.310$). In treated areas, remnants of mulch collected amounted 36 g m$^{-2}$, and consisted of small wood fragments, with no chopped bark found.

After removing vegetation and litter (Table 1), bare soil dominated the soil surface, accounting for 70–80% across both treatment conditions without showing a significant treatment effect ($P = 0.109$). Stone cover was higher in untreated areas (29%) compared to mulched areas (12%; $P = 0.013$). Charred biomass fragments (here expressed as ‘char’) remain visible five years after the wildfire in both untreated and mulched sampling areas, although covering small areas, 1% and 3% for untreated and mulched areas ($P = 0.485$), respectively. Small wood fragments (here expressed as ‘mulch’) covered 6% of treatment areas (reduced from 83% cover at the time of installation).

### Bare soil vs. underneath stones vs. underneath mulch fragments

Five years after wildfire, the observed SWR median under bare soil patches (Table 2) indicates moderately higher repellency, albeit not significantly different ($P = 0.779$; Table 3) from untreated areas (MED class 5), compared to mulched areas (MED class 4). At the same points, the corresponding SMC median tends to be lower, although not significantly different ($P = 0.069$), in untreated areas (4.7 versus 6.6 in mulched areas). Despite that, SOM was significantly lower ($P = 0.005$) in untreated areas compared to mulched areas (14.7 versus 37%).

Under stones, the SWR median records similar results ($P = 0.684$; Table 3) for both treated and untreated areas, indicating extremely repellent conditions with an ethanol class of 7. The corresponding SMC and SOM were very similar ($P = 0.829$ and $P = 0.543$, respectively) between untreated and mulched areas, with a SMC median registering 4.5% and 3.9%, and SOM median registering 18.6% and 13.7%, respectively. Despite all the similarities under stones between untreated and mulched areas, SWR was found to be significantly greater ($P < 0.001$) under stones compared to bare soil patches (within both mulched and untreated areas). The median MED class rises from 4 to 7 in the mulched areas and from 5 to 7 in the untreated areas. SMC under stones tends to be lower when compared to bare patches, but not significantly ($P = 0.503$ in untreated areas and $P = 0.091$

**Table 1.** Mean and standard deviation (sd) of the cover of the six cover classes (litter, vegetation, bare soil, stones, char and mulch remains; in %) percentages (%) and of the vegetation and litter biomass (in g m$^{-2}$) of the six mulched and six untreated sampling plots.

| | | **Cover (%)** | | | | **Biomass (g m$^{-2}$)** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | untreated | | mulched | | untreated | | mulched | |
| | | mean | sd | mean | sd | mean | sd | mean | sd |
| Soil surface | vegetation | 21 | 18 | 12 | 6 | 39 | 35 | 37 | 11 |
| | litter | 62 | 12 | 74 | 9 | 405 | 44 | 278 | 28 |
| | mulch | 0 | 0 | 0 | 0 | – | – | – | – |
| | char | 0 | 0 | 0 | 0 | – | – | – | – |
| | stones | 4 | 4 | 5 | 5 | – | – | – | – |
| | bare soil | 13 | 8 | 9 | 5 | – | – | – | – |
| After remove litter and vegetation | mulch | 0 | 0 | 6 | 2 | – | – | 36 | 7 |
| | char | 1 | 1 | 3 | 4 | 3.5 | 0.9 | 6.9 | 6 |
| | stones | 29 | 9 | 12 | 9 | – | – | – | – |
| | bare soil | 70 | 9 | 80 | 9 | – | – | – | – |

**Table 2.** Untreated and mulched medians and inter quartile range (iq) of soil water repellency (SWR) and soil moisture content (SMC), and soil organic matter (SOM) at the soil surface under stones, bare soil, and under mulch fragments.

| | | SWR | | | SMC | | | SOM | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | n | median | iq | n | median | iq | n | median | iq |
| untreated | bare soil | 24 | 5 | 5.8 | 24 | 4.7 | 5.4 | 24 | 15 | 12 |
| | stone | 24 | 7 | 2.0 | 24 | 4.5 | 11.3 | 24 | 19 | 30 |
| | mulch fragment | – | – | – | – | – | – | – | – | – |
| mulched | bare soil | 23 | 4 | 3.5 | 23 | 6.6 | 9.3 | 23 | 37 | 38 |
| | stone | 24 | 7 | 2.0 | 24 | 3.9 | 3.5 | 24 | 14 | 20 |
| | mulch fragment | 23 | 6 | 2.8 | 23 | 10.5 | 6.6 | 23 | 53 | 20 |

