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Temporal Impact of Mulch Treatments (*Pinus halepensis* Mill. and *Olea europaea* L.) on Soil Properties after Wildfire Disturbance in Mediterranean Croatia

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Abstract: On 28 July 2019, in the hinterland of Šibenik City, 900 ha were affected by wildfire of moderate to high severity. This study aims to evaluate the effects of two mulch treatments—needles of *Pinus halepensis* Mill. (PM) and leaves of *Olea europaea* L. (OM), as compared to an unmulched control (UM)—on soil quality. The study was conducted over 15 months, and soil samples were collected every 3 months. The studied soil properties were soil water repellence (SWR; composite, 1–2, 0.5–1, 0.5–0.25, <0.25 mm), soil hydraulic conductivity (SHC), mean weight diameter (MWD), water stability of aggregates (WSA), soil pH and electrical conductivity (EC), soil organic matter (SOM), total sulphur (TS), total carbon (TC), total nitrogen (TN), extractable phosphorus (P_2O_5), and available potassium (K_2O). Six principal component analyses (PCA) were applied to observe the temporal dynamics of the soil properties studied for each sampling date. Mulching increased the aggregate stability (MWD and WSA) and improved SHC. SWR was only indicated on the first sampling date. Soil pH and EC showed high variability due to natural soil processes and vegetation regrowth. PM showed higher efficiency in increasing the TS, TC, and SOM, while OM increased soil P_2O_5 and K_2O. Both mulch treatments increased the soil nutrient content, but the effect was variable due to the different chemical compositions of the material. Using native mulch is recommended because it improves soil quality.

Keywords: wildfire; post-fire management; nutrients; soil quality

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1. Introduction

Wildfire is a common phenomenon and part of the Mediterranean ecosystem. However, in recent decades, the number and intensity of wildfires over the entire Mediterranean area have increased due to long drought periods and higher temperatures [1]. Moreover, land abandonment, depopulation of rural areas, reduction in pastures, and flammable vegetation have contributed to the spate of increased wildfire frequency and magnitude [2,3]. In the Mediterranean environment, such cases often occur in the hinterland of large cities, especially in areas where landscape management and land use are not correctly implemented [2–5]. The climate, type of ecosystem, vegetation composition, soil type, topography, intensity and severity of the fire, effects of recurrent fires, and post-fire meteorological conditions are all factors that will determine the response of the environment to fire [6]. Forest ecology is particularly affected by disturbances caused by wildfires. Fires can affect ecosystem composition by selecting fire-adapted species and displacing others, affecting the nutrient levels and balances, altering and disturbing soil microorganisms, changing hydrologic processes, and affecting most soil properties. Given its often significant impacts on the environment, fire is widely recognized as a key factor affecting many ecosystem services. Wildfires are well known to change the soil's physical and chemical properties and increase soil degradation. The changes in soil usability associated with climate change in the Mediterranean region (higher temperatures and changing precipitation patterns) will increase the severity and frequency of wildfires [1,7] and, consequently, inhibit or slow down the soil regeneration process [8]. After this disturbance, the question often arises whether the soil needs to be rehabilitated, whether it is necessary to carry out remedial measures, or whether one should leave the environment to recover by itself [6]. Most rehabilitation practices include mulching or adding organic amendments to help soil nutrient recovery. Other practices include afforestation and seeding, salvage logging, erosion barriers, or soil preparation [6,9].

Mulching is a technique that belongs to emergency stabilisation techniques, as it immediately stabilises the soil of the burned area and reduces additional damage to the fragile bare soil [6]. The benefits of mulching have been described in the literature. However, most studies focus on post-fire erosion and overland runoff rather than the effect on temporal variation of physical and chemical soil properties [10,11]. The most-used materials for soil cover after a wildfire are straw mulch [12,13] and wood chips [14]. In addition to their positive impacts on improving soil quality, they also have some negative impacts, such as relatively rapid decomposition, the emergence of non-native plants in burned areas [15], and economic aspects [16]. Post-fire management is typically a trade-off between the cost and effectiveness of the applied treatment and the potential damage to valuable resources from unmitigated erosion. Additional costs and machinery are often required for application [6]. Using native or locally available material does not increase the likelihood of invasive weeds occurring and adds decomposed native material to the soil. Given all these facts, local, site-specific material should be preferred [16]. After a wildfire, there is a mosaic of low, moderate, and high soil burn severity conditions, but the cost of mulch material and the energy required to apply it must be considered. Preference should be given to local and available on-site material. It should also be considered that there will not be available plant material for covering the soil surface after a high-severity fire. Using native plant material on-site is only possible if the affected ecosystem can provide it. However, an intervention in fire-affected areas is a matter of discussion, since some areas can recover naturally; indeed, sometimes, an ecosystem should be left to recover by itself [6]. Adding organic matter and restoring the native vegetation is one of the most effective ways to control soil degradation in Mediterranean areas after wildfires [16,17]. However, there is a lack of research about mulching burned areas with available native organic material on site [16]. It is important to know the extent to which mulch made from available material affects soil properties and improves soil quality after wildfire disturbance. How much the ecosystem and soil have been degraded in terms of fire severity and whether it is necessary to implement stabilization and rehabilitation measures should be key questions in the post-fire management period.

The objective of our study was to investigate the effects of two native mulch treatments (*Pinus halepensis* Mill. and *Olea europaea* L.) on changes in soil properties following a moderate to severe wildfire that occurred in the Mediterranean environment in Croatia. Wildfires in this area frequently occur in summer, and the areas affected are increasing each year, as are the intensity and severity of the fires. There is an urgent need to study the effects of post-fire treatments on soil quality. It is hypothesised that both mulch materials will improve the soil quality compared to unmulched burned areas. To evaluate their effectiveness, some soil physical (water repellence (SWR), hydraulic conductivity (SHC), and aggregate stability (MWD and WSA)) and chemical (pH, electrical conductivity (EC), organic matter (SOM), total sulphur (TS), total carbon (TC), total nitrogen (TN), extractable K-K_2O-, and available P-P_2O_5) properties were studied during the 15-month study.

2. Materials and Methods

2.1. Study Site

The study was carried out in the Dalmatia region on the Adriatic coast (Croatia) in the hinterland of Šibenik City (5 km from the Coast; 43°45′06.0″ N 15°56′02.9″ E; Figure 1). The elevation ranges between 50 and 200 m a.s.l. and the aspect is NE. According to the Köppen classification, the study area's climate is Mediterranean Csa (warm temperatures with dry and warm summers). The mean annual temperature is 15.8 °C, and the annual precipitation is 800 mm (Šibenik meteorological station) [18]. The soil type is classified as Cambisol [19] (IUSS-WRB, 2015) with limestone parent material, and has a silty clay loam texture with 6.2%, 58.6%, and 35.2% sand, silt, and clay, respectively. The vegetation consists mainly of *Pinus halepensis* Mil., *Pistacia lentiscus* L., and *Juniperus oxycedrus* L. The study area is located on abandoned calcareous pastures associated with *Stipa eriocauli–Caricetum humilis*, cultivated olive groves (*Olea europaea* L.), and fig trees (*Ficus carica* L.). The pastures with dry stone structures were abandoned 60 years ago, and this type of management was an economic resource of the area in history. However, only Mediterranean plants (olives and figs) are cultivated today.

