Mid-term effects of fire on soil properties of North-East Mediterranean ecosystems

fire

MDPI

Article

Mid-Term Effects of Fire on Soil Properties of North-East Mediterranean Ecosystems

Panteleimon Xofis [1,*], Peter G. Buckley [2], George Kefalas [1], Michail Chalaris [3] and Jonathan Mitchley [4]

1 Department of Forestry and Natural Environment, International Hellenic University, 1st km Dra-ma-Mikrohori, 66100 Drama, Greece; gkefalas@emt.ihu.gr
2 Peter Buckley Associates, Oast Barn, 37a The Green, Woodchurch, Ashford TN26 3PF, UK; peterbuckleyassociates@gmail.com
3 Department of Chemistry, International Hellenic University, St. Loukas, 65404 Kavala, Greece; mchalaris@chem.ihu.gr
4 School of Biological Sciences, University of Reading, Whiteknights, Reading RG6 6AS, UK; j.mitchley@reading.ac.uk
* Correspondence: pxofis@for.ihu.gr; Tel.: +30-697-3035-416 or +30-25210-60430

Abstract: Fire is a fundamental ecological process with a long history on Earth, determining the distribution of vegetation formations across the globe. Fire, however, does not only affect the vegetation but also the soil on which vegetation grows, creating a post-fire environment that differs significantly in terms of soil chemical and physical properties from the pre-fire environment. The duration of these alterations remains largely unknown and depends both on the vegetation condition and the fire characteristics. In the current study, we investigate the effect of fire on some chemical and physical properties 11 years after the event in four plant communities. Two of them constitute typical Mediterranean fire-prone plant communities, dominated by sclerophyllous Mediterranean shrubs, such as *Quercus coccifera* and *Q. ilex*, while the other two are not considered fire prone and are dominated by deciduous broadleaved species such as *Q. petraea* and *Castanea sativa*, respectively. The results indicate that fire affects the soil properties of the various communities in a different manner. Burned sites in the *Q. coccifera* community have a significantly lower concentration of organic matter, total nitrogen, and available magnesium. At the same time, they have a significantly higher concentration of sand particles and a lower concentration of clay particles. The effect of fire on the soil properties of the other three communities is less dramatic, with differences only in total phosphorus, organic matter, and total nitrogen. The results are discussed in relation to the site conditions and the post-fire regeneration of plant communities.

Keywords: *Quercus coccifera*; *Q. ilex*; *Q. petraea*; *Castanea sativa*; fire intensity; fire induced ecosystem degradation

Citation: Xofis, P.; Buckley, P.G.; Kefalas, G.; Chalaris, M.; Mitchley, J. Mid-Term Effects of Fire on Soil Properties of North-East Mediterranean Ecosystems. *Fire* **2023**, *6*, 337. https://doi.org/10.3390/fire6090337

Academic Editor: Grant Williamson

Received: 20 July 2023
Revised: 17 August 2023
Accepted: 25 August 2023
Published: 28 August 2023

1. Introduction

Soil is a fundamental part of ecosystem functioning, determining not only the vegetation that grows on it but also the dynamics of the established vegetation over time. A number of studies have reported that fire can dramatically change the soil's chemical, physical, and biological properties, with subsequent effects on ecosystem dynamics [1–4].

Fire affects soil chemistry as a result of the partial or complete removal of organic matter both above ground and, under extremely severe fires, in the upper mineral soil layers [5] and as a result of the transformation of nutrient forms due to soil heating [6–8]. The effects of fire on soil are a function of fire severity and the amount of fuel consumed [9–12]. Organic matter is a critical component of the ecosystem, affecting the soil's physical and chemical properties as well as its biological activity. It provides a protective cover on the soil, reducing soil erosion, acting as a regulator mechanism of soil temperature, and providing a suitable habitat and energy source for soil microorganisms. Organic matter can be a major source of micro- and macronutrients in readily mineralizable forms [5,13]. Nutrients stored in organic matter are released slowly through decomposition, allowing for continuous plant uptake and the long-term sustainability and productivity of the ecosystem. Fire dramatically alters the decomposition rate of organic matter by partially or completely converting it into ash. The degree of organic matter combustion depends on fire severity, the thickness, compactness, and dryness of organic matter, and can range from scorching to complete ashing [13]. Even under less severe fires, such as prescribed fires, organic matter in the forest floor can decrease by up to 80%, as shown by Covington and Sacket [14].

Fire leads to a significant loss of nutrients from the ecosystem through gasification, volatilization, transfer of nutrients, increased leaching of ions, and increased soil erosion [15]. The element most affected by fire is nitrogen, where significant losses have been reported even in fires of low intensity [9]. Nitrogen is susceptible to fire for two main reasons: Firstly, because it is stored in organic matter, which is largely consumed by fire, and secondly, because its volatilization begins at relatively low temperatures (200 °C), which are easily developed during a wildfire [16]. Apart from nitrogen, the pool of other nutrients also decreases after a fire. Although phosphorus usually does not decrease significantly after fire [17], the organic forms of phosphorus, which are the most readily available for plants, may be lost through gasification and volatilization [13]. Small decreases in other nutrients such as potassium, magnesium, sodium, and calcium may also be observed after fire [15,18]. The reduced susceptibility of these nutrients to fire is mainly due to the high temperatures required for their oxidization and volatilization.

Significant losses of nutrients after the passage of fire also occur as a result of increased leaching and soil erosion. Losses of nutrients by leaching are relatively limited and largely dependent on the concentration of nutrients in the immediate post-fire environment [19,20]. Soil erosion, on the other hand, can lead to significant losses of nutrients through sediment transfer, especially when heavy rainstorms follow the passage of fire [21–23]. Soil erosion increases after fire because of the removal of vegetation and organic matter and the subsequent exposure of the soil to the increased kinetic energy of raindrops. The formation of a hydrophobic layer at a certain depth in the mineral soil decreases the soil infiltration capacity and increases the possibility of increased soil erosion [5,24–26]. Factors such as fire intensity, slope, and the severity of rainfall all affect the degree to which soil erosion may reduce the nutrient capital after a fire.

Despite the loss of nutrient capital after a fire, the available forms of nutrients may increase immediately after a fire [7,11,12,21,22,27–31]. The ash, resulting from the combustion of organic matter and standing vegetation, is very rich in these forms of nutrients. The destruction of vegetation by fire and the subsequent decrease in plant uptake also lead to an increase in soil-available nutrients immediately after the fire. A third reason for the increased nutrient availability after a fire is the increased microbial activity and nutrient mineralization rates often observed in the post-fire environment, resulting in more nutrient availability.

Soil texture, which is the only physical property examined in the current study, may also be affected by fire. Although there is a lack of agreement on whether fire can significantly change the soil particle distribution, there are some studies documenting an increase in sand particles and a decrease in clay particles after fire [6,32–34]. This effect is strongly affected by the initial proportion of clay and sand in the soil (clay soils are affected more significantly) as well as by the severity of the fire and the temperatures developed [33]. Some authors, however, consider that the soil temperatures developed under a wildfire are not adequate to cause significant changes in particle distribution [11,15].

The duration of the fire-induced changes in soil nutrient status and physical properties is poorly understood [35]. Most studies are confined to the first years after the fire, and only a few extend the study period any further. The increased availability of nutrients immediately after a fire, for instance, may quickly diminish if heavy rainfall occurs soon after the fire, causing increased soil erosion and runoff. If this occurs, in combination with the loss of nutrients during the fire, this may lead to significant degradation and a lowering of soil productivity.

Fire affects different plant communities in different ways, and since fire intensity was identified as a major factor affecting the extent of changes [36], it is likely that the effects of fire on soil properties will also vary between the communities. The aim of this study is to evaluate the effect of fire on some soil physical and chemical properties after a period of 11 years since the event and in a range of plant communities with varying fire proneness. The specific questions that this study attempts to address are: (a) Are the fire-induced alterations in soil properties still detectable several years after the event? (b) Does fire affect the soil properties in the same way for all plant communities? (c) Is the community structure, which affects the fire behavior, relevant to the effect on soil properties? Given that fires in the Mediterranean are expected to become more severe in the future due to changes in weather patterns and socioeconomic changes, the results are expected to provide useful insights into the long-term sustainability of some typical Mediterranean ecosystems under an altered fire regime.

2. Materials and Methods

2.1. Study Area

The study was conducted on the geographically and socially isolated peninsula of Mount Athos in northern Greece (40°11′40.01″ N, 24°13′55.95″ E; Figure 1), which is geographically and socially isolated due to the establishment of a monastic life more than a thousand years ago. It is now inhabited only by monks and hermits, and it is to a great extent intact from the anthropogenic activities that have ravaged the rest of the Mediterranean region [37]. The area has a long history of wildfires, which, however, according to the existing records, occur at relatively large intervals of more than 40 years (see also Xofis et al. [36] for a further description of the study area).

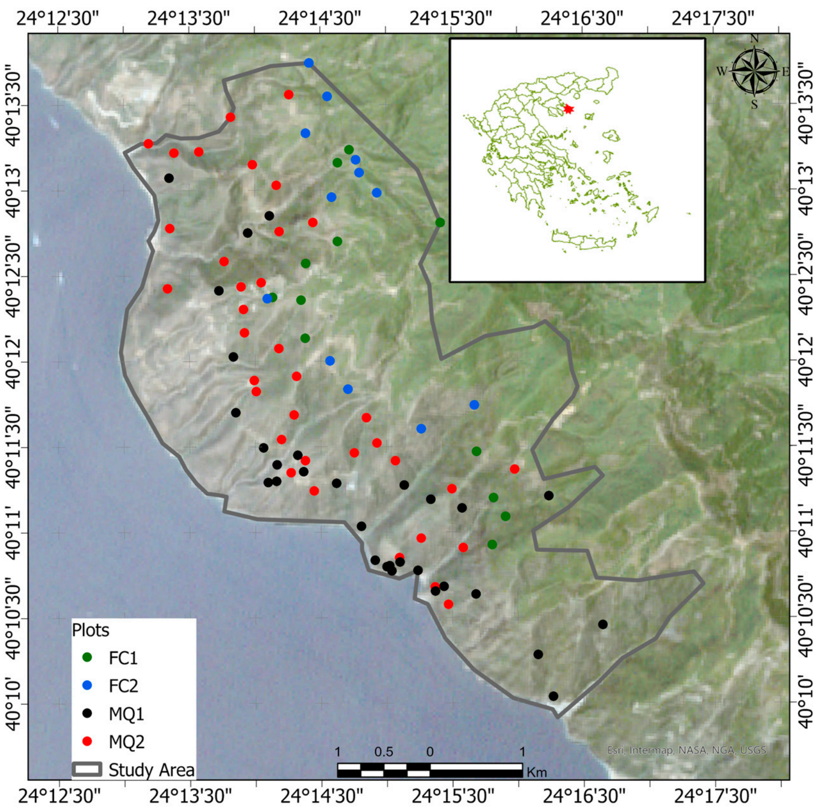

Figure 1. Location of the study area and plot distribution.

