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A Local-Scale, Post-Fire Assessment in a Double-Burned Area: A Case Study from Peloponnisos, Greece

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Abstract: In the summer of 2021, Greece experienced significant forest fires and mega-fires across multiple regions, leading to human casualties and damage to the natural environment, infrastructure, livestock, and agriculture. The current study aims to assess the ecosystem condition in terms of the natural regeneration and soil conditions of an area burnt by a forest fire (2021), specifically in the Ancient Olympia region situated in West Peloponnese (Ilia Prefecture), Greece. A standardized field sampling methodology was applied to record natural regeneration at chosen sites where a forest fire had also previously occurred (in 2007), resulting in the natural re-growth of the *Pinus halepensis* forest. Furthermore, an analysis was conducted on the geochemical, mineralogical, and sedimentological properties of soils obtained from this location. The findings of the research demonstrate the decline in the established natural regeneration of the *Pinus halepensis* forest and the overall tree layer. Species characteristic of post-fire ecological succession were observed in the shrub and herb layers, displaying varying coverage. The examination of soil mineralogy, sedimentology, and geochemistry indicated that the soil characteristics in the area are conducive to either natural or artificial regeneration. Ultimately, recommendations for landscape rehabilitation strategies are provided to inform decision-making processes, considering future climate conditions.

Keywords: double-burnt forest; ecosystem restoration; mineralogy; natural capital; conservation management; post-forest-fire assessment; soil; geochemistry; sedimentology

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1. Introduction

Wildfires are a significant component of the environmental characteristics of the Mediterranean, as well as other ecosystems (e.g., [1–4]), impacting and molding vegetation and landscapes over time. Presently, forest fires are occurring more frequently than before, particularly in the Mediterranean region, leading to adverse effects on the environment and the destruction of properties, crops, infrastructure, and economic endeavors, often resulting in human casualties. An example of this is the summer of 2023, where within just a 12-day timeframe, 135,000 hectares were ravaged in four Mediterranean nations (Greece, Italy, Tunisia, Algeria), affecting over 120,000 individuals [5]. Furthermore, wildfires often occur in areas that have previously been burned within a 20-year span, posing challenges for natural forests and species like the Aleppo pine (*Pinus halepensis*), which struggle to regenerate despite their adaptation mechanisms to fire.

Additionally, forest fires have a significant impact on the ecosystem and lead to alterations in the soil properties [6,7]. In such occurrences, substantial amounts of thermal energy influence not only the biota above and below the ground but also the physical, chemical, and mineralogical attributes of soils [7,8]. While the particle size distribution remains constant, the elimination of the fine fraction via runoff and surface erosion results in soil coarsening [9,10]. The degradation of organic carbon initiates at approximately 200 °C, with complete oxidation of organic matter occurring around 460 °C [11]. Following fires, the soil pH rises due to the destruction of organic acids, whereas the electrical conductivity experiences a temporary elevation due to the release of ions post-combustion of organic matter [12,13]. Despite minimal changes in the mineralogical composition, there are indications of mineral modification with temperature within the upper 1–8 cm of soil depth [12,14–16]. For example, kaolinite, a common clay mineral, can be transformed after a fire due to dehydration [17], causing soil content composition changes. This affects the vegetation due to limited hydration and ion exchange disturbances; for example, in nitrogen, phosphorus, potassium, and micronutrient availability, which are limiting factors for plants recovery [18].

The year 2021 was marked as one of the most devastating regarding catastrophic fires, as relevant data reveal that this year witnessed more than double the number of large forest fires compared to the average from 2008 to 2020 in the European Union [19]. By the beginning of August 2021, the European Forest Fire Information System (EFFIS) had documented 1100 fires, which is 300 more than the yearly average [20]. In August 2021, a wildfire in the region of Ancient Olympia in the prefecture of Ilia, Greece, brought about significant alterations in the natural landscape and environment.