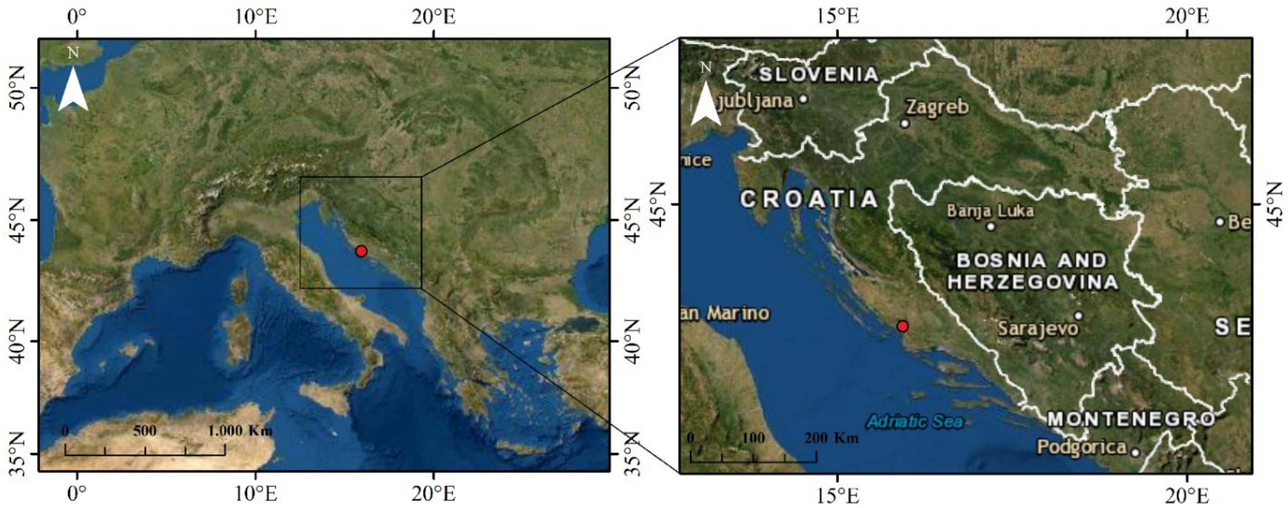

Figure 1. The study area (red dot shows the location of the experiment).

2.2. Experimental Design and Field Sampling

In the study area, a wildfire occurred on 28 July 2019 and affected an area of about 900 ha [5,20]; it lasted three days until local firefighters stopped the fire (Figure 2a,b). The first intervention to the burned area was 25 days after the wildfire occurrence due to safety reasons and recommendations from local firefighters. The severity of the wildfire was moderate to high, evident in partially burned canopy places (Figure 2c). The area provided natural organic materials for usage and implementation. For covering a burned soil surface, two different mulch treatments were applied (*Pinus halepensis* needles (PM) (Figure 2d) and *Olea europaea* leaves (OM) (Figure 2e). These mulches were used due to on-site availability and the value of native plants to the soil [16]. The mulches were applied in 0.5 kg m^2 on a 10 m^2 soil surface (each treatment). The effect of wildfire without any human intervention (unmulched, UM) was monitored next to mulch treatments to assess the impact of both mulches (Figure 2f). On the same plots, erosion equipment was set up to measure runoff and sediment yield (Figure 2d–f). During the monitoring time, erosion (sediment yield) was not observed, only runoff after major rainfall events, which was attributed to natural soil conditions and relatively low slopes. The sampling campaign was conducted 6 times: 25 days after fire (DAF), 3 months after fire (MAF), 6 MAF, 9 MAF, 12 MAF, and 15 MAF. During this period, rainfall amount and air temperature were measured by the Croatian Meteorological and Hydrological Service at the meteorological station Šibenik, which is 5 km away from the experiment (Figure 3). The difference in the amount of rainfall between sampling data was calculated from daily data. Soil samples (0–3 cm) were collected in each treatment in 5 repetitions after litter removal (90 in total). Repetitions of each treatment represented the same soil conditions under two mulched and unmulched soil surfaces.

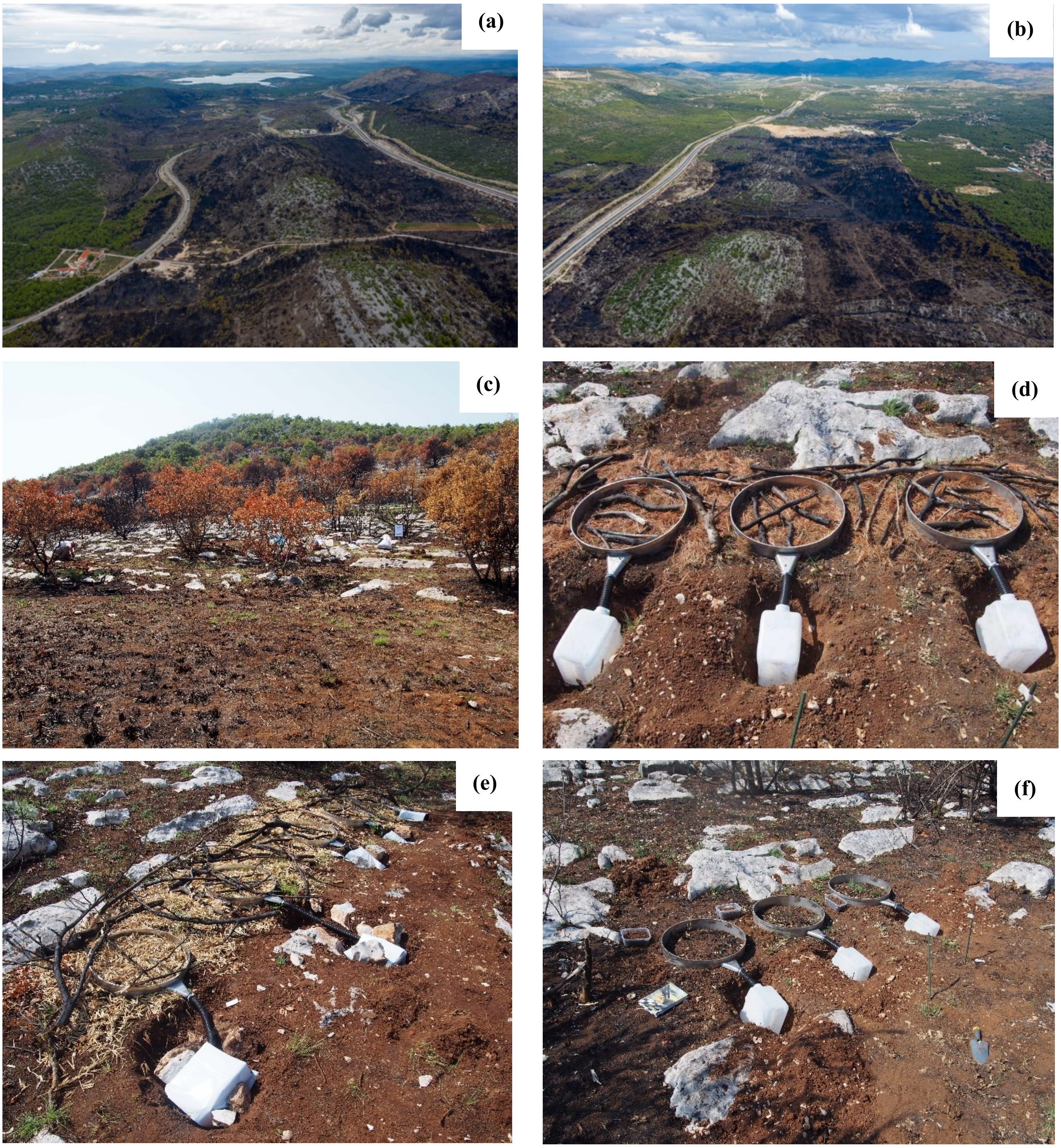

Figure 2. Aerial photographs of the wildfire-affected area (**a**,**b**); party burned vegetation canopy of the study site (25 days after fire) (**c**); *Pinus halepensis* mulch treatment (PM) (**d**); *Olea europaea* mulch treatment (OM) (**e**); unmulched burned soil (UM) (**f**).