The general orientation of the site is southwest; however, due to the complex and sharp relief, one can find all different aspects from north to south and east to west. The altitudinal range is from sea level to 889 m; however, the study is confined to up to approximately 500 m, which is part of the area affected by the studied wildfire. The climate is Mediterranean, with pronounced biseasonality in annual precipitation and a summer drought period. According to the existing data, the climate in the areas below 500 m has an annual precipitation of less than 500 mm, a mean annual temperature of 15.7 °C, a mean annual atmospheric moisture of 70%, and 2800 h of sunshine per year. Based on those data as well as on the vegetation characteristics of the study area, the climate was classified as Csa type according to Koppen, which is characterized by hot and dry summers and mild winters [38].

2.2. Field Sampling, Data Collection and Analysis

Field sampling was performed eleven years after the last fire event for the collection of vegetation and environmental parameter data. One hundred and fifty points were randomly located, which ensured a minimum sample density of one sample per 25 hectares, which according to Tzanopoulos et al. [38] is sufficient to capture the heterogeneity of the Mediterranean landscape. The random location of sampled points and the large variation in topographic conditions ensure that the variation in environmental factors and vegetation structure and composition will be sufficiently represented in the dataset. Of the 150 points, only 134 were eventually visited and sampled because 16 of them were inaccessible. These 134 samples contain both burned and unburned sites.

During sampling, the exact location of the sampled quadrat was adjusted by a few meters if necessary in order to ensure homogeneity in environmental conditions and vegetation characteristics. Their size varied between 300 and 500 m^2 depending on vegetation type [39], with smaller-sized quadrats being used to sample maquis vegetation and larger-sized quadrats for forest vegetation. The four corners and the center of each quadrat were marked using a GARMIN eTrex Vista GPS with a spatial accuracy of 4 m. In each quadrat, the cover of all woody species was visually estimated using a 20-point cover scale. The 20-point cover scale was based on the 9-point Braun–Blanquet cover-abundance scale [40], which was further divided in order to achieve a much more accurate recording of the vegetation composition. The collected data on vegetation composition were used to identify the plant communities present in the study area.

From each quadrat, five soil samples were taken in a W shape to a depth of 10 cm into the inorganic soil layers. The five samples were air-dried for 48 h and then mixed in equal quantities to produce one bulk sample representative of the whole quadrat.

The following physical and chemical soil properties were determined with the aim of investigating their effect on vegetation distribution and composition (see Xofis et al. [36]) and also the effect of fire on them: Total organic nitrogen (N), total phosphorus (P), total potassium (K), available phosphorus (phosphate), available calcium (Ca), available magnesium (Mg), available potassium, available sodium (Na), organic matter content (OM), pH, and soil particle size distribution. Total N, P, and K were determined from the same extract produced using the Kjeldahl procedure [41]. For available phosphorus, the molybdenum blue method [41,42] was employed after extracting the phosphorus from soil using a 0.5 M sodium bicarbonate reagent (pH = 8.5). Available potassium and magnesium were estimated from the same soil extract using ammonium nitrate as the extraction agent [42]. Available Ca and Na were extracted from the soil using ammonium acetate as the extraction agent [42]. A pH meter [42] was used for pH estimation. The loss-on-ignition method [43] was employed for organic matter content after drying both the porcelain crucibles for 12 h at 105 °C and the soil for another 12 h at 105 °C and then placing the samples in a furnace at 550 °C for 15 h. Soil particle size distribution was determined by using a Buyoucos hydrometer in a water-soil suspension.

The collected vegetation data were used to perform a vegetation classification analysis using the hierarchical polythetic divisive method Two-Way INdicator SPecies ANalysis

(TWINSPAN) [44,45], assisted by a Detrended Correspondence Analysis (DCA) [46]. Details on the exact parameters used for the classification can be seen in Xofis et al. [36]. The classification analysis revealed the existence of four distinctive plant communities in the study area, namely:

- Community of *Quercus coccifera*, *Philyrea latifolia* and *Olea europaea* (Henceforth MQ1)

This community is the most widespread in the study area, with 74 out of the 134 samples having been classified in this community, and it constitutes the most common maquis community in the Mediterranean region. The most characteristic species of the community are, apart from the three that were used for its denomination, species such as *Ruscus aculeatus*, *Fraxinus ornus*, *Cistus creticus*, *Arbutus unedo*, *Asparagus acutifolious*, *Calicotome villosa*, *Erica arborea*, *Spartium junceum*, and *Pistacia terebinthus.* Of the 74 samples from the community, 59 were from burned areas, and 15 were from unburned areas. A particular characteristic of this community is the important differences in species relative abundance between the unburned and burned sites. While the mature sites are dominated mainly by the species *Q. coccifera* and *P. latifolia*, the burned sites are dominated primarily by the species *C. vilosa*, with a cover exceeding 50%, and also by the species *C. creticus.*

- Community of *Q. ilex* and *F. ornus* (Henceforth MQ2)

This community is also a maquis community dominated by the two denominating species and includes other broadleaved evergreen species such as *Q. coccifera*, *P. latifolia*, *S. junceum*, and *Laurus nobilis*, while *Q. petraea* also occurs in some plots. According to Xofis et al. [36] this community occupies the most favorable sites in the low altitudinal zone of the study area and often occurs close to streams where the soil moisture conditions are less arid. Thirty-six plots were classified under this community, while 30 of them were on burned sites and six on mature sites.

- Community of *Q. petraea* (Henceforth FC1)

This is the first of the two forest communities that occupy the part of the study area with an altitude exceeding 400 m. Apart from *Q. petraea*, other characteristic and abundant species of the community include *Q. ilex*, *F. ornus*, *Q. fraineto*, *Genista trinctoria*, and *Cytisus vilosus*. Twelve plots have been classified in this community, with seven of them having been burned and five being mature sites.

- Community of *Castanea sativa* (Henceforth FC2)

This is the second of the two forest communities, and it generally occurs at slightly higher altitudes and in better conditions compared to the previous ones. Apart from *C. sativa*, other characteristic and abundant species of the community include *Abies borisii-regis*, *Q. fraineto*, *Q. petraea*, and *C. vilosus*. Of the 134 plots, 12 were classified under this community, with six of them having been burned and six being mature sites.

The effect of fire on soil properties was examined separately for each community. Before running any test for significant differences between burned and mature sites in the same community, the Global Moran's I test was performed for all samples of each community and for all studied soil properties using the software ArcGIS Pro v 3.1.0. The test detected significant spatial autocorrelation for the plots of the MQ1 community. For this reason, a sub-sample of the 59 burned plots in the community was selected using the random number generator platform at https://www.gigacalculator.com/ (accessed on 9 August 2023). Fifteen samples were randomly selected in this way. The results of the spatial autocorrelation test for all communities after the random selection of the MQ1 community are reported in Table 1 for the soil property of organic matter content, which is the most highly affected by fire. The location of the plots that participated in the analysis after random selection is shown in Figure 1. The chemical and physical properties of soil were compared between burned and unburned sites of the same community using the Mann–Whitney U test in the software Statistica, Version 13.5. This test was considered most appropriate for the analysis due to the unequal variances observed, particularly for the MQ2 community, where an imbalance between burned and mature sites exists. The

Mann–Whitney U test is a non-parametric test for comparisons between populations with no particular assumptions for distribution or variance.

Table 1. Results of the spatial autocorrelation test for the soil property of organic matter content.

Community	Moran's Index	z-Score	*p*-Value
MQ1	−0.047141	0.13177	0.895166
MQ2	0.146227	1.480381	0.138772
FC1	−0.096026	−0.023153	0.981528
FC2	−0.103312	−0.052988	0.957741

3. Results

The differences between burned and mature sites in each of the four identified communities are presented separately for each community.

3.1. *Quercus coccifera, Philyrea latifolia and Olea europaea (MQ1) Community*

The Mann–Whitney U test results showed a number of significant differences in soil chemical and physical properties between burned and mature sites (Table 2). Organic matter content and total nitrogen are both lower in the burned sites compared to the mature ones (Figure 2a,b). Most of the available nutrients, apart from available magnesium (Figure 2c), showed no significant differences between burned and mature sites, although available calcium and sodium were only marginally insignificant. Regarding soil texture, burned sites appear to have a higher concentration of sand and a lower concentration of clay compared to the mature sites (Figure 2d,e; boxplots of soil properties where there is no significant difference between burned and mature sites of the MQ1 community are shown in Appendix A Figure A1).

Table 2. Mann–Whitney U test results for the differences in soil chemical and physical properties between burned and mature sites for community MQ1. Significant differences ($p < 0.05$) are in bold.