This research focuses on the Pelopio region within the Ancient Olympia Municipality, located in the Ilia prefecture of Western Peloponnese, Greece. The primary objectives of this study are to evaluate the capacity for natural regeneration in an area that has experienced two major wildfires in the past two decades (specifically, in 2007 and 2021). This assessment aims to explore the succession patterns observed in the region, where the natural regrowth of the *Pinus halepensis* forest occurred successfully between the two fire events. Through this, we want to assess if the regrowth of the *Pinus* forest after the 2007 fire is capable of undergoing natural regeneration once more. *Pinus halepensis* is a fire-adapted species, and in most cases, its natural regeneration in mature stands is secured after a forest fire [21–26]. However, the observation and investigation conducted in various Mediterranean regions have indicated that in certain circumstances, the natural recovery of *Pinus halepensis* may be impeded by specific constraining factors (e.g., steep terrain, excessive grazing), leading to unsuccessful outcomes [24,27,28]. *Pinus halepensis* is classified as an obligate seeder, with its natural forests typically requiring around 15 years to yield a substantial quantity of mature seeds [29]. Even-aged *Pinus halepensis* woodlands achieve reproductive maturity after 15–20 years, subject to varying ecological conditions and site characteristics [30,31]. Consequently, if wildfires reoccur at frequencies shorter than the mentioned timeframe, the absence of sufficient seed quantities for germination leads to a deficiency in post-fire recovery [27,32,33]. Furthermore, terrains with a slope inclination exceeding 50% may experience diminished post-fire regeneration [26]. Heightened slope angles pose challenges to pine regeneration, as seeds could potentially be washed away [24]. To facilitate the regeneration of P. halepensis in such scenarios, artificial interventions are deemed necessary [34].

Additionally, this study seeks to analyze the environmental conditions of the area by examining the sedimentological, mineralogical, and geochemical properties of selected soil samples.

The main goal is to provide evidence-based support to decision and policy making regarding landscape restoration and to transfer the study's findings to a wider area in Peloponnisos and the region of Western Greece, Municipality of Ancient Olympia, where it is possible that only artificial reforestation will support *Pinus halepensis* forest restoration.

2. Materials and Methods

2.1. Study Area

The study site (designated as a pilot sampling site for vegetation and soil), shown in Figure 1, is a region that has experienced two instances of burning due to the 2007 and 2021 forest fires, located within a regenerating forest of Aleppo pine (*Pinus halepensis*) that is about 15 years old, believed to have regenerated following the 2007 forest megafire. The prevailing orientation of the area is towards the east and northeast, with elevations varying between 200 and 290 m. The topography mainly comprises two principal slopes, one facing south and the other north, divided by a central ridge and a small watercourse. It is easily accessible through the local network of forest and agricultural roads. The slopes within the area range from gentle to extremely steep, exceeding 100%. Within the pilot sampling zone, the predominant slopes fall within the range of 15 to 30%, with notable areas having slopes surpassing 45%. To the west, the study site is bordered by farmland, while in the other directions, it is surrounded by woodlands, forests, and rural roads.