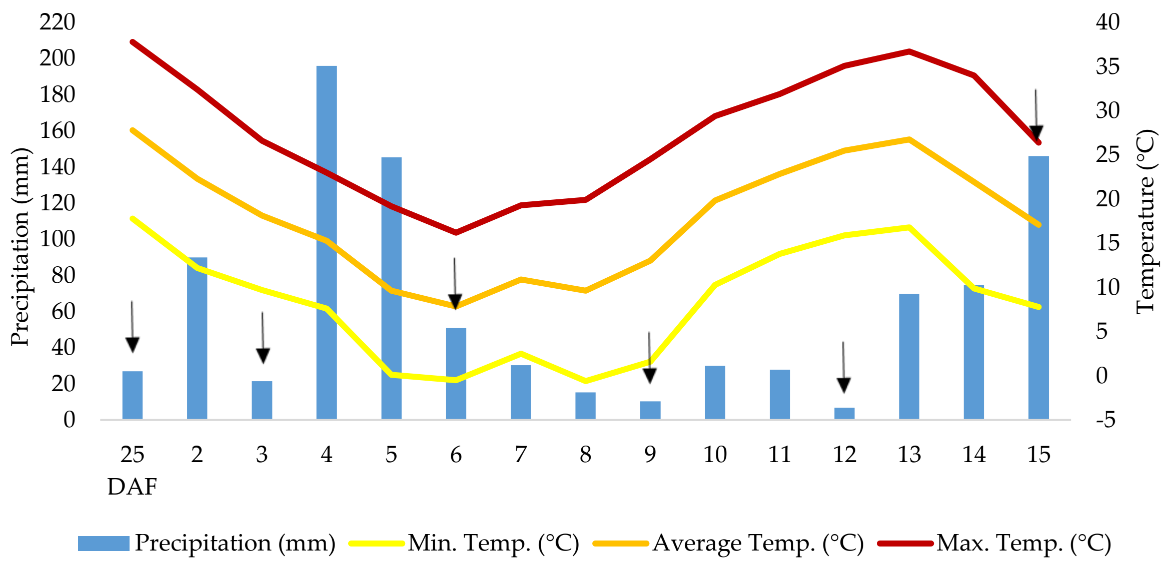

Figure 3. Monthly precipitation and air temperatures throughout the study period. Arrows point to the days and months when the sampling campaigns were performed. Numbers indicate days after fire (DAF) and months after fire (MAF).

2.3. Soil Physical Analysis

After each sampling campaign, the soil was stored in a plastic bag and transported to the laboratory, where it was air-dried for 48 h at room temperature (±22 °C in the range of 20 to 24 °C) [20]. Soil water repellence was measured on composite and individual fractions (<0.25, 0.25–0.5, 0.5–1, 1–2 mm) using the water drop penetration time method (WDPT) according to Doerr et al. [21]. Mean weight diameter (MWD) was used to express soil aggregation. The soil aggregate fractions (<0.25, 0.25–0.5, 0.5–1, 1–2, 2–4, 4–5, and 5–8 mm) were determined by dry sieving for 30 s and calculated after weighing the aggregate soil fraction size. Water stable aggregates (WSA) were determined by soaking 4 g of aggregates (1–2 mm fraction) in distilled water for 3 min, after which dispersing solution (2 g L^{-1} sodium hexametaphosphate) was applied [20]. The Mini-Disk Infiltrometer (MDI) was used for measuring soil hydraulic conductivity (SHC), as commonly done for field measurements due to its small size and easy handling (Decagon Devices, Inc., Pullman WA, USA). Measurements by MDI were done according to the procedures suggested in its technical manual and by Robichaud [22], in which more details can be found. To summarise, the mulch material was moved, and an MDI was placed on the flat soil surface.

2.4. Soil Chemical Analysis

Before chemical analyses, soil samples were air-dried and sieved through a 2 mm diameter sieve. The electrometric method observed soil pH in a 1:2.5 (*w*/*v*) soil:solution ratio using a Beckman pH meter Φ72, in KCl suspension. Electrical Conductivity (EC) was calculated at 25 °C with a soil water ratio 1:5. The soil organic matter (SOM) content was calculated using the digestion method [23]. A Vario MACRO CHNS analyser was used to determine the content (%) of total sulphur (TS), total nitrogen (TN), and total carbon (TC) by dry combustion method [24]. P_2O_5 and K_2O concentrations were extracted with ammonium lactate (AL) solution and detected by spectrophotometry and flame photometry [4].

2.5. Statistical Analysis

Data normality and homogeneity of variances were assessed using the Shapiro–Wilk and Levene tests ($p > 0.05$). Data normality and homogeneity of variances were only observed for SOM, TC, TN, and TS. All other variables did not follow the Gaussian distribution and homogeneity of variances even after logarithm, square root, and Box-Cox transformations. A parametric two-way ANOVA was applied to the SOM, TC, TN, and TS data to identify differences between sampling time and treatments. For all other variables, a non-parametric Friedman ANOVA was applied to observe differences between sample time, and a non-parametric Kruskal–Wallis ANOVA (K–W) to observe differences between treatments. If significant differences were observed at $p < 0.05$, a Turkey HSD post hoc (for SOM, TC, TN, and TS) and multiple comparisons rank tests were applied [20]. Six principal component analysis (PCA) were applied to identify the relationship among all soil properties for each sampling date. Logarithmically transformed data were used for the PCA since it was the closest to normality [4,25]. All analyses were performed using Statistica 12.0 (StatSoft Inc., Tusla, OK, USA) for Windows and CANOCO 5 (Microcomputer Power, Ithaca, NY, USA) software.

3. Results

3.1. Meteorological Observations

Total rainfall over the study period was 942 mm over 15 months. Between wildfire occurrence and setting up the experiment (25 DAF), 27 mm rainfall was observed. On the second (3 MAF) soil sampling, 111 mm rainfall was observed. The highest amount of rainfall (392 mm) was noted 6 MAF. Between 6 and 9 MAF, it rained 55 mm, while between 9 and 12 MAF, 68 mm, respectively. Finally, on the last sampling date (15 MAF), 291 mm was noted. The highest average temperature was observed at the experimental set up (25 DAF), 27.8 °C, while the lowest was 7.8 °C at 6 MAF (Figure 3).

3.2. Soil Physical Properties

Table 1 shows the SWR measured in the composition and different soil fractions. In the composite soil fraction, the SWR was significantly higher in PM 25 DAF than in later months (9, 12, and 15 MAF). In the 0.25–0.5 and <0.25 mm soil fractions, significantly higher SWR was observed 25 DAF than in the rest of the sampling dates. Between treatments, significant differences were only observed in the <0.25 mm fraction at 25 DAF; at 12 and 15 MAF, we identified higher values in PM than in UM.

Table 1. Soil water repellence (SWR) was measured with water drop penetration time (s) on different soil fractions in the pine mulch (PM), olive mulch (OM), and unmulched (UM) treatments during the studied period (T, treatments; DAF, days after fire; MAF, months after fire) (mean ± standard deviation). Different letters indicate significant differences between sampling dates (capital letters), and treatment (lowercase letters). Kruskal–Wallis (K-W) (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and n.s. non-significant at $p < 0.05$) are shown for each comparison between treatments, and Friedman ANOVA (F) between sampling dates.