Soil Property	Rank Sum Burned	Rank Sum Mature	U	Z	*p*-Value
Organic matter	162.0	303	42.0	−2.90346	**0.004**
pH	264.5	200.5	80.5	1.306559	0.191
Total nitrogen	170.0	295	50.0	−2.57164	**0.010**
Total phosphorus	218.0	247.0	98.0	−0.580693	0.561
Available phosphorus	202.0	263.0	82.0	−1.24424	0.213
Total potassium	252.0	213.0	93.0	0.788083	0.431
Available potassium	214.0	251.0	94.0	−0.746605	0.455
Available magnesium	181.0	284.0	61.0	−2.11538	**0.034**
Available calcium	187.0	278.0	67.0	−1.86651	0.062
Available sodium	187.0	278.0	67.0	−1.86651	0.062
Sand content	289.0	176.0	56.0	2.322772	**0.021**
Silt content	228.0	237.0	108.0	−0.165912	0.868
Clay content	182.0	283.0	62.0	−2.07390	**0.038**

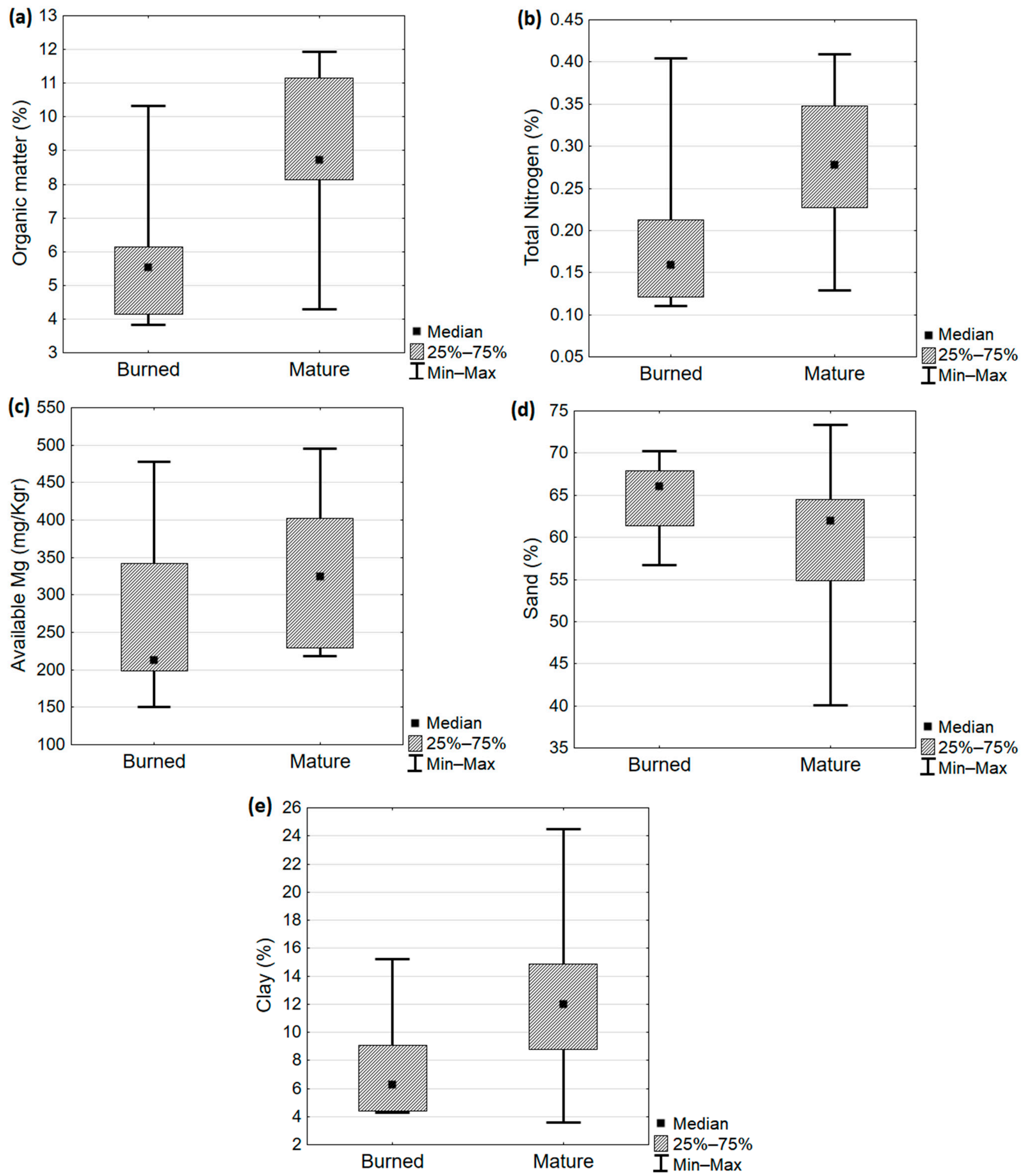

Figure 2. Differences in organic matter (**a**), total nitrogen (**b**), available magnesium (**c**), sand percentage (**d**) and clay percentage (**e**) between burned and mature sites of community MQ1. Only properties where significant differences were detected are shown.

3.2. *Quercus ilex-Fraxinus ornus* (MQ2) Community

In the case of the MQ2 community, only total phosphorus was found to be significantly different between burned and mature sites (Table 3, Figure 3; boxplots of soil properties where there is no significant difference between burned and mature sites of the MQ2 community are shown in Appendix A Figure A2).

Table 3. Mann–Whitney U test results for the differences in soil chemical and physical properties between burned and mature sites for community MQ2. Significant differences ($p < 0.05$) are in bold.

Soil Property	Rank Sum Burned	Rank Sum Mature	U	Z	*p*-Value
Organic matter	574.0	92.0	71.0	0.785281	0.432
pH	567.5	98.5	77.5	0.509372	0.610
Total nitrogen	590.0	76.0	55.0	1.464443	0.143
Total phosphorus	608.0	58.0	37.0	2.228501	**0.026**
Available phosphorus	582.0	84.0	63.0	1.124862	0.261
Total potassium	582.0	84.0	63.0	1.124862	0.261
Available potassium	590.0	76.0	55.0	1.464443	0.143
Available magnesium	547.0	119.0	82.0	−0.318357	0.750
Available calcium	586.0	80.0	59.0	1.294653	0.195
Available sodium	551.0	115.0	86.0	−0.148567	0.882
Sand content	539.0	127.0	74.0	−0.657938	0.511
Silt content	559.0	107.0	86.0	0.148567	0.882
Clay content	580.0	86.0	65.0	1.039967	0.298

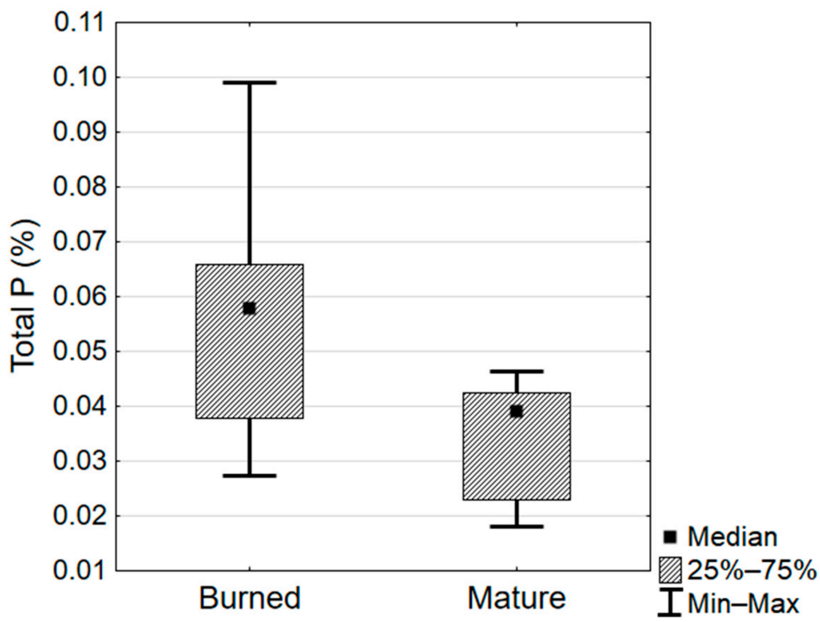

Figure 3. Differences in total phosphorus content between burned and mature sites of community MQ2.

3.3. *Quercus petraea (FC1) Community*

The FC1 community is affected by fire in the same way as community MQ2: i.e., the differences between burned and mature sites are minimal, with total phosphorus being the only soil nutrient differing between burned and mature sites (Table 4, Figure 4; boxplots of soil properties where there is no significant difference between burned and mature sites of the FC1 community are shown in Appendix A Figure A3).

Table 4. Mann–Whitney U test results for the differences in soil chemical and physical properties between burned and mature sites for community FC1. Significant differences ($p < 0.05$) are in bold.

Soil Property	Rank Sum Burned	Rank Sum Mature	U	Z	*p*-Value
Organic matter	42.0	36.0	14.0	−0.487199	0.626
pH	49.0	29.0	14.0	−0.487199	0.626
Total nitrogen	47.0	31.0	16.0	0.162400	0.88
Total phosphorus	59.0	19.0	4.0	2.111195	**0.035**
Available phosphorus	54.0	24.0	9.0	1.299197	0.194
Total potassium	51.0	27.0	12.0	0.811998	0.417
Available potassium	49.0	29.0	14.0	0.487199	0.626
Available magnesium	49.0	29.0	14.0	0.487199	0.626
Available calcium	46.0	32.0	17.0	0.000000	1.000
Available sodium	45.0	33.0	17.0	0.000000	1.000
Sand content	46.0	32.0	17.0	0.000000	1.000
Silt content	41.0	37.0	13.0	−0.649598	0.516
Clay content	50.0	28.0	13.0	0.649598	0.516

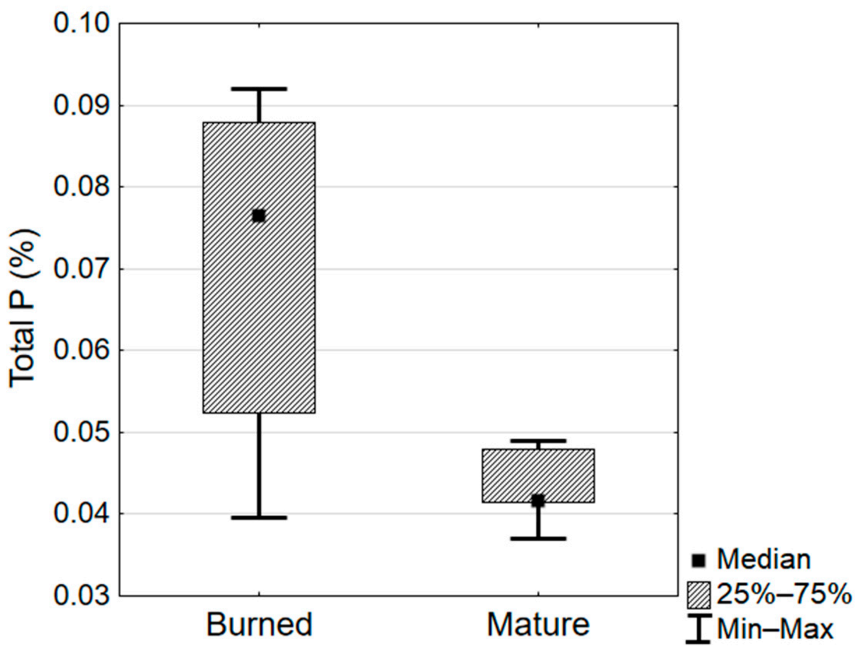

Figure 4. Differences in total phosphorus content between burned and mature sites of community FC1.