**Table 3.** Pair-wise (effect of treatment: untreated vs. mulched and effect of microsite within treatments: bare soil vs. stones vs. mulch fragment) Mann–Whitney U-test for soil water repellency (SWR), soil moisture content (SMC) and soil organic matter (SOM). Bold values correspond to significant measurements.

| Mann–Whitney U-test | | | SWR | | SMC | | SOM | |
|---|---|---|---|---|---|---|---|---|
| | | | p-value | n | p-value | n | p-value | n |
| untreated vs. mulched | | bare soil | 0.779 | 48 | 0.069 | 46 | **0.005** | 46 |
| | | stones | 0.684 | 48 | 0.829 | 48 | 0.543 | 48 |
| within treatments | untreated | bare soil vs. stones | **<0.001** | 48 | 0.503 | 48 | 0.439 | 48 |
| | mulched | bare soil vs. stones | **<0.001** | 48 | 0.091 | 47 | **0.025** | 47 |
| | | bare soil vs. mulch fragment | **0.006** | 48 | **0.018** | 46 | **0.028** | 46 |
| | | stones vs. mulch fragment | 0.059 | 48 | **<0.001** | 47 | **<0.001** | 47 |

**Table 4.** Spearman's rank correlation coefficients (rho), p-values (p), and number of measurements (n) of soil water repellency (SWR) with soil moisture content (SMC) and soil organic matter (SOM) and topsoil dry litter (litter) within treatments and coverage type. The significant values at α = o.05 are in bold.

| Spearman's rank correlation coefficients | | SWR vs. SMC | | | SWR vs. SOM | | | SWR vs. litter | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | rho | pvalue | n | rho | pvalue | n | rho | pvalue | n |
| untreated | bare soil | **0.71** | <0.001 | 24 | **0.66** | <0.001 | 24 | **0.66** | <0.001 | 24 |
| | stones | **0.82** | <0.001 | 24 | **0.72** | <0.001 | 24 | **0.58** | 0.003 | 24 |
| mulched | bare soil | **0.76** | <0.001 | 23 | **0.51** | 0.012 | 23 | -0.12 | 0.586 | 24 |
| | stones | **0.47** | 0.019 | 24 | 0.18 | 0.410 | 24 | 0.02 | 0.930 | 24 |
| | mulch fragment | 0.15 | 0.483 | 23 | 0.17 | 0.423 | 23 | -0.26 | 0.209 | 24 |

in mulched areas). Defiantly, SOM under stones compared with bare soil shows different tendencies between untreated and mulched areas. In mulched areas, the SOM under stones was found to be significantly lower (P = 0.025) then that under bare soil, decreasing from 37.1% to 13.7%, while in untreated areas, the SOM was similar (P = 0.439) under stones and bare soil patches.

In treated areas, beneath the remnants of mulch fragments, SWR indicates strong repellent conditions (MED class of 6), somewhat intermediate between the repellency observed under bare soil (MED class of 4) and stones (MED class of 7). These values were found to be significantly greater than those of bare soil patches (P = 0.006) but statistically similar to the values under stones (P = 0.059). Under mulch fragments, SMC was the highest recorded (10.5%) and significantly greater than that of bare soil (P = 0.018) or stones (P < 0.001). Likewise, SOM was the highest recorded at 53.1% and significantly greater than that of bare soil (P = 0.028) or stones (P < 0.001).

### SWR dynamics with SMC, SOM and topsoil litter

The relationships between MED class and SMC, SOM, and topsoil litter amounts under the different micro-site coverages (bare soil, stones and mulch fragments) are illustrated in Figure 1. In the untreated areas, the MED class measured under bare soil shows a positive correlation with SMC, SOM and litter amounts (rho = 0.71, 0.66 and 0.66 respectively; Table 4). Differently, in the treated areas, the MED class measured under bare soil exhibits a positive relationship with SMC and SOM (rho = 0.76 and 0.51 respectively) but was found to have no relationship with litter amounts (rho = –0.12).