Soil Fraction	T	Sampling Date						F
		25 DAF	3 MAF	6 MAF	9 MAF	12 MAF	15 MAF	*p*
Composite	PM	3 ± 1.1Aa	1.8 ± 0.75ABb	1.8 ± 0.75ABb	1.4 ± 0.49Bb	1 ± 0.63Bb	1.3 ± 0.4Bb	***
	OM	1.8 ± 0.75	2.1 ± 0.63	1.6 ± 0.8	1.8 ± 0.75	1.4 ± 0.49	1.4 ± 0.49	n.s.
	UM	2.4 ± 1.02	1.8 ± 0.75	1.8 ± 0.75	1.8 ± 0.75	1.8 ± 0.75	1.4 ± 0.49	n.s.
	K-W *p*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
1–2 mm	PM	1.4 ± 049	2.1 ± 0.63	1.8 ± 0.75	1.1 ± 0.7	1.4 ± 0.49	1.4 ± 0.49	n.s.
	OM	1.8 ± 0.4	1.2 ± 0.4	1.8 ± 0.4	1.4 ± 0.8	1.6 ± 0.49	1.6 ± 0.49	n.s.
	UM	1.4 ± 0.49	1.6 ± 0.49	1.8 ± 0.75	1.4 ± 0.49	2.2 ± 0.75	1.2 ± 0.4	n.s.
	K-W *p*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
0.5–1 mm	PM	6.23 ± 1.64Aa	1.33 ± 0.63Bb	1.8 ± 0.75Bb	1.4 ± 0.49Bb	1.4 ± 0.49Bb	1.4 ± 0.49Bb	*
	OM	4.33 ± 1.26Aa	1.33 ± 0.63Bb	1.8 ± 0.4ABab	1.6 ± 0.49ABab	1.6 ± 0.49ABab	1.6 ± 0.49ABab	*
	UM	3.39 ± 1.07A	1.8 ± 0.75AB	1.8 ± 0.75AB	1.5 ± 0.45B	2.2 ± 0.75AB	1.86 ± 0.74AB	n.s.
	K-W *p*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
0.25–0.5 mm	PM	25.82 ± 13.89Aa	4.4 ± 1.85Bb	1.8 ± 0.62Bb	2.4 ± 0.25Bb	1.65 ± 0.25Bb	2.4 ± 0.25Bb	***
	OM	23.34 ± 0.43Aa	4.47 ± 1.04Bb	1.73 ± 0.33Bb	1.73 ± 0.33Bb	1.92 ± 1.51Bb	2.93 ± 1.51Bb	***
	UM	21.56 ± 2.14Aa	3.65 ± 1.32Bb	1.73 ± 0.44Bb	1.01 ± 0.31Bb	1.73 ± 0.44Bb	1.07 ± 0.13Bb	***
	K-W *p*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
<0.25 mm	PM	38.75 ± 18.83Aa	6.15 ± 1.83Bb	1.95 ± 0.76Bb	2.07 ± 1.04Bb	2.67 ± 0.76Bb	2.87 ± 0.69Bb	***
	OM	23.25 ± 2.27Aa	3.39 ± 1.41Bb	2.19 ± 0.43Bb	2.2 ± 0.4Bb	2.07 ± 0.83Bb	2.67 ± 0.92Bb	***
	UM	28.8 ± 4.96Aa	3.05 ± 0.77Bb	1.93 ± 0.61Bb	2.2 ± 0.75Bb	1.73 ± 0.33Bb	1.4 ± 0.49Bb	***
	K-W *p*	**	n.s.	n.s.	n.s.	*	*	

SHC was significantly higher 12 and 15 MAF than 3 MAF in both mulch treatments. There was significantly higher SHC in UM at 6 MAF than at 25 DAF, 9, and 15 MAF. By comparing treatments, significantly higher SHC was noted in UM than in mulch treatments 6 MAF. The opposite results were observed 12 and 15 MAF, when significantly higher SHC was observed in both mulch treatments than in UM (Table 2).

Table 2. Soil hydraulic conductivity (SHC) in the soil in the pine mulch (PM), olive mulch (OM), and unmulched (UM) treatments during the studied period (T, treatments; DAF, days after fire; MAF, months after fire) (mean ± standard deviation). Different letters indicate significant differences between sampling dates (capital letters), and treatment (lowercase letters). Kruskal–Wallis (K-W) (* $p < 0.05$, ** $p < 0.01$, and n.s. non-significant at $p < 0.05$) are shown for each comparison between treatments, and Friedman ANOVA (F) between sampling dates.

Variable	T	Sampling Date						F
		25 DAF	3 MAF	6 MAF	9 MAF	12 MAF	15 MAF	p
SHC (mm h^{-1})	PM	3.53×10^{-4}AB	2.81×10^{-4}Bb	5.84×10^{-4}AB	5.51×10^{-4}ABb	7.31×10^{-4}Aa	7.54×10^{-4}Aab	**
	OM	3.93×10^{-4}AB	3.06×10^{-4}Bab	6.49×10^{-4}AB	5.32×10^{-4}ABb	7.96×10^{-4}Aa	8.87×10^{-4}Aa	*
	UM	4.03×10^{-4}B	5.23×10^{-4}ABa	4.48×10^{-4}B	9.93×10^{-5}Aa	5.37×10^{-4}ABb	4.46×10^{-5}Bb	**
	K-W p	n.s.	*	n.s.	*	*	*	

Significantly higher MWD within PM and OM was observed 6, 9, and 15 MAF than 25 DAF. In the UB, significantly higher MWD was observed 3 and 9 MAF than 12 and 15 MAF. Both mulch treatments had significantly higher MWD than UB 6 and 12 MAF, while PM had significantly higher MWD 15 MAF than UB. Significantly higher WSA within PM and OM was observed 6, 9, 12, and 15 MAF than 25 DAF. In the UB, significantly higher WSA was measured 6 MAF compared to 25 DAF and 9, 12, and 15 MAF (Table 3).

Table 3. Mean weight diameter (MWD) and water stable aggregates (WSA) of the soil in the pine mulch (PM), olive mulch (OM), and unmulched (UM) treatments during the studied period (T, treatments; DAF, days after fire; MAF, months after fire) (mean ± standard deviation). Different letters indicate significant differences between sampling dates (capital letters) and treatment (lowercase letters). Kruskal–Wallis (K-W) (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and n.s. non-significant at $p < 0.05$) are shown for each comparison between treatments, and Friedman ANOVA (F) between sampling dates.

Variable	T	Sampling Date						F
		25 DAF	3 MAF	6 MAF	9 MAF	12 MAF	15 MAF	p
MWD (mm)	PM	1.92 ± 0.24Ca	2.32 ± 0.12ABCa	2.83 ± 0.5Aa	2.66 ± 0.35Aa	2.57 ± 0.19ABCa	2.78 ± 0.21Aa	***
	OM	1.96 ± 0.19Ba	2.28 ± 0.31ABa	2.83 ± 0.25Aa	2.69 ± 0.34Aa	2.44 ± 0.45ABa	2.67 ± 0.13Aab	***
	UM	2.25 ± 0.07ABa	2.32 ± 0.29Aa	2.05 ± 0.1ABb	2.46 ± 0.18Aa	1.71 ± 0.09BCb	1.38 ± 0.55Cb	***
	K-W p	n.s.	n.s.	*	n.s.	*	**	
WSA (%)	PM	50.02 ± 0.18Ca	52.21 ± 0.79Ba	53.93 ± 0.82Aa	55.46 ± 7.28Aa	54.4 ± 1.48Aab	55.47 ± 0.63Aa	***
	OM	49.59 ± 0.3Bb	52.79 ± 1.86ABa	56.55 ± 4.48Aa	56.94 ± 2Aa	55.13 ± 1.9Aa	55.1 ± 1.57Aa	***
	UM	49.93 ± 0.1Cab	52.61 ± 3.21ABa	55.86 ± 1.78Aa	50.76 ± 0.77Cb	48.9 ± 3BCb	50.91 ± 0.76BCb	***
	K-W p	*	n.s.	n.s.	*	*	**	

3.3. Soil Chemical Properties

Table 4 shows the soil chemical properties. No significant differences were observed in UB for pH between sampling dates. Significantly higher pH in PM was identified 3 MAF than 6, 9, 12, and 15 MAF, while, in OM, significantly higher pH was observed 15 MAF than at 25 DAF and 6, 9, and 12 MAF. EC was significantly higher within all treatments 25 DAF and 3 MAF compared to the rest of the sampling dates. Comparing EC between treatments, 6 MAF OM had significantly higher values than UB, while PM had significantly higher EC 12 and 15 MAF than UB. In UB, significantly higher SOM was observed 25 DAF compared to the rest of the sampling dates, while, in PM, significantly higher SOM was observed 25 DAF than 3 and 6 MAF. No significant differences were observed within OM between sampling dates. By comparing SOM between treatments, significantly higher SOM was seen for UM 25 DAF than OM. Significantly higher SOM was seen 12 MAF in