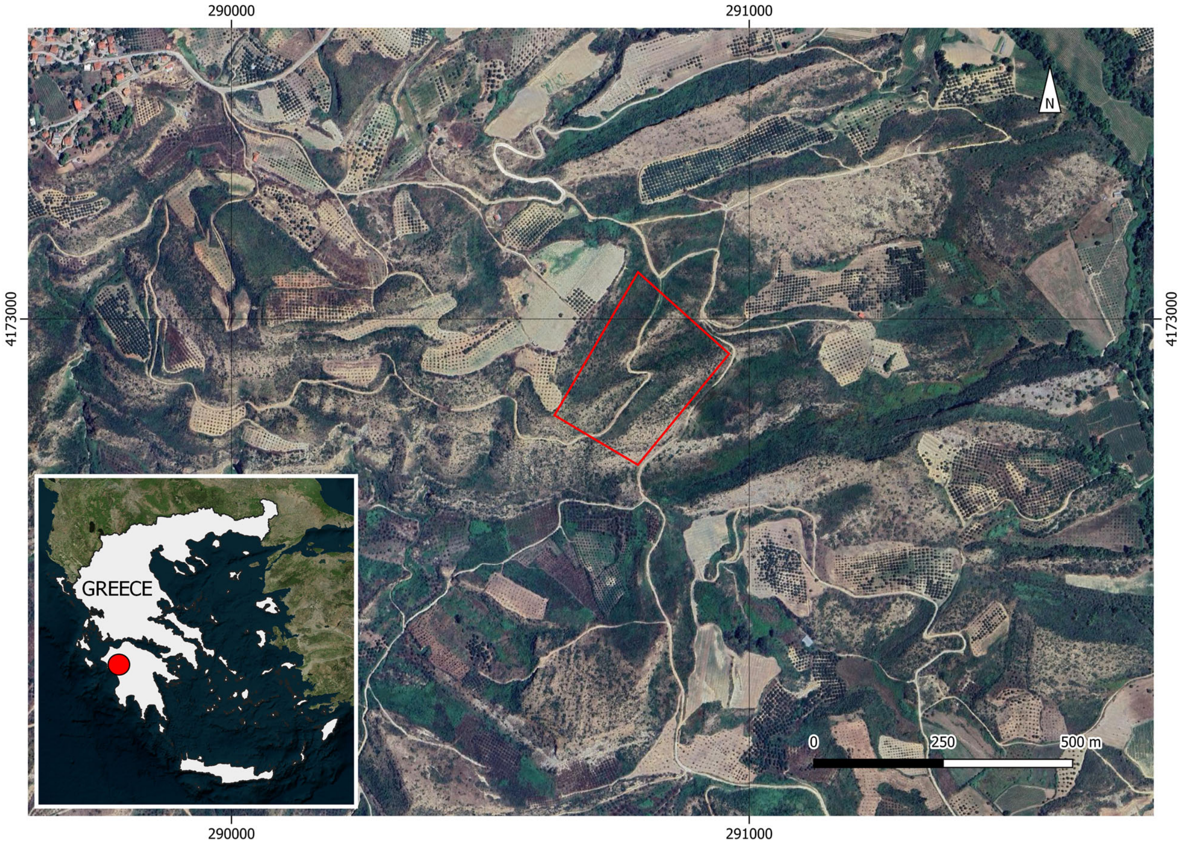

Figure 1. Map of the study (sampling) area, delineated by a red outline, situated within the Ancient Olympia Municipality in Western Peloponnisos, Greece (red dot) (EGSA87 Greek Geodetic Reference System).

From a geological perspective, the study area is characterized by the presence of clays, sands, and conglomerates, with the potential presence of gypsum layers (Figure 2). These deposits have a marine origin; thus, the presence of fossilized remains is possible.