Once again, in untreated areas, the MED class measured under stones (Figure 1a, d, g) also conserves positive relationship with SMC, SOM and litter amounts (rho = 0.82, 0.72 and 0.58, respectively). In treated areas, the MED class measured under stones exhibits a negligible positive relationship only with SMC (rho = 0.47). SOM and litter amounts were found to be

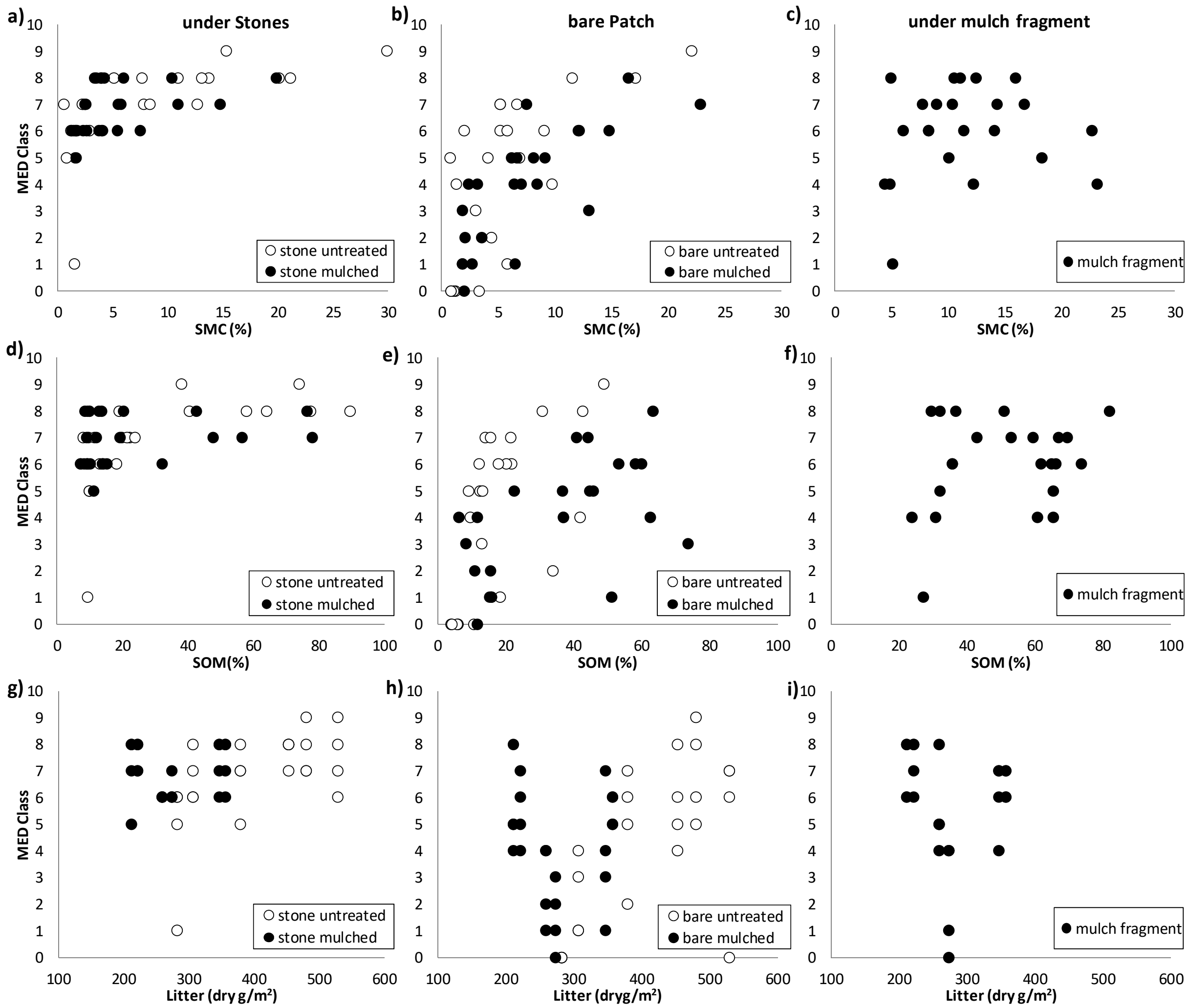


**Fig. 1.** Relationships of surface SWR median (MED class) in bare soil, underneath stones, and underneath mulch fragments with: i) gravimetric soil moisture content (SMC; a, b, c); ii) soil organic matter content (SOM; d, e, f); and iii) topsoil litter amounts (Litter; g, h, i).

unrelated to the MED class measured under stones (rho = 0.18 and 0.02 respectively).

Mulch fragments (Figure 1c; 1f and 1i), evidently only present in treated areas, were found to be the most distinct factor with the lowest relationships for all measured parameters (rho = 0.15 with SMC; 0.17 with SOM and –0.26 with litter).