OM compared to UM, while, 15 MAF, both mulch treatments had significantly higher SOM than UM. Within UB, significantly higher TS was observed 25 DAF than 3, 6, and 9 MAF. Regarding the mulch treatment, significantly higher TS was 25 DAF than 3 and 6 MAF in OM, while in PM, significantly higher TS was seen 25 DAF compared to the rest of the sampling dates. For TC, a significantly higher value in PM was observed 15 MAF than 3 and 6 MAF. In OM, a significantly higher value was observed 25 DAF and 12 and 15 MAF compared to 6 MAF. Within UB, a significantly higher TC was observed 25 DAF than 6 and 9 MAF. Comparing treatments, significantly higher TC was seen in PM compared to UM at 9 MAF. At 15 MAF, a significantly higher TC was seen in both mulch treatments than in UM. No significant differences were observed regarding TN within treatments and between sampling dates. A significantly higher P_2O_5 in PM was observed 3 MAF compared to 25 DAF and 6–15 MAF. Within OM, a significantly higher P_2O_5 was observed 3 MAF than at 25 DAF and 6 MAF. No significant differences were observed between sampling dates within UB for P_2O_5. Significantly higher K_2O in PM was observed 3 MAF compared to 6–12 MAF, while a significantly higher K_2O in OM was observed 3 MAF compared to the rest of the sampling dates. By comparing treatments, a significantly higher K_2O was 3, 9, and 15 MAF in OM than in UB. Between PM and UB, no significant differences were observed for K_2O.

Table 4. Soil pH, electrical conductivity (EC), soil organic matter (SOM), total sulphur (TS), total nitrogen (TN), total carbon (TC), and concentrations of P_2O_5 and K_2O in the pine mulch (PM), olive mulch (OM), and unmulched (UM) treatments (T) during the studied period (T, treatments; DAF, days after fire; MAF, months after fire) (mean ± standard deviation). Different letters indicate significant differences between sampling dates (capital letters) and treatment (lowercase letters). [1] Two-way ANOVAs are shown for each treatment–sampling date comparison. [2] Kruskal–Wallis (K-W) tests (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and n.s. non-significant at $p < 0.05$) are shown for each comparison between treatments, and [3] Friedman ANOVA between sampling dates.

Variable	T	Sampling Date						*p*
		25 DAF	3 MAF	6 MAF	9 MAF	12 MAF	15 MAF	
pH	PM	6.57 ± 0.2B	6.95 ± 0.1A	6.15 ± 0.19C	6.34 ± 0.21BC	6.43 ± 0.1BC	6.93 ± 0.14A	[3] ***
	OM	6.71 ± 0.11BC	6.93 ± 0.05AB	6.6 ± 0.1C	6.49 ± 0.1C	6.7 ± 0.21BC	6.97 ± 0.08A	[3] ***
	UM	6.8 ± 0.37ABb	6.8 ± 0.16ABb	6.35 ± 0.35B	6.33 ± 0.35B	6.66 ± 0.14AB	7.00 ± 0.3A	[3] *
	K-W *p*	[2] n.s.	[2] n.s.	[2] n.s.	[2] n.s.	[2] n.s.	[2] n.s.	
EC (μS cm^{-1})	PM	203 ± 24Aa	198 ± 18Aa	144 ± 27Bab	114 ± 14BCa	85 ± 2.7Ca	188 ± 6.43Aa	[3] ***
	OM	200 ± 16Aa	191 ± 12Aa	153 ± 14Ba	123 ± 15Ca	73 ± 6Dab	154 ± 20.6Ba	[3] ***
	UM	258 ± 64Aa	194 ± 27Aa	112 ± 11Bb	107 ± 52Ba	63 ± 2.6Cb	130 ± 44.4Bb	[3] ***
	K-W *p*	[2] n.s.	[2] n.s.	[2] *	[2] n.s.	[2] **	[2] **	
SOM (%)	PM	8.34 ± 1.13Aab	6.32 ± 1.26Ba	6.28 ± 0.23Ba	6.60 ± 0.48ABa	6.85 ± 0.64ABab	6.96 ± 0.38ABa	[1] ***
	OM	7.27 ± 1.3Ab	6.46 ± 0.95ABa	6.24 ± 0.54Ba	6.67 ± 0.16ABa	7.06 ± 0.7Aa	6.85 ± 0.41ABa	[1] *
	UM	9.10 ± 1.42Aa	6.19 ± 0.43Ba	4.59 ± 0.77Ba	5.39 ± 0.61Ba	5.56 ± 0.51Bb	4.68 ± 0.45Bb	[1] *
	p			[1] ***				
TS (%)	PM	0.11 ± 0.01Aa	0.08 ± 0.01Ba	0.06 ± 0.01Ca	0.09 ± 0.01Ba	0.11 ± 0.02Aa	0.11 ± 0.02Aa	[1] **
	OM	0.11 ± 0.01Aa	0.08 ± 0.01Ba	0.04 ± 0.01Ca	0.09 ± 0.01ABa	0.09 ± 0.01ABa	0.09 ± 0.01ABa	[1] **
	UM	0.11 ± 0.01Aa	0.07 ± 0.01Ba	0.05 ± 0.01Ca	0.09 ± 0.01Ba	0.09 ± 0.01Bb	0.09 ± 0.01Ba	[1] **
	K-W *p*			[1] ***				
TC (%)	PM	5.92 ± 0.62ABCa	5.19 ± 0.97BCa	4.54 ± 0.17Ca	5.68 ± 0.84ABCa	6.64 ± 0.61ABa	6.72 ± 0.13Aa	[1] **
	OM	5.16 ± 0.6Aa	5.02 ± 0.93ABa	3.65 ± 0.25Ba	5.05 ± 0.75ABab	5.74 ± 0.47Aa	6.14 ± 0.28Aab	[1] **
	UM	5.82 ± 0.97Aa	4.80 ± 0.19ABCa	3.42 ± 0.21Ca	4.11 ± 0.64BCb	5.31 ± 0.35ABa	4.51 ± 0.35ABCb	[1] ***
				[1] ***				
TN (%)	PM	0.5 ± 0.06	0.47 ± 0.11	0.42 ± 0.04	0.47 ± 0.07	0.55 ± 0.06	0.55 ± 0.06	[1] n.s.
	OM	0.45 ± 0.04	0.42 ± 0.06	0.41 ± 0.02	0.45 ± 0.08	0.47 ± 0.03	0.47 ± 0.03	[1] n.s.
	UM	0.47 ± 0.08	0.4 ± 0.01	0.44 ± 0.04	0.39 ± 0.09	0.45 ± 0.02	0.45 ± 0.02	[1] n.s.
				[1] n.s.				
P_2O_5 (mg/kg)	PM	2.33 ± 0.49BCa	6.64 ± 0.84Aa	0.89 ± 0.74Ca	1.12 ± 0.89Ca	2.29 ± 0.94Bb	3.74 ± 0.32Bab	[3] ***
	OM	2.52 ± 1.64Ba	7.79 ± 1.32Aa	1.49 ± 1.29Ba	3.84 ± 5.11Aba	3.69 ± 0.72ABa	4.31 ± 0.33Aba	[3] ***
	UM	422 ± 2.37Aa	6.83 ± 2.22Aa	2.03 ± 1.05Aa	3.89 ± 4.26Aa	3.03 ± 0.38Aab	2.96 ± 0.56Ab	[3] n.s.
	K-W *p*	[2] n.s.	[2] n.s.	[2] n.s.	[2] n.s.	[2] *	[2] **	
K_2O (mg/kg)	PM	44.94 ± 4.3ABa	51.1 ± 11.66Ab	28.85 ± 3.11Ca	29.69 ± 2.83Cab	36.17 ± 3.36BCa	41.4 ± 2.27ABab	[3] ***
	OM	44.2 ± 9.49BCa	90.71 ± 8.89Aa	30.78 ± 8.22Ca	41.05 ± 7.64BCa	45.88 ± 6.65BCa	49.02 ± 5.64Ba	[3] ***
	UM	45.85 ± 9.62ABa	47.36 ± 4.94Ab	30.7 ± 4.06Ca	27.92 ± 3.51Cb	38.31 ± 3.8ABCa	24.62 ± 5.52BCb	[3] ***
	K-W *p*	[2] n.s.	[2] **	[2] n.s.	[2] *	[2] n.s.	[2] *	

4. Multivariate Analysis

The six PCAs were carried out for the determination of each sampling date.