3.4. *Castanea sativa (FC2) Community*

Soil organic matter and total nitrogen were both significantly different between burned and mature sites of community FC2 (Table 5, Figure 5; boxplots of soil properties where there is no significant difference between burned and mature sites of the MQ1 community are shown in Appendix A Figure A4). Although the differences are marginally significant and cover a broad range of values, they still show a trend, which will be discussed below.

Table 5. Mann–Whitney U test results for the differences in soil chemical and physical properties between burned and mature sites for community FC2. Significant differences ($p < 0.05$) are in bold.

Soil Property	Rank Sum Burned	Rank Sum Mature	U	Z	*p*-Value
Organic matter	26.0	52.0	5.0	−0.200160	**0.045**
pH	38.0	40.0	17.0	−0.080060	0.936
Total nitrogen	26.0	52.0	5.0	−0.200160	**0.045**
Total phosphorus	39.0	39.0	18.0	0.080060	0.936
Available phosphorus	46.0	32.0	11.0	1.04083	0.298
Total potassium	44.0	34.0	13.0	0.47117	0.721
Available potassium	40.0	38.0	17.0	0.08006	0.936
Available magnesium	35.0	43.0	14.0	−0.56045	0.575
Available calcium	33.0	45.0	12.0	−0.88070	0.378
Available sodium	31.0	47.0	10.0	−1.20096	0.230
Sand content	38.0	40.0	17.0	−0.08006	0.936
Silt content	41.0	37.0	16.0	0.24019	0.810
Clay content	36.0	42.0	15.0	−0.40032	0.689

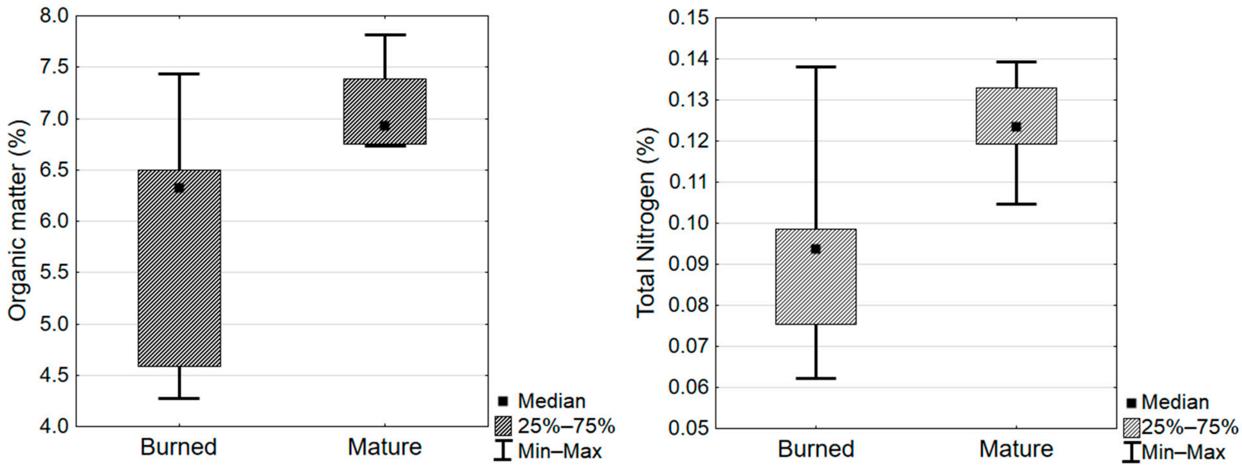

Figure 5. Differences in soil organic matter and total nitrogen between burned and mature sites of community FC2.

4. Discussion

4.1. Quercus coccifera, Philyrea latifolia and Olea europaea (MQ1) Community

Of the four communities studied, the chemical and physical properties of the MQ1 community were the most significantly affected by fire, with important differences between burned and mature sites. It should be noted here that the relatively small sample sizes of the FC1 and FC2 communities may have obscured some significant differences; however, it was not possible to have a larger sample size of these communities in the area without ending up with a spatially autocorrelated dataset. Organic matter was the soil property most affected, and on the burned MQ1 sites, it is 65% of the value of the mature sites. The degree of organic matter destruction can be considered an indicator of fire intensity, with greater reduction being associated with higher-intensity fires [47]. Loss of volatile organic compounds in the atmosphere occurs between soil temperatures of 100 and 300 °C, while temperatures higher than 450 °C can cause complete loss of organic matter [6,48]. According to the literature, despite the initial loss of organic matter, soon after fire it tends to recover to its pre-fire values within a period ranging from a few months to 3 years, depending on the degree of destruction [8,48–50]. In the current study, however, even eleven years after the fire, organic matter remains significantly lower on the burned sites, which suggests a high-intensity fire on sites occupied by the MQ1 community. Xofis et al. [36], based on different criteria, also concluded that the MQ1 sites were those burned with the highest intensity compared to all other communities. The temperature developed on the soil surface of the MQ1 community is likely to have been the highest among the communities studied here. One reason supporting this hypothesis is that the MQ1 community is dominated by species such as *Q. coccifera*, *P. latifolia*, and *A. unedo*, which not only resprout after fire but also grow new resprouts throughout the life cycle of the plant [51]. As a result, the plants seldom grow taller than 3–4 m, and the crown starts from the soil surface. Subsequently, on MQ1 sites, there is potentially a high fuel load on or close to the soil surface, which may cause the temperatures to rise to very high levels during a wildfire. Another reason for the poor recovery of soil organic matter is the fact that the burned sites are dominated by *C. vilosa*, which has a relatively low proportion of leaf biomass. Given that leaves are one of the main sources of organic matter in the soil, the annual addition of organic matter is likely to be lower in *C. vilosa*-dominated vegetation than in vegetation dominated by species of the mature community, such as *Q. coccifera* and *P. latifolia*.

Total soil nitrogen was also found to be significantly lower on the burned sites compared to the mature ones. The loss of nitrogen during a fire is proportional to the loss of fuel and organic matter [9,10], and a linear relationship between soil organic matter and soil nitrogen has been observed by Kennard and Gholz [48]. A similar linear relationship was also observed in the current study, as shown in Figure 6. This indicates that the slow recovery of total nitrogen in the soil can be attributed, to a large extent, to the slow recovery of organic matter. Total organic nitrogen is the element most affected by fire due to the oxidation that occurs at temperatures as low as 200 °C [9,10,52]. Raison et al. [10] found that even under a low-intensity fire, 54–75% of the nitrogen initially present in the fuel was lost through oxidation, volatilization, or other means, which again suggests that the loss of nitrogen should be proportional to the amount of lost organic matter. The fact that in the current study, total soil nitrogen on the burned sites is still only 63% of the nitrogen content of the mature sites after 11 years, despite the high abundance of the nitrogen-fixing shrub *C. villosa*, is another indication that the fire was of high intensity. Furthermore, it indicates that fire return intervals as low as 10–15 years could cause a significant degradation of critical soil properties.

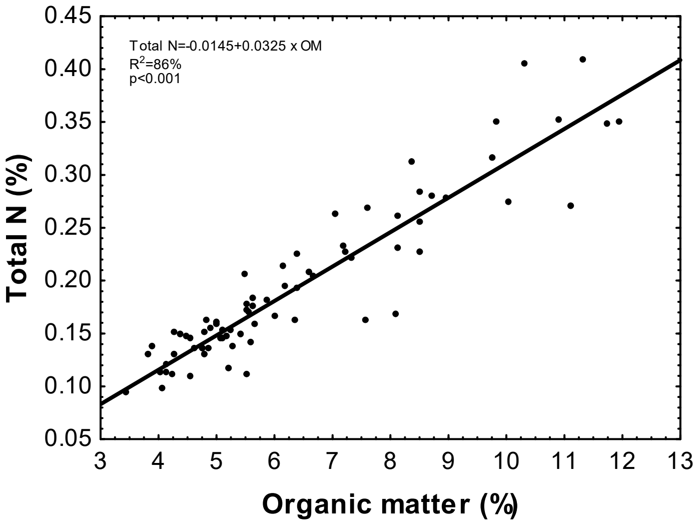

Figure 6. The relationship between soil organic matter and total soil nitrogen on MQ1 community sites.