## DISCUSSION

### SWR of bare soil

The SWR classes measured in this study for bare soil five years after fire (MED class 4 to 5) were slightly lower than those typically observed in previous studies in more recently burnt eucalypt plantations in north-central Portugal during dry summer conditions. For example, Keizer et al. (2008), Malvar et al. (2016a) and Martins et al. (2020) all reported very high to extreme topsoil SWR (MED class 8–9). This could indicate a decline in SWR during mid-term fire recovery, which could be explained by reduced fire impact, on the one hand, and, on the other, a temporary decrease in input of fresh litter from eucalypt trees. Such reduced fire impact was in line with the predominantly moderate soil burn severity suggested by Prats et al. (2016b). Such decline in SWR would probably be temporary, as long unburnt eucalypt plantations in the study region also typically reveal extreme SWR during dry conditions (e.g., Santos et al., 2013). Unfortunately, temporal patterns in post-fire SWR continue to be poorly known, except for relatively short periods.

The same is true for the underlying biogeochemical processes of the production, "activation" and decomposition of (potentially) hydrophobic organic compounds. Nevertheless, the study into soil organic matter quality by De la Rosa et al. (2019) which concerned the same study site and involved the same sampling period as the present study, suggested that the input of fresh organic matter could play an important role in the case of the most labile molecular SOM constituents. This included fatty acids, even if carbohydrates and n-alkyl compounds were the main constituents. Fatty acids and their salts are the compounds most closely associated with SWR (Doerr et al., 2000; Smettem et al., 2021). Therefore, the role of the quality of organic matter may be a key factor in explaining the observed decline in SWR in our study, as the reduction in fresh inputs of hydrophobic compounds, such as fatty acids, likely contributed to this decrease.

**SWR under stones**

In both untreated and treated areas, soils underneath stones were statistically more repellent than in bare soil areas. Similar results were found by Gordillo-Rivero et al. (2014) in a snapshot sampling seven days following a wildfire. According to their results, SWR was greater under rock fragments, and they reported a patchy distribution varying with fire severity. On one hand, soils under stones reach temperature peaks some minutes later than exposed bare soil, while on the other hand, temperatures reached were higher and lasted longer under stones (García-Moreno et al., 2013). In agricultural soils, stones were also found to increase soil temperatures when compared with a bare soil surface (Fairboum, 1973).

In our study, soil moisture differences between under stones and bare soil areas did not differ statically in both untreated and treated areas. This was unexpected in treated areas since soil organic matter was significantly greater in bare soil at these locations, and therefore should also affect moisture content. In addition, the majority of studies found stones to increase infiltration, reduce evaporation, promote organic matter richness, improve soil aggregation and stability, and decrease density (Cerdà, 2001; Fairboum, 1973; Martínez-Zavala and Jordán, 2008; Poesen and Lavee, 1994). Katra et al. (2008) reported that moisture content under rock fragments following rainfall events was higher than in bare soil areas. Whether this pattern also occurred in the present study is unknown, as sampling was done three weeks after the last rainfall event. Since our study was conducted during the drier season, potential differences in SWR may have been minimized due to the low soil moisture content in both treatments.

Soil organic matter differences were directly related to treatment effectiveness in reducing post-fire erosion (Prats et al., 2016b). Under stones, burned soils continued to be protected from post-fire erosion. Therefore, the mulch treatment had either no effect or a reduced effect on SOM contents under stones. The bare soil patches of mulched areas retained more ashes and charred material than the untreated areas, whereas untreated areas experienced greater losses of soil, particularly ashes and chars, which have relatively low density and are easily transported (Godoy et al., 2022; Malvar et al., 2016a; Prats et al., 2016b). However, the relationship between SOM quality and SWR under stones remains poorly established. We can hypothesise that stones may create localized microenvironments in the area attached to the soil and that may enhance repellency. However, the lack of difference in SMC and SOM indicates that other factors related to stone cover or soil surface characteristics might be influencing this effect. Therefore, we recommend further research to explore this aspect.

Our study registers an unexpected positive correlation between MED class and SMC. Typically, the literature reports the opposite in studies that comprise a temporal analysis of at least one year (Leighton-Boyce et al., 2007; Malvar et al. 2016a; Santos et al., 2013). However, the measurements in our study were conducted during a dry period of the year with low rainfall in the previous months. This could potentially reduce some soil moisture variances. The positive and direct relationship between SMC and SOM suggests that SOM may better explain SWR variances during dry periods, while SMC variations may be less significant during this period. Repeating such studies across a wide range of wet and dry periods is needed to clarify these gaps.