In the PCA calculated 25 DAF, Factor 1 explained 37.4% of the variance, while Factor 2 explained 20.4%. At 25 DAF, three groups were identified: (i) SWR (composite, <0.25, 0.5–1, 1–2), WSA, K_2O; (ii) SHC, SWR (0.25–0.5); and (iii) MWD, TS, TN, TC, pH, SOM, EC, P_2O_5 (Figure 4a).

In the PCA computed for 3 MAF, Factor 1 explained 33.4% of the variance, while Factor 2 explained 22.2% of the variance. At 3 MAF, we identified three groups as well: (i) SWR (0.5–1), SHC; (ii) SWR (composite, 0.25–0.5), K_2O, P_2O; and (iii) EC, TC, TN, SOM, TS, pH, WSA, SWR (<0.25, 1–2) (Figure 4b).

For the PCA calculated for 6 MAF, Factor 1 explained 41.7% and Factor 2 19.7% of the variance. At 6 MAF, we identified three groups: (i) SWR (<0.25, 1–2), pH, TN, P_2O_5, K_2O; (ii) EC, WSA, MWD, SOM, TS, SHC, TC; and (iii) SWR (composite, 0.25–0.5, 0.5–1) (Figure 4c).

In the PCA computed for 9 MAF, Factor 1 explained 57.8%, while Factor 2 13.5% of the variance. At 9 MAF, we identified two groups: (i) SOM, WSA, MWD, TC, TS, TN, SHC, SWR (composite), K_2O, EC, pH; and (ii) SWR (<0.25, 0.25–0.5, 0.5–1, 1–2) (Figure 4d).

In the PCA determined for 12 MAF, Factor 1 explained 38.5% of the variance, while Factor 2 explained 28.1%. At 12 MAF, we identified three groups: (i) TS, TN, TC, EC, MWD, SOM, SWR (<0.25), WSA, SHC; (ii) K_2O, SWR (0.25–0.5), pH, P_2O_5; and (iii) SWR (composite, 0.5–1, 1–2) (Figure 4e).

Finally, in the PCA computed for 15 MAF, Factor 1 explained 45.9% of the variance, while Factor 2 explained 23.7%. At 15 MAF, we identified three groups: (i) SWR (composite, 0.25–0.5, 0.5–1); (ii) pH, SWR (1–2); and (iii) TN, TS, EC, TC, SOM, MWD, SWR (<0.25), P_2O_5, K_2O, SHC, WSA (Figure 4f).