The losses of organic matter and total nitrogen observed in the current study are largely predictable from the literature. In contrast, the losses in available magnesium were less predictable or expected. In fact, fire has been reported to cause a short-term flush of available nutrients due to the increased mineralization rate of organic forms of nutrients caused by the increased temperatures, but mainly due to the deposition of ash, which is rich in nutrients [6,8,10,34,48]. Even under fires of high intensity, available nutrients still increase in the short term [34,48], to a greater or lesser extent. Although Giovannini et al. [6] and Giovannini et al. [8] reported some losses in available forms of nutrients when soil was heated in the laboratory to temperatures as high as 900 °C, this trend has not been confirmed in relevant field studies. Hence, it is unlikely that the decrease in soil nutrients is the direct effect of high fire intensity. The initial flush of available forms of nutrients has been reported to last no longer than 18 months after a high-intensity fire [48] or for up to some years [11], after which it returns to pre-fire levels. Long-term decreases in available nutrients as a result of the fire have not been reported. Given that fire intensity alone is unlikely to have caused these decreases, the decreases must have occurred during the period after the fire event. Post-fire soil erosion and runoff form the two main ways of nutrient loss, followed by leaching and the transfer of ash by wind during or soon after the fire. Although there are no precise measurements available on the degree of soil erosion and runoff, after the fire event in the study area, local inhabitants (monks) confirmed that during the first autumn after the fire, massive amounts of ash were transported to the sea, turning its reflection from blue to black. Apart from the local witnesses, there are several factors that would lead to the conclusion that soil erosion and runoff were the two factors responsible for the degradation of soil properties in the study area. As already mentioned, the fire was likely to have been of very high intensity, and this may have caused the formation of a water-repellent layer in the top few centimeters of the mineral soil, reducing the infiltration capacity and increasing soil erosion and runoff [25]. The porosity of sandy-loam soils was found to be reduced when heated to temperatures reaching and exceeding 220 °C, which was likely to have been the case in the current study as suggested by the loss of organic matter described earlier [33]. Further, the destruction of soil structure and the formation of new soil aggregates that are less plastic and less porous can also accelerate soil erosion and runoff [33] and may decrease infiltration rates after high-intensity fires compared with low- to moderate-intensity fires [48]. Robichaud [53] reported a 10–40% reduction in hydraulic conductivity on sites that had undergone a high-intensity burn, causing a subsequent increase in soil erosion and runoff. The positive relationship between increasing fire intensity and soil erosion and runoff has also been described in many studies from different parts of the world [54–56]. Cerda et al. [57] identified aspect as one of the factors having a significant impact on the degree of soil erosion after fire, with southern aspects more susceptible than northern aspects due to the greater structural complexity of vegetation on the latter sites. As shown in Xofis et al. [36], most of the sites on the southern aspects of the study area were occupied by the MQ1 community. If one also takes into account the very steep slopes prevailing in the area, then it is quite likely that soil erosion and runoff were intense during the first autumn following the fire, when accelerated erosion normally occurs after fire [55,58]. Losses of nutrients through leaching after fire have also been found to increase as fire intensity increases, but these losses are generally of a lower magnitude compared with atmospheric losses and losses through soil erosion and runoff [19,20]. Further, given that the most susceptible element to soil leaching is potassium [20], this did not show a significant difference between burned and mature sites in the current study, confirming the hypothesis that leaching was not the main factor affecting soil properties in the current community.

The effect of fire on soil nutrient budgets has been studied at a number of locations across the globe, where fire is either a natural disturbance factor or a management tool. However, the effects of fire on soil physical properties, especially under field conditions, are relatively poorly understood. In the current study, burned sites appear to have a higher sand content and a lower clay content than on mature MQ1 sites. The phenomenon of increasing the sand fraction and simultaneously decreasing the clay fraction of the soil after fire has been observed in other studies and is associated with high-intensity fires and exposure of soils to high temperatures, where clay particles aggregate into sand-sized particles [33,34,59]. Ulery and Graham [59] suggested that the formation of sand-sized particles under the effect of burning is the result of the cementation action of poorly crystalline aluminosilicates and amorphous silica and aluminum released during the decomposition of kaolin. The duration of this altered soil texture has not been extensively studied, but Ulery and Graham [59] found that the sand fraction was still elevated and the clay fraction reduced three years after burning. The fact that in the current study, the sand-sized particles remained significantly higher on the burned sites after 11 years is an additional indication of the high fire intensity experienced on the MQ1 sites.

4.2. *Quercus ilex-Fraxinus ornus (MQ2) and Quercus petraea (FC1) Communities*

Fire affected the soil properties of these communities in the same way, and they are discussed together here. Eleven years after the fire event, the burned and mature sites showed only minor differences in soil chemical and physical properties. The only statistically significant difference was a higher total phosphorus content on the burned sites. The less profound effects of fire on the MQ2 and FC1 communities, compared to MQ1, were expected since these two communities were probably burned with relatively lower intensity [36]. However, the fire was still intensive, as suggested by the high tree mortality observed. The important factor altering the magnitude of the effects caused by fire on soil is probably the vegetation structure. Unlike the MQ1 community, where the crown of the plants extends to the surface, the MQ2 and FC1 communities are dominated by *Q. ilex*, *F. ornus*, and *Q. petraea*, where the canopy base height is well above the surface. Given that these sites had been undisturbed for at least 45 years before the last fire, even *Q. ilex*, which is often found as a shrub, had grown into a tree exceeding 10 m in height, forming what Oliver Rackham has termed “Mediterranean rain forests”. The cover of the upper canopy layer in mature MQ2 sites reaches or exceeds 100%, and while an understorey is not completely absent, there are big gaps in its cover, making it unlikely that a high-intensity fire would be sustained at ground level. Hence, although much energy was probably released during the fire on these sites, the low fuel load on or close to the ground may have prevented the exposure of the soil to very high temperatures, reducing the occurrence of very destructive effects such as those described for the MQ1 community.

The higher level of total phosphorus on burned sites was a rather surprising result. The only possible explanation of this result is that the initial increase in available P immediately after the fire in acidic soils is followed by the binding of phosphate with aluminum, iron, and manganese into non-available forms [18]. Leaching of iron was found not to be affected by low to moderate fires and actually to decrease when soil temperatures increase above 300 °C [18]. Thus, it is possible that the formation of phosphate compounds with iron resulted in an increase in total phosphorus in the soil and also prevented the leaching of phosphorus to deeper soil layers.

4.3. *Castanea sativa Community (FC2)*

From a vegetation compositional and structural point of view, the differences between burned and mature sites of the FC2 community were the least among all the communities studied, as shown in Xofis et al. [36]. However, the differences in soil properties between burned and mature sites were actually rather more profound than those of the MQ2 and FC1 communities. Eleven years after the fire, organic matter and total nitrogen content on the burned sites were only 84% and 75% of the values for the mature sites, respectively. Based on the previous discussion, it might be assumed that the FC2 community was burned at a higher intensity than the FC1 and MQ2 communities. However, this assumption is not necessarily correct. FC2 stands are managed by coppicing every 25–30 years, and they form the only productive forests in the study area, generating a significant income for the monastic communities. It is for this reason that *C. sativa* was favored for centuries over other species growing in the same zone, such as *A. borisii-regis*, and has resulted in its overwhelming dominance at altitudes between 500 m and 1000 m [60]. Because the main objective of the management is to produce good-quality timber for construction purposes, the stands are dense and little light reaches the ground, preventing the establishment of ground vegetation, and the ground fuel consists predominantly of a thick litter layer of dead leaves and twigs.

C. sativa forests are rarely subject to recurrent fires, so the literature is rather limited in this respect [61,62]. In the current study area, FC2 stands were burned by a surface fire that did not reach the canopy layer due to the absence of understorey vegetation and the high canopy base height. Despite this, however, the FC2 community experienced very high tree mortality, according to the local forest managers, possibly due to the high temperatures developed close to the ground as a result of the thick litter layer. Such high temperatures could kill a tree by overheating the cambium under the bark [63,64], especially in species such as *Castanea*, which has a thin bark. The fire was sustained by consuming the thick litter layer present in the FC2 stands, which cannot cause such a high-intensity fire compared with the FC1 and MQ2 sites, where fire also consumed part of the canopy, releasing higher amounts of energy. One fundamental difference, however, between the two cases is that in the case of FC2 stands, during the consumption of the thick litter layer, the soil was probably exposed to temperatures higher than the temperatures of the fire burning in the MQ2 and FC1 communities, where the available fuel on or near the soil surface was neither large nor continuous. Hence, the more significant effects of fire on the soil properties of the FC2 community were not the result of a high-intensity fire but rather the result of the high temperatures experienced at the soil surface. This fire behavior has caused a significant reduction in soil organic matter and a consequent reduction in total nitrogen.

5. Conclusions

Fire is a fundamental ecological process [65] and at the same time a significant destructive factor, threatening, in many cases, ecosystem integrity and long-term sustainability [66]. In the current study, the effect of fire on soil properties was studied in four different ecosystems present in the Mediterranean region. The results suggest that the various ecosystems are affected by fire in different ways, depending on the pre-fire vegetation structure and composition, which in turn affect fire behavior. High-intensity fires appear to dramatically affect the soil properties, with the detrimental effects lasting for more than a decade on sites that have been burned with high intensity. Given that climatic crises and socio-economic changes are likely to increase the risk of high-intensity fires, it is important to improve our understanding of the mid- and long-term effects of fire on ecosystem properties in order to achieve more effective planning for fire prevention and ecosystem restoration.

The study followed a synchronic approach where burned and mature sites with different fire histories were compared in terms of the studied chemical and physical soil properties. Although the results show trends that are in accordance with what has been reported in the literature, a diachronic study where data on soil chemical and physical properties existed before fire would allow a more direct interpretation of the fire-induced changes in soil properties.