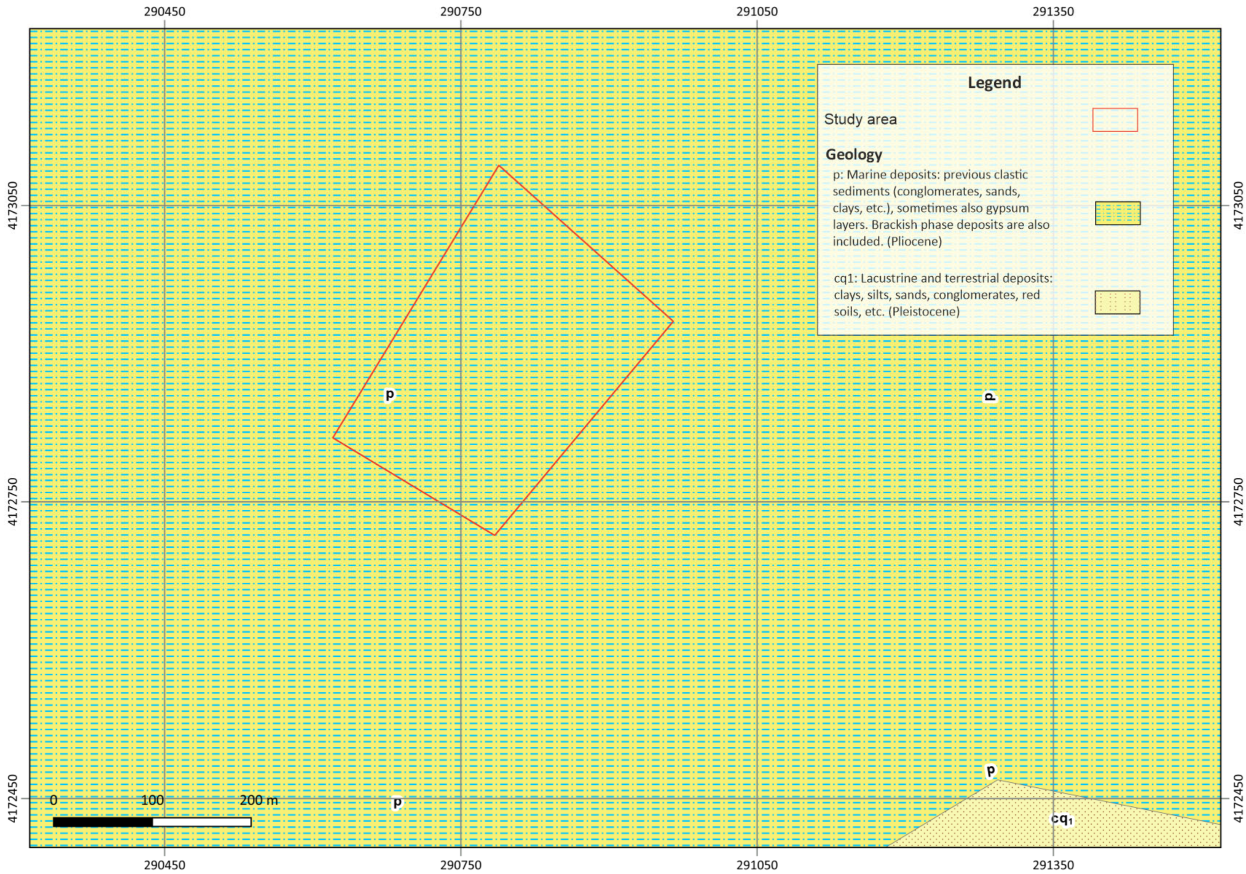

Figure 2. Geological map of the study (sampling) area (red outline) in the Ancient Olympia Municipality, Western Peloponnisos, Greece (EGSA87 Greek Geodetic Reference System).

2.2. Vegetation Survey

For the assessment and mapping of the regeneration rate in the study site, the methodology outlined in the project "Predicting the establishment of natural regeneration in burned Aleppo pine (*Pinus halepensis*) forests in the prefecture of Ilia" [35] was followed. The fieldwork for sampling regeneration utilized the methodology and recommended protocol established by the aforementioned project, based on references [4,24,36]. More precisely, 50 field protocols were conducted at each site by using a pattern of five circles (corresponding to sampling plots) having a radius of 2.5 m, each encompassing a cumulative area of 20 square meters. The circles were positioned at a distance of 15 m from one another, culminating in a collective outer area of 100 m^2 for all five circles (Figure 3). The filed sampling protocol, which was filled in at each sampling plot, included the following fields: plot number, coordinates (X, Y),elevation (m), slope (%) aspect, branches/trunks (%), rocks/stones (%), pine individuals, total vegetation cover (%), *Arbutus unedo* (% cover), *Pistacia lentiscus* (% cover), *Erica* spp. (% cover), *Quercus coccifera* (% cover), *Olea europaea* (% cover), *Phillyrea latifolia* (% cover), *Cercis siliquastrum* (% cover), *Cistus* sp. (% cover), *Arundo plinii* (% cover), *Asphodelus* sp. (number of individuals), herb layer (% cover), legumes (% cover), poaceae (% cover).