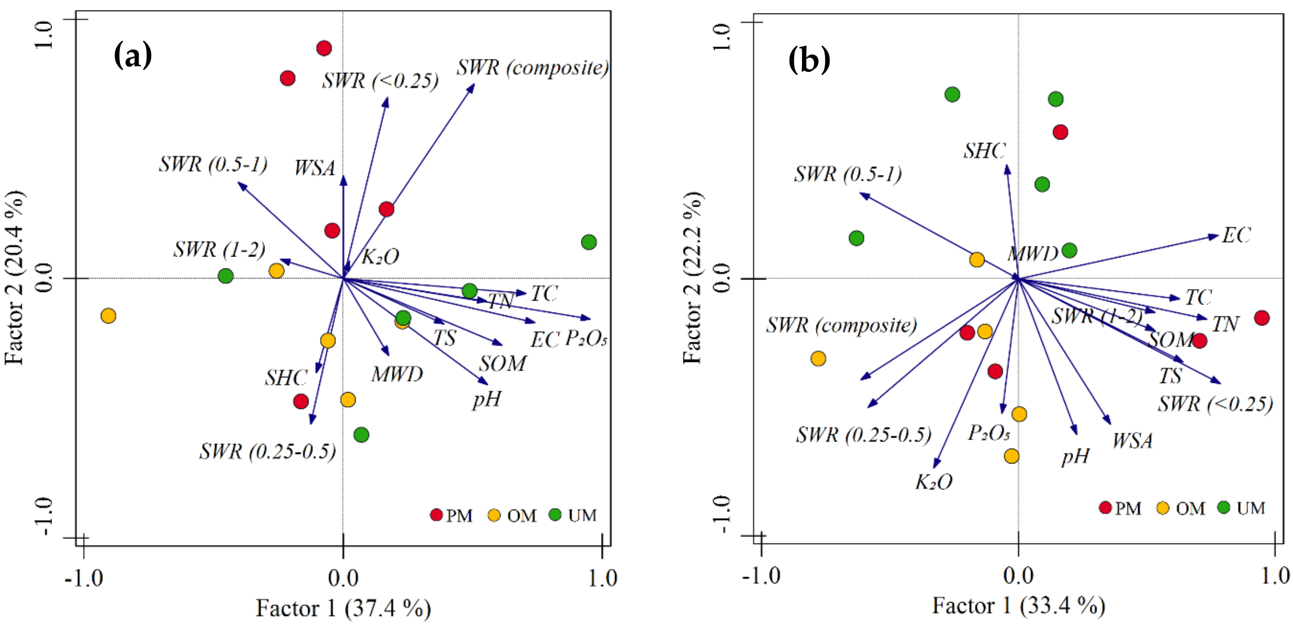

Figure 4. *Cont.*

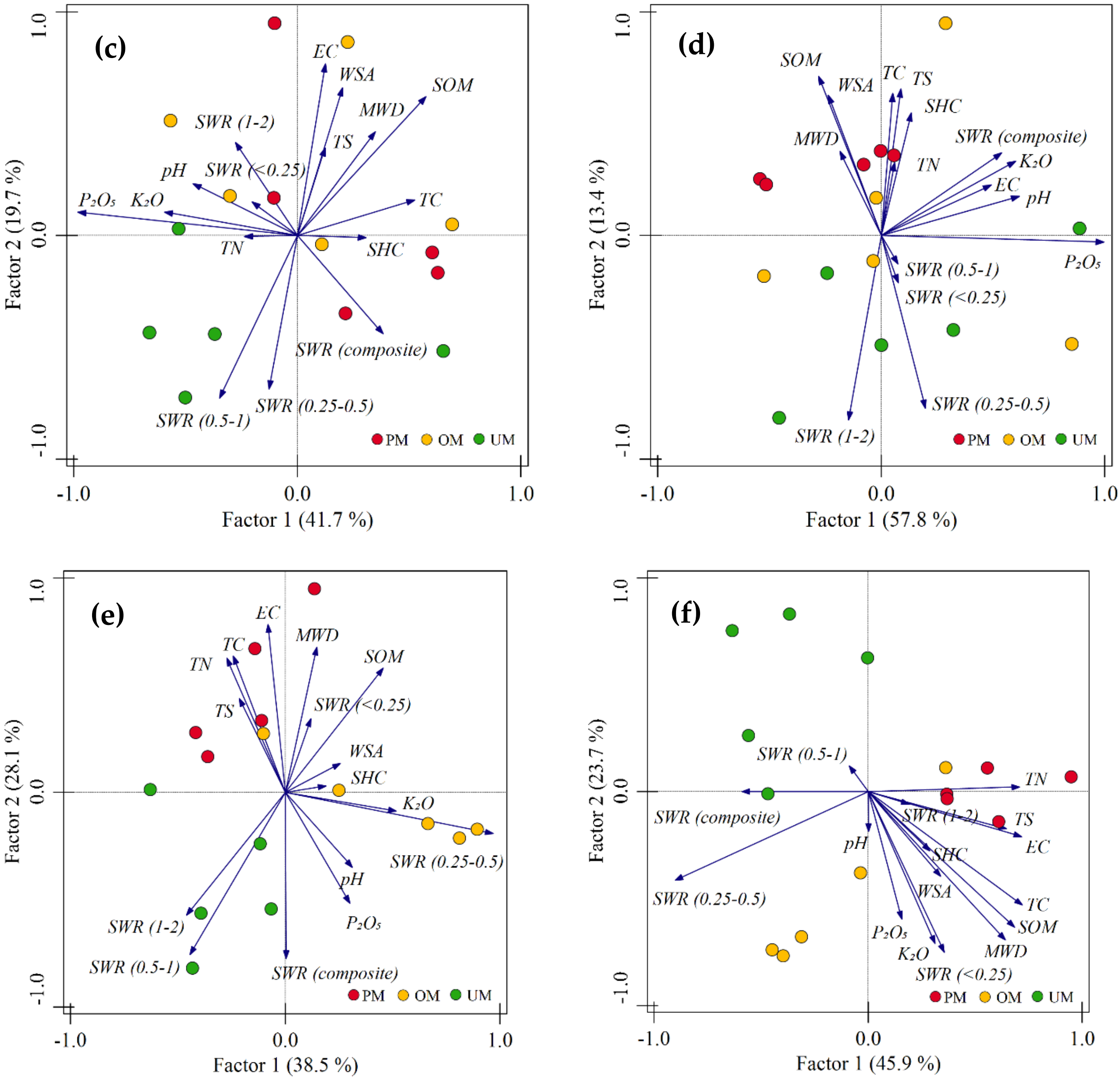

Figure 4. Principal component analysis for the relation between Factors 1 and 2 for six sampling dates. Soil water repellence (SWR; fraction values are expressed in mm), soil hydraulic conductivity (SHC), mean weight diameter (MWD), water stable aggregates (WSA), electrical conductivity (EC), soil organic matter (SOM), total sulphur (TS), total carbon (TC), total nitrogen (TN), pine mulch (PM), olive mulch (PM), and unmulched (UM) treatments: (**a**) 25 days after fire; (**b**) 3 months after fire (MAF); (**c**) 6 MAF; (**d**) 9 MAF; (**e**) 12 MAF; (**f**) 15 MAF.

5. Discussion

5.1. Soil Physical Properties

The first soil samples (25 DAF) exhibited the highest SWR in the finest soil fraction (<0.25 mm) in all treatments. The relatively high content of ash and charred residues incorporated into the soil surface after a wildfire and the low humification enhanced the observed hydrophobic effect [20,26]. Mataix-Solera and Doerr [27] showed a similar behaviour of SWR in the finest fraction studied (<0.25 mm). However, during the study period, soil hydrophobicity decreased in all treatments. It was found that both mulch treatments did not increase SWR during the decomposition process. Organic hydrophobic substances can be produced during litter (mulch) decomposition, which was not the case in our study. Although hydrophobic molecules are relatively resistant to physical or chemical degradation [28], the decline in hydrophobic compounds is attributed to rainfall events (i.e., leaching and washing hydrophobic compounds) in the post-fire period. These results can be reconciled well with the soil hydraulic conductivity response.

SHC in the post-fire period depends on the severity of the fire and the creation and persistence of hydrophobic substances [29]. The presence of hydrophobic substances leads to a water-repellent response of the soil and reduces water infiltration capacity, but after heavy rainfall, this effect is usually attenuated [29], which was the case in our study. Our results are also comparable with those of Robichaud et al. [11,22], who found lower infiltration rates in the early months after fire than in the later months using the same MDI. In our study, the infiltration capacity of the soil in the untreated burned area showed recovery values, i.e., an increase of soil infiltration capacity 9 MAF. Nine MAF corresponds to the spring season, when vegetation begins to overgrow, improving the soil conditions (e.g., soil structure and porosity), allowing the soil to store large amounts of water while improving infiltration rates. Similar results were observed Cerdà and Robichaud [29] and Lucas-Borja et al. [30]. In our study, the comparison between mulch treatments showed no significant differences in soil infiltration, but soil infiltration was slightly higher at OM 12 and 15 MAF.

The lowest values in the mulch treatments for MWD and WSA were found 25 DAF, after which the values increased. According to Velasco and Úbeda [31], the time the soil is exposed to raindrops is more important than the temperature reached by the fire. Thus, the soil aggregate stability, a measure of the soil's resistance to external disturbance forces, increases with the mulch rate [32]. In addition, among the most important factors affecting soil aggregation is the SOM content [33,34], which also increases with the application of mulch [16,35]. The increased aggregation due to the mulch application can also be attributed to the increased activity of fungi and bacteria [36]. The clay content, which was determined to be 35.2% in our study, also has an effect on the soil aggregation. Formation of stable aggregates can be promoted by the clay fractions, which usually change after fire disturbance [34]. UM treatment was bare and exposed to external factors such as rainfall and root growth, which diminished soil aggregation at the later sampling times. The most pronounced effect of mulches was seen at the end of the sampling period (15 MAF), with higher soil stability under mulch than unmulched soil surfaces.

5.2. Soil Chemical Properties

Soil pH usually increases immediately after burning due to soil heating caused by the denaturation of organic acids and ash incorporation into the soil [8]. This is evident in the UM treatment, where the highest values were found (25 DAF and 3 MAF). However, at the end of the monitoring period (15 MAF), an increase in soil pH was also observed. This was attributed to vegetation regrowth and the incorporation of organic matter into the soil. Due to plant consumption, the possible reduction in nitrate in the topsoil caused the soil pH to increase, as observed elsewhere [20,24,37]. The lowest values were found after the rainfall season (6 MAF) in all treatments. Indeed, in Mediterranean environments, soil pH usually increases during dry periods, while it decreases during wet periods due to the leaching of cations responsible for pH behaviour [38]. During the mulch treatments, the decomposition process of the organic material on the soil surface extracts essential oils and humic and hydrofluoric acids, which, together with the regrowth of vegetation, increase the soil pH 15 MAF [39]. In the case of EC, significantly, the highest values were found in the two first sampling dates (25 DAF and 3 MAF) in all treatments, which can be attributed to the wildfire effects due to the release of inorganic ions from the burned organic matter [26]. At the end of the monitoring period (15 MAF), an increase in soil EC was observed, even when relatively heavy rains were observed. These results can be attributed to vegetation regrowth, as observed in other studies [4,25]. Moreover, soil pH and EC increased in the last date compared to 12 MAF. This increase was considered a result of the input of soluble salts during the mulch decomposition [40]. In addition, the mineralisation of SOM and TC due to the addition of organic matter during dry periods releases ions that lead to high EC values [41]. Guang-Ming et al. [41] and Hueso-González et al. [40] showed that applying certain organic amendments can cause a change in pH and slight increase in EC.

The SOM and TC losses are often observed in the short term after wildfire due to high temperatures and the combustion process [26,33]. However, the opposite situation was observed in our study. The highest SOM and TC values were found 25 DAF in all treatments. Between wildfire and the first sampling (25 DAF), it rained 27 mm, contributing to ash accumulation and partially burned plant material in the upper soil profile [33]. The other possible explanation is the formation of black carbon that usually occurs after a severe or moderate wildfire severity, which also has been observed elsewhere [8]. However, a different situation occurred in the plots where mulch was applied. Here, an increase in SOM and TC contents were observed. The results were not surprising since an increase in soil organic matter was observed due to mulch addition [16,42]. The increase in SOM could also be explained by the improvement in water availability due to mulching by reducing evaporation and by the uptake of available nutrients and organic carbon compounds in the soil [42]. However, the lowest TC values were observed after the rainy season (6 MAF), indicating the washout of carbon-rich molecules. When comparing different plant materials (pine needles and olive leaves), a higher increase was observed under PM than under OM, although not significantly. Needles of *Pinus halepensis* are mainly composed of monoterpene hydrocarbons (~80%) [43], so their decomposition increased the SOM and TC 15 MAF. The main compounds of olive leaves are secoiridoids, flavonoids, and phenolics [44]. Their decomposition resulted in a lower SOM and TC than in PM. Mulches of organic origin usually enter into a relationship with the soil and increase the activity of enzymes that degrade plant residues. Soil microbes facilitate nutrient dynamics and availability, and microbial biomass is a sensitive indicator of SOM regulation and transformation [45].