Author Contributions: Conceptualization, P.X., J.M. and P.G.B.; methodology, P.X., J.M., G.K. and M.C.; validation, P.X., J.M., P.G.B. and M.C.; formal analysis, P.X. and G.K.; resources, P.X., J.M. and P.G.B.; data curation, P.X; writing—original draft preparation, P.X., J.M. and P.G.B.; visualization, P.X.; supervision, J.M. and P.G.B. funding acquisition, P.X. writing—review and editing, P.X., P.G.B. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: Part of this research was funded by the State Scholarship Foundation of Greece.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy reasons.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A. Boxplots on Soil Properties with No Significant Differences between Burned and Mature Sites of All Communities

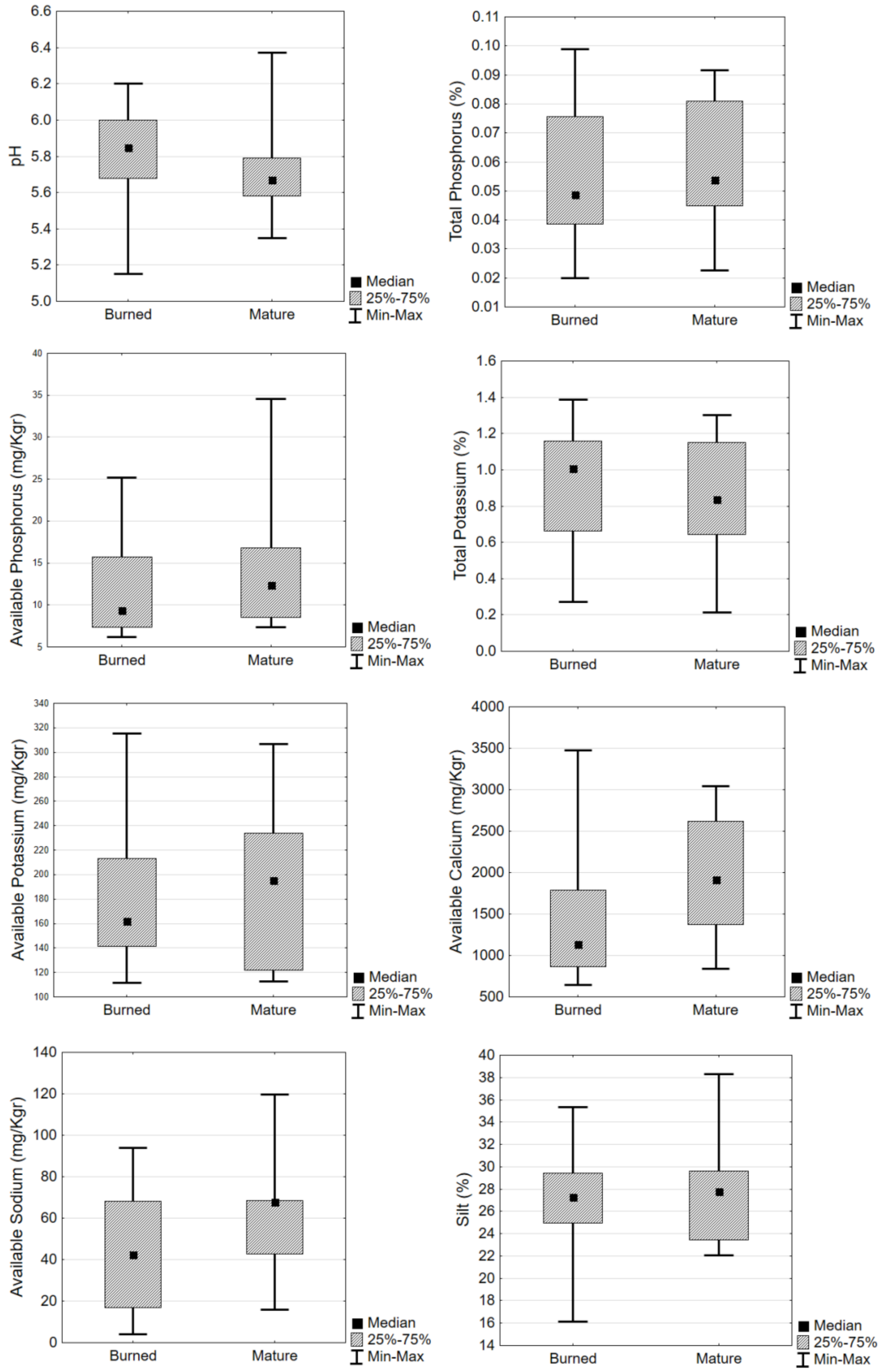

Figure A1. Boxplots on soil properties with no significant differences between burned and mature sites of the MQ1 community.

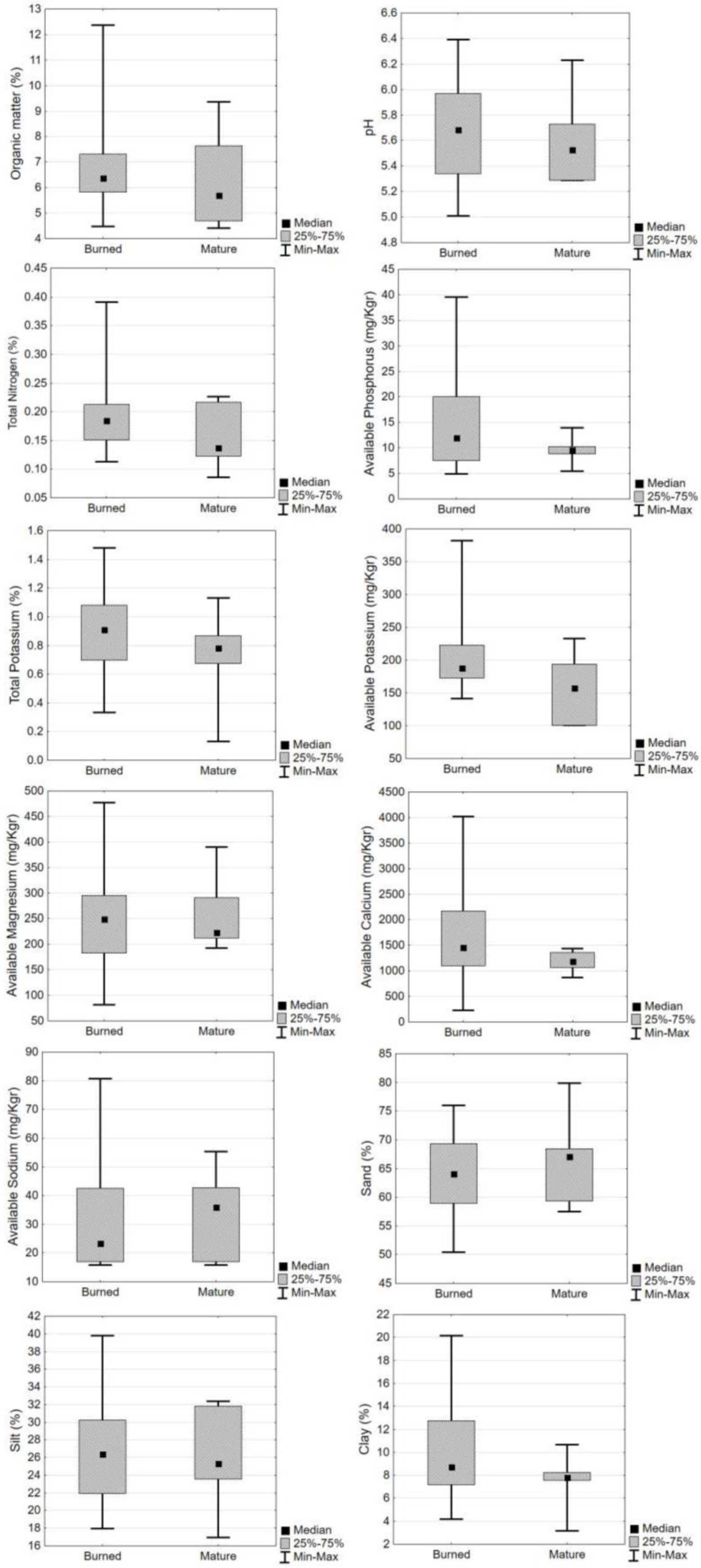

Figure A2. Boxplots on soil properties with no significant differences between burned and mature sites of the MQ2 community.

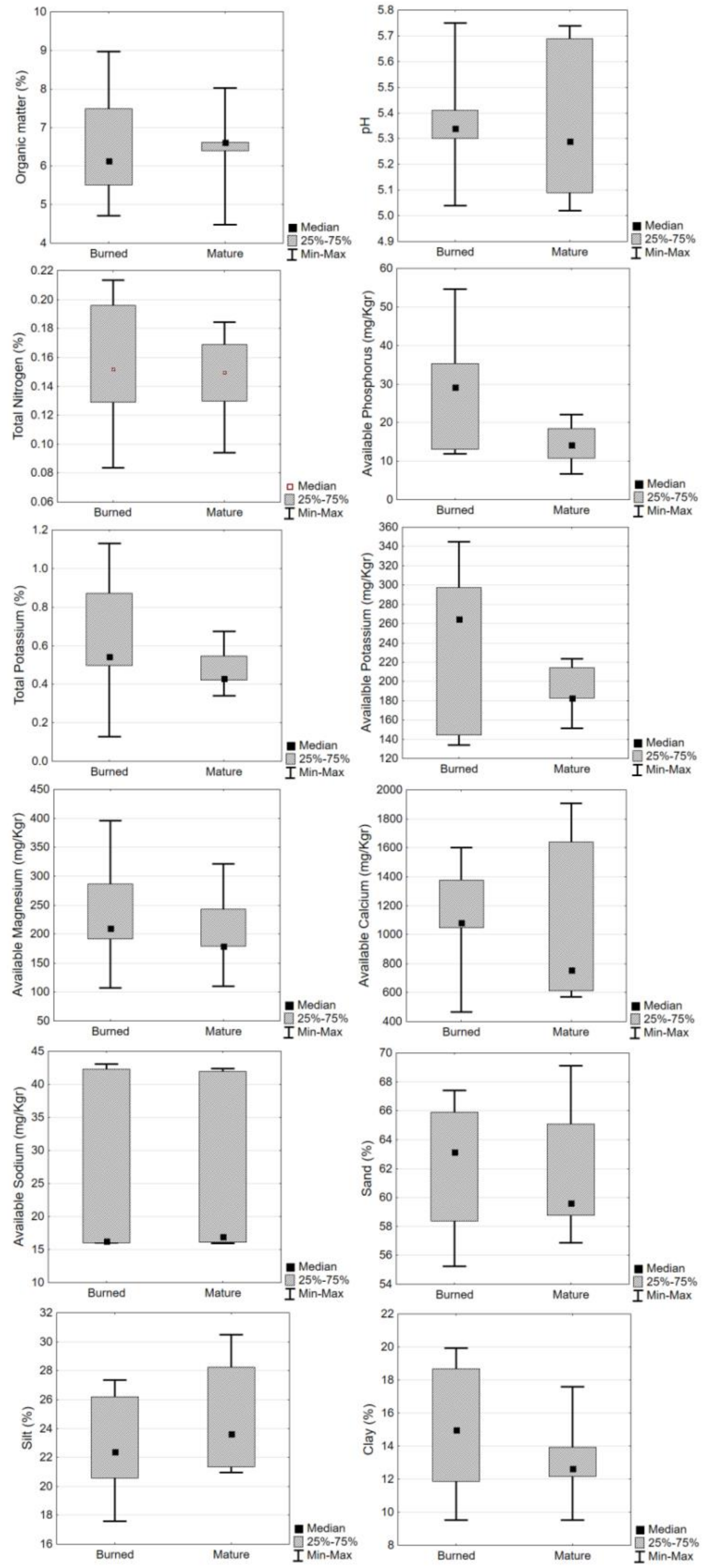

Figure A3. Boxplots on soil properties with no significant differences between burned and mature sites of the FC1 community.