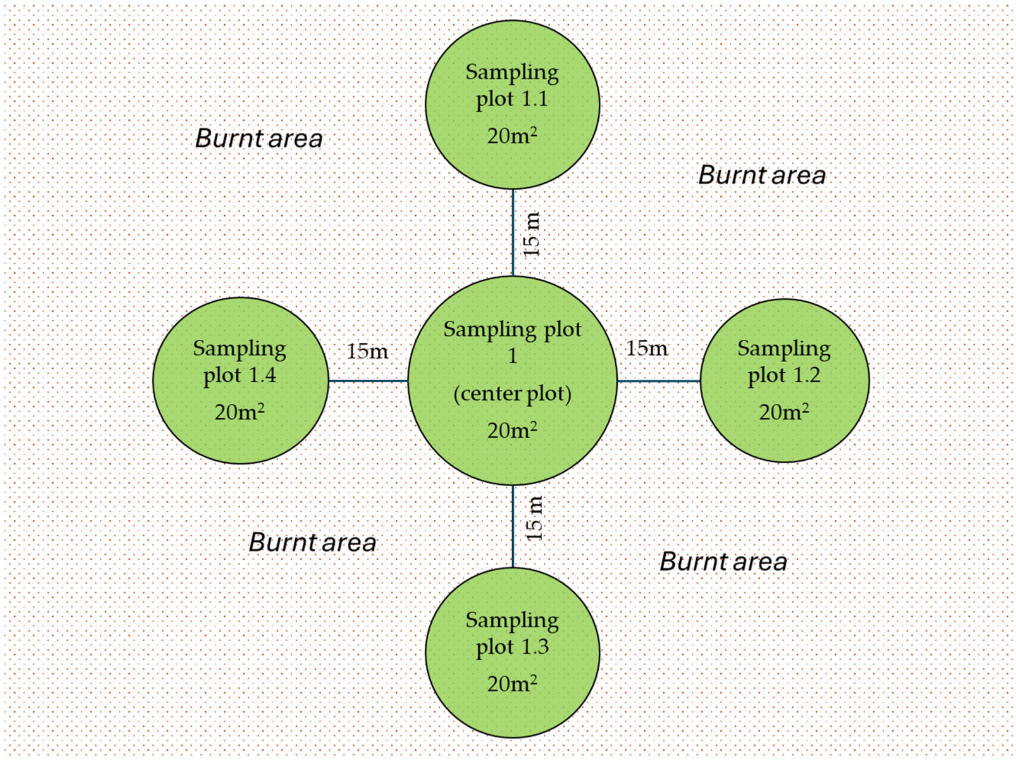

Figure 3. Schematic representation of the sampling plot arrangement for assessing regeneration at the study area. Adapted from and following Poirazidis et al. [35].

In order to obtain a rapid assessment rating of vegetation regeneration, we used experts' (authors) elicitation (see e.g., [37–40]) provided via a five-level Likert scale, i.e., "Very good", "Good", "Medium", "Bad", and "Very bad". The ratings were based on the findings at each sampling plot and the observed condition of the neighboring areas using classic photointerpetation techniques by comparing recent pre- and post-fire satellite imagery from the Google Earth Pro platform (images from 2021 and 2023, respectively) [41] to document changes and the current status of the vegetation cover and structure (i.e., the presence of small, medium, or high shrubs, bare soil, and fragmentation). This approach was selected to overcome the absence of *Pinus halepensis* regeneration, which would have led to a "No regeneration" mapping for the study area, considering the previously established forest. Through this, and by using geotagged photographs from the field surveys and photointerpetation of recent satellite imagery (GoogleEarth 2023), a thematic map was prepared depicting the regeneration rating (degree) of natural vegetation in the study area using the QGIS platform [42].

Field assessments were conducted on the 10th of April (initial reconnaissance survey of the broader region and overview of the magnitude of the fire impact), on the 2nd of August 2022 (field sampling, photographic documentation, vegetation regeneration mapping), and on the 10th of July 2023 (last visit for additional assessment and overview of natural regeneration two years after the fire). In total, ten sites and 50 sampling plots were assessed using the aforementioned method and protocol.

2.3. Soil Survey

The sampling was carried out in woodland and forest areas of the Pelopio region at the Ancient Olympia Municipality, part of the Ilia prefecture Western Peloponnese, Greece, in July 2023. For the procedure, 18 sampling sites (samples 1–18) were chosen along the area of interest, and one more sampling site was used as a reference. All the samples were extracted from the uppermost 10 cm of the soil horizon and well mixed and homogenized according to LUCAS topsoil survey methodology [43]. The coordinates of the sites were estimated using Maggelan Explorer XL G.P.S.

During the extraction procedure, all the sampling sites were pictured with a scale index of 20 cm. The amount of each soil sample was approximately 100 g. After the extraction, all the samples were sealed in zipped polybags, transported to the lab, and dried in the oven for 1 h at 72 °C. After the drying process, the samples were prepared for the geochemical and sedimentological analyses (Figure 4).

Figure 4. Prepared soil samples for the geochemical and sedimentological analyses.

For the sediment classification of the soil samples, a grain size analysis was carried out using Malvern Mastersizer 2000 Hydro. The percentage calculation of the sand, silt, and clay fractions resulted in the statistical and lithological description of the samples based on soil terminology. The results of the grain size analysis were plotted using ternary diagrams according to the USGS and ASTM-D2487 standard. The statistical parameters of the soil samples were calculated using GRADISTAT V.4 software [44].

The values of electrical conductivity and pH were estimated according to the standard methods of ISO 122565, 1997 and ISO 10390, 1997, respectively [45]. The solution for the analysis required 2 g of fine powdered soil samples diluted in a beaker with 50 mL of purified water. After 1 h of resting time with periodical stirring, the solution was analyzed using a portable multi-meter HACH HQ4300.