Regarding TS, the highest content was observed 25 DAF. This observation can be explained due to mineralisation and oxidation of soil organic matter [26]. The volatilisation temperature of sulphur is higher than that of nitrogen and carbon (>800 °C) [8]. Biological processes cannot fix sulphur as an element but instead is added primarily by burning biomass and acid rain [46]. A decrease was observed 6 MAF due to the heavy rainfall season and washing. At the end of the monitoring period, the decomposition of PM increased the TS content.

Regarding the TN, neither the pine nor olive mulch significantly affected TN, although differences in values were observed. It is believed that the increased microbial activity and mulch decomposition somehow immobilised the soil's TN stock. In our study, 15 MAF, PM, and OM had a higher TN than UB, although not significantly different. Organic mulches may temporarily deplete the soil of nitrogen due to microbial activity, and the differences also affect the content of macro and micronutrients in the mulched soil, and its acidity [47].

The soil P_2O_5 content after wildfire was attributed to mineralisation effects due to heat released during the fire. However, the UM showed no significant change in P_2O_5 values during the study period. The optimum soil pH for extractable phosphorous is between 6.5 and 7, and when soil pH is lower or higher, the solubility of these elements is limited. In our study, soil pH was optimal for P availability throughout the study period and in each treatment. A similar trend was previously observed by Ekinci and Kavdir [48]. The oxidation of phosphorus and the consequent increase in inorganic P in the pH range of the studied plots also increased the P availability, evident at 3 MAB [49]. The lowest values observed 6 MAF in all treatments were due to the washing and leaching of compounds containing available P (ash and charred residue) caused by the highest rainfall observed on that date. In a study conducted by Gómez-Rey et al. [13], no significant effect of straw mulch on P_2O_5 was observed, suggesting that these treatments do not affect the phosphatase activity of P fractions disturbed in burned topsoil due to constant pH values. The highest values of P_2O_5 observed in OM 15 MAF, indicates that this mulch has a measurable effect on P availability after the fire. K_2O is highly soluble at pH above 7.5 and is one of the elements responsible for increasing the EC [6]. The greatest increase in K_2O is observed under OM, followed by PM. Decomposition of olive leaves increased the K_2O content in soil due to the chemical composition of olive leaves [44]. As for all other nutrients, the lowest values were observed 6 MAF due to heavy rainfall and the resulting leaching and washing, as observed elsewhere [50]. Both soil P_2O_5 and K_2O in 15 MAF showed a higher content in OM than UM. The PM did not show significant values regarding the PM and UM. The main chemical composition of olive leaves is secoridoids, which degrade on the soil surface and increase the soil nutrients (P_2O_5 and K_2O) [51].

6. Overall Discussion and Implications for Post-Fire Management

In the fire-prone Mediterranean environment, soil services provide an important role. Depending on the type and materials used, the effectiveness of mulch treatments can vary greatly in time [6]. For our case study, we applied PCAs to observe the temporal effects of mulch materials on soil chemical and physical properties for six sampling dates. The burned area was laid out without human intervention to compare the mulch materials' effects. On the first sampling date (25 DAF), there was no clear trend between treatments as expected (Figure 4a) [13]. However, soil properties (TC, TN, TS, EC, P_2O_5, SOM, pH, MWD) were inversely related to SWR (0.5–1, 1–2). This observation can be clearly attributed to the heating effect and the two-way process of organic matter combustion and element volatilisation, while the ash layer has enough time to penetrate the soil 25 DAF after combustion. In addition, an evident trend was also observed between SHC and SWR (composite, and <0.25). In the PCA 3 MAF, SHC was highest in UM treatment, which could be explained due to soil saturation effects and the highest increase of soil water content under mulches [30] (Figure 4b). TN, TC, TS, SOM, and SWR (<0.25, 1–2) were observed to be highest in PM, and P_2O_5, K_2O, and SWR (composite, 0.25–0.5) in OM. It seems that mulch composed of pine needles contributed to the increase in TN, TC, TS, and SOM content in the soil, while mulch composed of olive leaves enhanced concentrations of P_2O_5 and K_2O. The explanation is the difference in the chemical composition of the organic materials [43,44]. The PCA 6 MAF results were different from the previous sampling months (Figure 4c). However, P_2O_5 and K_2O again showed the highest values in OM, while the other soil properties were somehow between OM and PM. The highest SWR values (composite, 0.5–1, and 0.25–0.5) were observed in UM. The natural regrowth of vegetation can explain these observations and the effects of heavy rainfall observed during this period, which contributed to the leaching of organic compounds in deeper soil layers under the mulches [4,20]. The situation was evident in the PCA 9 MAF for SOM, MWD, WSA, TC, TS, and SHC (Figure 4d). The values of these parameters increased significantly due to the decomposition of PM. An unexpected finding was regarding P_2O_5, which had the highest values at the UM treatment. This can be explained by the soil pH and EC values, which affect P availability in the soil [4,8,25]. At 12 MAF, the TN, TS, TC, EC, and MWD again had the highest values under PM (Figure 4e). WSA, SHC, K_2O, and SWR (0.25–0.5) showed the highest values under OM. At the same time, UM showed the highest SWR (composite, 1–2, 0.5–1) values. Finally, at 15 MAF, the outcome of the soil properties was obvious for the UM treatment (Figure 4f). Only SWR (composite, and 0.5–1) showed the highest values. The values were intermediate between the two mulches for all other soil properties. Fifteen months after the fire, the positive effects of mulch on improving the quality of physical and chemical soil properties were indicated and confirmed. The two mulch treatments can be considered suitable to achieve targeted rehabilitation objectives. The PM showed a higher increase in TN, TS, and SOM, while OM indicated the highest levels in P_2O_5 and K_2O, which was the case in most sampling campaigns. Using natural plant residues as mulch makes it possible to conserve and rehabilitate soil resources in the post-fire period, improve nutrient recycling and the efficiency of humification processes, and provide an important source of organic matter in the soil. It should also be considered that the use of additional energy, such as fossil fuels, are reduced to the lowest level during implementation of available plant materials in the post-fire period. The need to purchase additional materials, such as straw and wood chips, is also eliminated, which is favourable from an economic aspect. However, following a wildfire disturbance, the ecosystems conditions should first be considered to determine the direction of the potential implementation treatments. If the ecosystem is partially affected by moderate wildfire severity, the implementation of on-site mulch materials should be utilized as much as possible. Primarily because of their beneficial effects on soil properties and energy and cost efficiency.

7. Conclusions

In our case study, post-fire management practices, such as mulching, in the wildfire-affected area affected the physical and chemical properties of the soil. During the 15-month soil sampling campaign, both mulches (pine needles and olive leaves) improved the soil's physical properties; however, they had different effects regarding untreated soil. The soil aggregate stability (MWD and WSA) increased after mulch application. Soil infiltration (SHC) was increased under mulch due to the SOM increase and soil aggregates' stability. PM showed slightly higher effectiveness in increasing MWD, while OM slightly increased SHC. For the WSA, the mulches had similar effects. SWR was reduced in both the mulched and unmulched treatment due to the degradation of hydrophobic compounds. PM increased SOM, TC, and TN regarding soil chemical properties, while OM increased soil P_2O_5 and K_2O. Soil pH and EC showed high variability due to natural soil processes and vegetation regrowth. Considering our results, on-site mulch improves soil quality; however, the decomposition of native mulch materials showed different effects on enhancing soil properties. It is recommended that the studied post-fire management be implemented, although consideration should be given to whether native mulches are available in the areas affected by wildfire. Overall, the data from this study aim to better understand the chemical and physical soil processes affected by post-fire mulch decomposition, which can assist land managers in determining the most appropriate soil conservation measures to mitigate undesirable post-fire responses in Mediterranean environments.

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