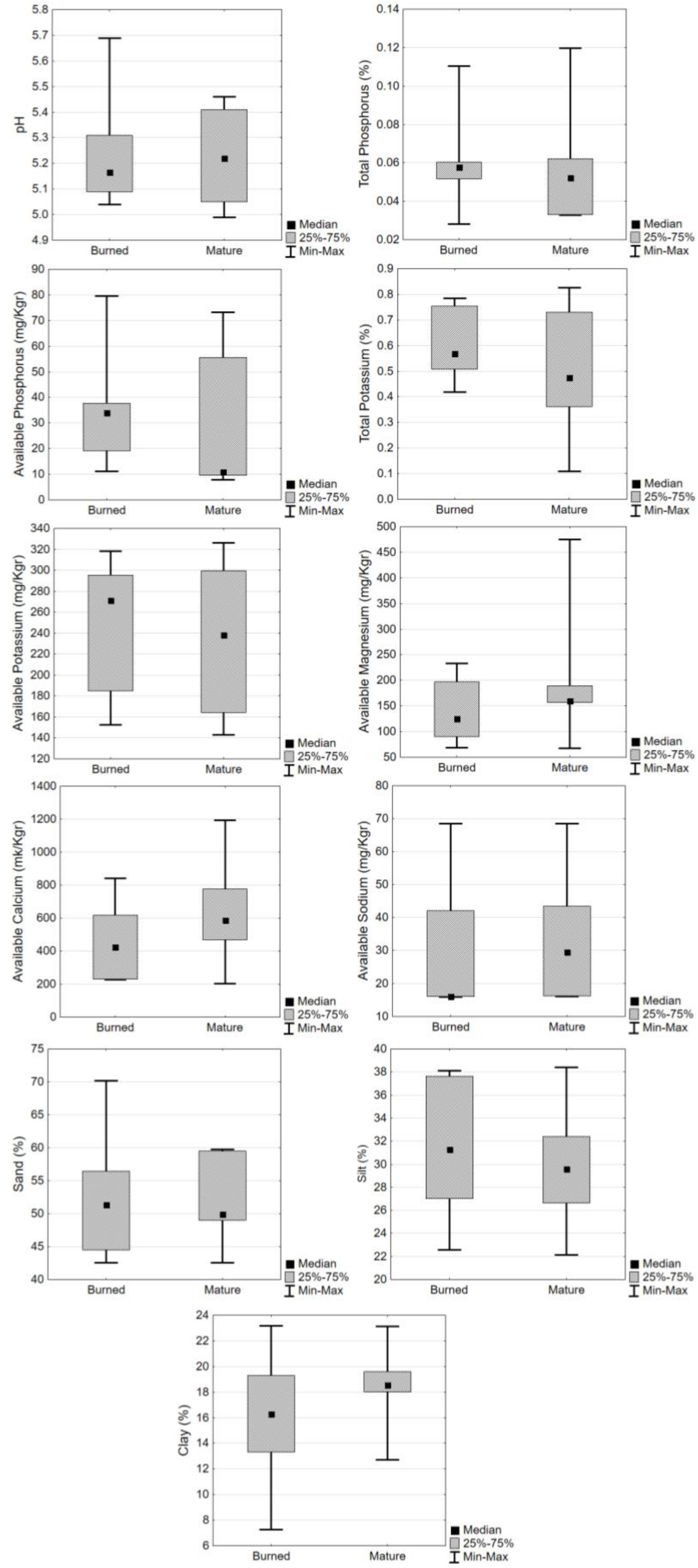

Figure A4. Boxplots on soil properties with no significant differences between burned and mature sites of the FC2 community.

References

1. Dymov, A.A.; Startsev, V.V.; Yakovleva, E.V.; Dubrovskiy, Y.A.; Milanovsky, E.Y.; Severgina, D.A.; Panov, A.V.; Prokushkin, A.S. Fire-Induced Alterations of Soil Properties in Albic Podzols Developed under Pine Forests (Middle Taiga, Krasnoyarsky Kray). *Fire* **2023**, *6*, 67. [CrossRef]
2. Hrenović, J.; Kisić, I.; Delač, D.; Durn, G.; Bogunović, I.; Mikulec, M.; Pereira, P. Short-Term Effects of Experimental Fire on Physicochemical and Microbial Properties of a Mediterranean Cambisol. *Fire* **2023**, *6*, 155. [CrossRef]
3. Samburova, V.; Schneider, E.; Rüger, C.P.; Inouye, S.; Sion, B.; Axelrod, K.; Bahdanovich, P.; Friederici, L.; Raeofy, Y.; Berli, M.; et al. Modification of Soil Hydroscopic and Chemical Properties Caused by Four Recent California, USA Megafires. *Fire* **2023**, *6*, 186. [CrossRef]
4. Sion, B.; Samburova, V.; Berli, M.; Baish, C.; Bustarde, J.; Houseman, S. Assessment of the Effects of the 2021 Caldor Megafire on Soil Physical Properties, Eastern Sierra Nevada, USA. *Fire* **2023**, *6*, 66. [CrossRef]
5. DeBano, L.F.; Neary, D.G.; Ffolliot, P.F. *Fire's Effects on Ecosystems*; John Willey & Sons: New York, NY, USA, 1998.
6. Giovannini, G.; Lucchesi, S.; Giachetti, M. Benefitial and detrimental effects of heating on soil quality. In *Fire in Ecosystem Dynamics: Mediterranean and Northern Perspectives*; Goldamer, J.G., Jenkins, M.J., Eds.; SPB Academic Publishing: The Hague, The Netherlands, 1990; pp. 95–102.
7. Giovannini, G.; Lucchesi, S. Effect of fire on soil physico-chemical characteristics and errosion dynamics. In *Fire in Mediterranean ecosystems*; Trabaud, L., Prodon, R., Eds.; ECSC-EEC-EAEC: Brussels, Belgium, 1993; pp. 403–411.
8. Giovannini, G.; Lucchesi, S.; Giachetti, M. Efects of heating on some chemical parameters related to soil fertility and plant growth. *Soil Sci.* **1990**, *149*, 344–350. [CrossRef]
9. Raison, R.J.; Khanna, P.K.; Woods, P.V. Mechanisms of element transfer to the atmosphere during vegetation fires. *Can. J. For. Res.* **1985**, *15*, 132–140. [CrossRef]
10. Raison, R.J.; Khanna, P.K.; Woods, P.V. Transfer of elements to the atmosphere during low-intensity prescribed fires in three Australian subalpine eucalypt forests. *Can. J. For. Res.* **1985**, *15*, 657–664. [CrossRef]
11. Certini, G. Effects of fire on properties of forest soils: A review. *Oecologia* **2005**, *143*, 1–10. [CrossRef]
12. Carter, M.C.; Foster, C.D. Prescribed burning and productivity in southern pine forests: A review. *For. Ecol. Manag.* **2004**, *191*, 93–109. [CrossRef]
13. Neary, D.G.; Klopatek, C.C.; DeBano, L.F.; Ffolliott, P.F. Fire effects on belowground sustainability: A review and synthesis. *For. Ecol. Manag.* **1999**, *122*, 51–71. [CrossRef]
14. Covington, W.W.; Sacket, S.S. Soil mineral nitrogen changes following prescribed burning in ponderosa pine. *For. Ecol. Manag.* **1992**, *54*, 175–191. [CrossRef]
15. Christensen, N.L. The effects of fire on physical and chemical properties of soils in Mediterranean-climate shrublands. In *The Role of Fire in Mediterranean-Type Ecosystems*; Moreno, J.M., Oechel, W.C., Eds.; Ecological studies 107; Springer-Verlag Inc.: New York, NY, USA, 1994; pp. 79–95.
16. Fisher, R.F.; Binkley, D. *Ecology and Management of Forest Soils*; John Willwy & Sons: New York, NY, USA, 2000.
17. Raison, R.J.; O'Connell, A.M.; Khanna, P.K.; Keith, H. Effects of repeated fires on nitrogen and phosphorus budgets and cycling processes in forest ecosystems. In *Fire in Mediterranean Ecosystems*; Trabaud, L., Prodon, R., Eds.; ECSC-EEC-EAEC: Brussels, Belgium, 1993; pp. 347–363.
18. Carballas, M.; Acea, M.J.; Cabaneiro, A.; Trasar, C.; Villar, M.C.; Diaz-Ravina, M.; Fernandez, I.; Prieto, A.; Saa, A.; Vazquez, F.J.; et al. Organic matter, nitrogen, phosphorus and microbial populations evolution in forest humiferous acid soils after wildfires. In *Fire in Mediterranean Ecosystems*; Trabaud, L., Prodon, R., Eds.; ECSC-EEC-EAEC: Brussels, Belgium, 1993; pp. 379–385.
19. Ferreira, A.J.D.; Coelho, C.O.A.; Boulet, A.K.; Lopes, F.P. Temporal patterns of solute loss following wildfires in Central Portugal. *Int. J. Wildland Fire* **2005**, *14*, 401–412. [CrossRef]
20. Belillas, C.M.; Feller, M.C. Relationships between fire severity and atmospheric and leaching nutrient losses in British Columbia's coastal Western Hemlock zone forests. *Int. J. Wildland Fire* **1998**, *8*, 87–101. [CrossRef]
21. Gimeno-Garcia, E.; Andreu, V.; Rubio, J.L. Changes in organic matter, nitrogen, phosphorus and cations in soil as a result of fire and water erosion in a mediterranean landscape. *Eur. J. Soil Sci.* **2000**, *51*, 201–210. [CrossRef]
22. Diaz-Fierros, F.; Benito, E.; Vega, J.A.; Castelao, A.; Soto, B.; Perez, R.; Taboada, T. Solute loss and soil erosion in burnt soil from Galcia (NW Spain). In *Fire in Ecosystem Dynamics: Mediterranean and Northern Perspectives*; Goldamer, J.G., Jenkins, M.J., Eds.; SPB Academic Publishing: The Hague, The Netherlands, 1990; pp. 103–116.
23. Lasanta, T.; Cerda, A. Long-term erosional responses after fire in the Central Spanish Pyrenees—2. Solute release. *Catena* **2005**, *60*, 81–100. [CrossRef]
24. DeBano, L.F. The effect of hydrophobic substances on water movement in soil during infiltration. *Soil Sci. Soc. Am. Proc.* **1971**, *35*, 340–343. [CrossRef]
25. DeBano, L.F. The role of fire and soil heating on water repellency in wildland environments: A review. *J. Hydrol.* **2000**, *231–232*, 195–206. [CrossRef]
26. DeBano, L.F. Water repellency in soils: A historical overview. *J. Hydrol.* **2000**, *231*, 4–32. [CrossRef]
27. Christensen, N.L. Fire and the Nitrogen cycle in California chaparral. *Science* **1973**, *181*, 66–68. [CrossRef]
28. Christensen, N.L.; Muller, C.H. Effects of fire on factors controlling plant growth in *Adenostoma* chaparal. *Ecol. Monogr.* **1975**, *45*, 29–55. [CrossRef]