**SWR under forest residue mulch**

In relation to the effect of forest residue mulch, we found no difference in SWR severity between mulched and untreated areas five years after the wildfire and its application, while significant differences were observed in SMC and SOM, indicating a clear treatment effect. However, in the same plots of this study, SWR and SMC did not show differences between treated and untreated areas during the first year after the fire, as reported by Prats et al. (2016b). Additionally, in another area, the same authors found an increase of SMC after the application of forest residue mulching during the first year after the fire, but SWR was not measured (Prats et al., 2012). These studies were done immediately after treatment application when the area covered by mulching was rather high (80 to 90%) compared to our study (0 to 6%). This amount of mulching may have increased rainfall infiltration and storage capacity, thereby influencing the SMC and thus the SWR (Prats et al., 2012). Nevertheless, it is worth noting that the remaining mulch fragments in the treated plots, which had not yet decomposed, were found to be significantly more repellent than the bare soil areas. This may suggest a key role for the quality of organic matter, as the observed higher repellency of the mulch fragments could be attributed to the persistence of hydrophobic organic material. Compared to areas beneath stones, the SWR was similar, while SMC and SOM were higher. Mulch protects post-fire ash, which is expected to result in higher SOM levels compared to those beneath stones. This, in turn, can influence SMC, as organic matter plays a crucial role in water retention within soils. We may also hypothesize that the elevated SWR under mulch fragments may be driven by the higher SOM content, while under stones, as previously noted, the microenvironments adjacent to the soil may also enhance repellency. Future research should explore the mechanisms behind the increase of SWR under mulch fragments and access their long-term impacts, particularly given their low coverage observed five years after application.

**Temporal implications**

Overall, post-fire mulching did not increase the severity of SWR five years after its application, either on bare soil or under stones. However, these assumptions need careful evaluation. The reported increase in surface stones (12 % versus 29 %) is mainly explained by the occurrence of high rates of soil erosion in the untreated areas (Verheijen et al., 2024), which might have implications for the soil hydrology of the entire slope. However, during a dry period, it did not increase soil moisture in untreated areas, in fact, the opposite occurred. The mulched areas registered higher SMC overall, and this increase was attributed to the increase in SMC under the mulch fragments.

Litter amounts were statistically higher in the untreated areas and positively correlated with the SWR values. On one hand, the physical covering of the soil surface by mulching might reduce the growth of herbaceous cover (Dragumilo et al., 2015), while on the other hand, mulch might immobilize nitrogen in the topsoil, thereby reducing herbaceous, shrubs and possibly tree growth (Homyak et al., 2008). These suggestions should be further studied as our data is insufficient to validate these assumptions.

Admittedly, the snapshot nature of our study is limited to the dry season. It would be of great importance to clarify the seasonal dynamics of SWR versus SMC for these two cover types (stones and mulch fragments) throughout an entire hydrological year. Therefore, future studies targeting seasonal measurements of SWR differences under bare soil, stones and mulch are suggested.

Moreover, most slope hydrological studies focus solely on the hydraulic dynamics of bare soil and tend to overlook or exclude other elements such as stones and mulch fragments. Improving our understanding of these micro-cover elements could be essential to better explaining runoff generation in forested plantations, and thus, potentially leading to marked improvements in soil hydrological modelling (Lopes et al., 2021).

## CONCLUSIONS

The principal conclusions of this study concerning SWR under stones, forest residue mulch and bare soil following wildfire were as follows:

1) mid-term post-fire SWR was not significantly impacted by immediate-post-fire mulching with eucalypt logging residues, when compared with bare soil, possibly because mulch effects on SOM (increasing it) and SMC (increasing it) affect SWR in opposite ways, in spite of the relatively high mulch application rate and, associated input of fresh organic material, on the one hand, and, on the other, its elevated effectiveness in reducing sediment and organic matter losses;

2) stones contributed markedly to the spatial variability in mid-term post-fire SWR, with 40% higher MED values than in bare soil, but this variability was poorly related to differences SOM content, suggesting that follow-up research should address SOM quality too;

3) mulching did affect mid-term post-fire SWR in an indirect manner, since stone cover was twice as low in the mulched than control plots, which, in turn, was in line with the elevated effectiveness of mulching in reducing sediment losses.

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