29. DeBano, L.F.; Eberlein, G.E.; Dumm, P.H. Effects of burning on Chaparral soils: Soil Nitrogen. *Soil Sci. Soc. Am. J.* **1979**, *43*, 504–509. [CrossRef]
30. Iglesias, T.; Cala, V.; Gonzalez, J. Mineralogical and chemical modifications in soils affected by a forests fire in the Mediterranean area. *Sci. Total Environ.* **1997**, *204*, 89–96. [CrossRef]
31. Kutiel, P.; Naveh, Z.; Kutiel, H.T. The effect of wildfire on soil nutrients and vegetation in an Alepo pine forest on Mount Carmel Israel. In *Fire in Ecosystem Dynamics: Mediterranean and Northern Perspectives*; Goldamer, J.G., Jenkins, M.J., Eds.; SPB Academic Publishing: The Hague, The Netherlands, 1990; pp. 85–94.
32. Chandler, C.; Cheney, P.; Thomas, P.; Trabaud, L.; Williams, D. *Fire in Forestry. Volume I. Forest Fire Behavior and Effects*; John Wiley & Sons: New York, NY, USA, 1983.
33. Giovannini, G.; Lucchesi, S.; Giachetti, M. Effect of Heating on Some Physical and Chemical-Parameters Related to Soil Aggregation and Erodibility. *Soil Sci.* **1988**, *146*, 255–261. [CrossRef]
34. Giovannini, G.; Lucchesi, S. Modifications induced in soil physico-chemical parameters by experimental fires at different intensities. *Soil Sci.* **1997**, *162*, 479–486. [CrossRef]
35. Navidi, M.; Lucas-Borja, M.E.; Plaza-Álvarez, P.A.; Carra, B.G.; Parhizkar, M.; Zema, D.A. Mid-Term Changes in Soil Properties after Wildfire, Straw Mulching and Salvage Logging in Pinus halepensis Mill. Forests. *Fire* **2022**, *5*, 158. [CrossRef]
36. Xofis, P.; Buckley, P.G.; Takos, I.; Mitchley, J. Long Term Post-Fire Vegetation Dynamics in North-East Mediterranean Ecosystems. The Case of Mount Athos Greece. *Fire* **2021**, *4*, 92. [CrossRef]
37. Rackham, O. The Holly Mountain. *Plant Talk* **2002**, *27*, 19–23.
38. Makrogiannis, T.; Flokas, A. The analysis of climatic parameters in the major area of Agion Oros. In *Mount Athos. Nature-Worship-Art*; Dafis, S., Tsigaridas, E.N., Fountoulis, I.M., Eds.; Shape & Art: Thessaloniki, Greece, 2001; Volume 1, pp. 83–92.
39. Mueller-Dombois, D.; Ellenberg, H. *Aims and Methods of Vegetation Ecology*; John Willey and Sons: New York, NY, USA, 1974.
40. Westhoff, V.; van der Maarel, E. The Braun-Blanquet approach. In *Classification of Plant Communities*; Whittaker, R.H., Ed.; Dr. W. Junk b.v. Publishers: The Hague, The Netherlands, 1978; pp. 287–399.
41. Allen, S.E. *Chemical Analysis of Ecological Materials*; Blackwell Scientific Publication: Oxford, UK, 1989.
42. ADAS. *The Analysis of Agricultural Materials*; Ministry of Agriculture Fisheries and Food: London, UK, 1986.
43. McRae, S.G. *Practical Pedology-Studying Soils in the Field*; Ellis Horwood Ltd.: Chichester, UK, 1988.
44. Hill, M.O. *TWINSPAN-a Fortran Program for Arranging Multivariate Data in an Ordered Two Way Table by Classification of the Individuals and the Atributes*; Cornell University, Department of Ecology and Systematics: Ithaca, NY, USA, 1979.
45. Hill, M.O.; Bunce, R.G.H.; Shaw, M.W. Indicator Species Analysis, a divisive polythetic method of classification, and its application to a survey of native pinewoods in Scotland. *J. Ecol.* **1975**, *63*, 597–613. [CrossRef]
46. Gauch, H.G.; Whittaker, R.H. Hierarchical classification of community data. *J. Ecol.* **1981**, *69*, 537–557. [CrossRef]
47. Kutiel, P.; Inbar, M. Fire impact on soil nutrients and soil erosion in a Mediterranean pine forest plantation. *Catena* **1993**, *20*, 129–139. [CrossRef]
48. Kennard, D.K.; Gholz, H.L. Effects of high- and low-intensity fires on soil properties and plant growth in a Bolivian dry forest. *Plant Soil* **2001**, *234*, 119–129. [CrossRef]
49. Giovannini, G.; Lucchesi, S.; Giachetti, M. The Natural Evolution of a Burned Soil—A 3-Year Investigation. *Soil Sci.* **1987**, *143*, 220–226. [CrossRef]
50. Andreu, V.; Rubio, J.L.; Forteza, J.; Cerni, R. Postfire effects on suil properties and nutrient losses. *Int. J. Wildland Fire* **1996**, *6*, 53–58. [CrossRef]
51. Mesleard, F.; Lepart, J. Continuous basal sprouting from a lignotuber: *Arbutus unedo* L. and *Erica arborea* L., as woody mediterranean examples. *Oecologia* **1989**, *80*, 127–131. [CrossRef]
52. White, E.M.; Thompson, W.W.; Gartner, F.R. Heat effects on nutrient release from soils under ponderosa pine. *J. Range Manag.* **1973**, *26*, 22–24. [CrossRef]
53. Robichaud, P.R. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *J. Hydrol.* **2000**, *231–232*, 220–229. [CrossRef]
54. Soto, B.; Diaz-Fierros, F. Runoff and soil erosion from areas of burnt scrub: Comparison of experimental results with those predicted by the WEPP model. *Catena* **1998**, *31*, 257–270. [CrossRef]
55. Rubio, J.L.; Forteza, J.; Andreu, V.; Cerni, R. Soil profile characteristics influencing runoff and soil erosion after forest fire: A case study (Valencia, Spain). *Soil Technol.* **1997**, *11*, 67–78. [CrossRef]
56. Prosser, I.P.; Williams, L. The effect of wildfire on runoff and erosion in native Eucalyptus forest. *Hydrol. Process.* **1998**, *12*, 251–265. [CrossRef]
57. Cerda, A.; Imeson, A.C.; Calvo, A. Fire and aspect induced differences on the erodibility and hydrology of soils at La Costera Valencia, southeast Spain. *Catena* **1995**, *24*, 289–304. [CrossRef]
58. Inbar, M.; Tamir, M.; Wittenberg, L. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. *Geomorphology* **1998**, *24*, 17–33. [CrossRef]
59. Ulery, A.L.; Graham, R.C. Forest fire effects on soil color and texture. *Soil Sci. Soc. Am. J.* **1993**, *57*, 135–140. [CrossRef]
60. Moulopoulos, C. Forestry in Mount Athos. In *Athoniki Politeia (in Greeks)*; Aristotelean University of Thessaloniki: Thessaloniki, Greece, 1963; pp. 679–706.

61. Wuthrich, C.; Schaub, D.; Weber, M.; Marxer, P.; Conedera, M. Soil respiration and soil microbial biomass after fire in a sweet chestnut forest in southern Switzerland. *Catena* **2002**, *48*, 201–215. [CrossRef]
62. Providoli, I.; Elsenbeer, H.; Conedera, M. Post-fire management and splash erosion in a chestnut coppice in southern Switzerland. *For. Ecol. Manag.* **2002**, *162*, 219–229. [CrossRef]
63. Cheney, N.P. Fire Behaviour. In *Fire and the Australian Biota*; Gill, A.M., Groves, R.H., Noble, I.R., Eds.; Australian Academy of Science: Canberra, Australia, 1981; pp. 151–175.
64. Fox, M.D.; Fox, B.J. The role of fire in the scleromorphic forests and shrublands of eastern Australia. In *The Role of Fire in Ecological Systems*; Trabaud, L., Ed.; SPB Academic Publishing: Tha Hague, The Netherlands, 1987; pp. 23–48.
65. McLauchlan, K.K.; Higuera, P.E.; Miesel, J.; Rogers, B.M.; Schweitzer, J.; Shuman, J.K.; Tepley, A.J.; Varner, J.M.; Veblen, T.T.; Adalsteinsson, S.A.; et al. Fire as a Fundamental Ecological Process: Research Advances and Frontiers. *J. Ecol.* **2020**, *108*, 2047–2069. [CrossRef]
66. Xofis, P.; Konstantinidis, P.; Papadopoulos, I.; Tsiourlis, G. Integrating Remote Sensing Methods and Fire Simulation Models to Estimate Fire Hazard in a South-East Mediterranean Protected Area. *Fire* **2020**, *3*, 31. [CrossRef]