The geochemical analyses that were conducted in the soil samples included the determination of the total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and the X-ray fluorescence analysis [46]. After the homogenization, the suspension was transferred to an elemental Shimadzu TOC analyzer (TOC-VCSH) for measurement. A certain amount of the sample was inserted in a receptor full of the oxidative catalyst, Pt/Al_2O_3. Vaporization of water leads to the oxidation of the organic and inorganic carbon to H_2O and CO_2. The CO_2 was moved to the analyzer and was measured, calculating the concentration of total carbon (TC). The acidification of the sample with HCl acid caused dissolution of carbonate salts, transformed finally into CO_2. In this way, inorganic carbon (IC) was measured separately, and based on the difference between TC and IC, the TOC concentration was inferred. For the determination of TN, a small amount of the sample was led into an inert purified air stream through a quartz pyrolysis tube [17]. The total concentration of chemically bound nitrogen was converted into NO. The NO encountered O_3, contained in the gas stream, resulting in the production of metastable nitrogen dioxide (NO_2*). The signal of the light emission during the decay of NO_2* was measured and was equivalent to the TN concentration.

The determination of the total phosphorus values (TP) was performed according to Standard Methods APHA (2005) using a multi-meter HACH HQ4300.

A geochemical analysis of the soil samples was carried out using an S1 Titan Bruker Handheld XRF Analyzer. An amount of 0.5–1 g of fine powdered soil sample was put under pressure to make pressed powder pellets. Afterwards, these pellets were measured at a range of 10–50 kV and 10–200 μA using a rhodium tube with a 30 s exposure time.

For the preparation of the mineralogical analysis, the bulk soil samples were placed in an oven at 50 °C for 1 h to remove any absorbed moisture and were subsequently sieved to a size of less than 10 μm.

The mineralogical phase of each sample was determined using X-Ray diffraction (XRD) using a Bruker D8 Advance XRD diffractometer with CuK_{α} radiation (λ = 1.54 Å) and a nickel filter at a scanning speed of 2°/min. The measurements were acquired between the angle range of 2θ, 3–70°. Lastly, using Topas v.3 software, the phase identification as well as the semi-quantitative analysis were achieved.

3. Results

3.1. Regeneration of Natural Vegetation

The primary findings indicate the absence of pine regeneration within the specified area, characterized by the lack of survival among existing trees from prior nature and the absence of newly recorded pine seedlings. The landscape predominantly features standing, charred specimens and clusters of *Pinus halepensis*, some of which exhibit exposed cones. Notably, no viable tree layer of any species is currently recorded.

In the shrub layer, *Cistus* spp. has the highest cover, followed by evergreen and sclerophyllous species (mainly *Phillyrea latifolia* and *Olea europaea,* followed by *Pistacia lentiscus*, *Quercus coccifera* and *Spartium junceum*). The presence and cover of *Cistus* spp., which is well adapted to fire species and post-fire succession, contribute significantly to soil retention and erosion control, alongside larger shrubs of lower cover. Regeneration of *Cercis siliquastrum* and *Arbutus unedo* is also found throughout the study area; however, it is scattered. Other typical species of the pre-fire vegetation are also present and frequently recorded, i.e., *Asparagus acutifolious*, *Anthyllis hermanniae*, and *Hippocrepis emerus* subsp. *emeroides*. In general, (and as expected), evergreen sclerophyllous species regenerate and grow well, although their cover is relatively low, two years after the fire.

In the herb layer, the most frequently recorded species are *Arundo plinii*, *Pteridium aquilinum*, *Smilax aspera* (in herbaceous form or slightly climbing on burnt individuals of *Pinus halepensis* and sclerophyllous shrubs), *Avena barbata*, *Dorycnium* sp. *Lotus* sp., and *Trifolium* sp. The cover of legumes is limited to an area cover of 0 to 15%.

Mapping the Degree of Regeneration of Natural Vegetation Units

The mapping and assessment of the regeneration level indicate that the research area demonstrates an insufficient regeneration of the *Pinus halepensis* forest, as anticipated, along with a spectrum of natural vegetation regeneration ranging from "Very good" to "Very bad", predominantly encompassing "Medium" to "Very bad" zones. The mapping of natural vegetation regeneration level corresponds not to *Pinus halepensis* regeneration (which is absent), but to the overall vegetation regeneration in the study area and as depicted in Figure 5. Representative sampling results (the center plot of each site) with all documented variables, are presented in Table 1, as well as in Figure 6, highlighting the current condition of the study area.

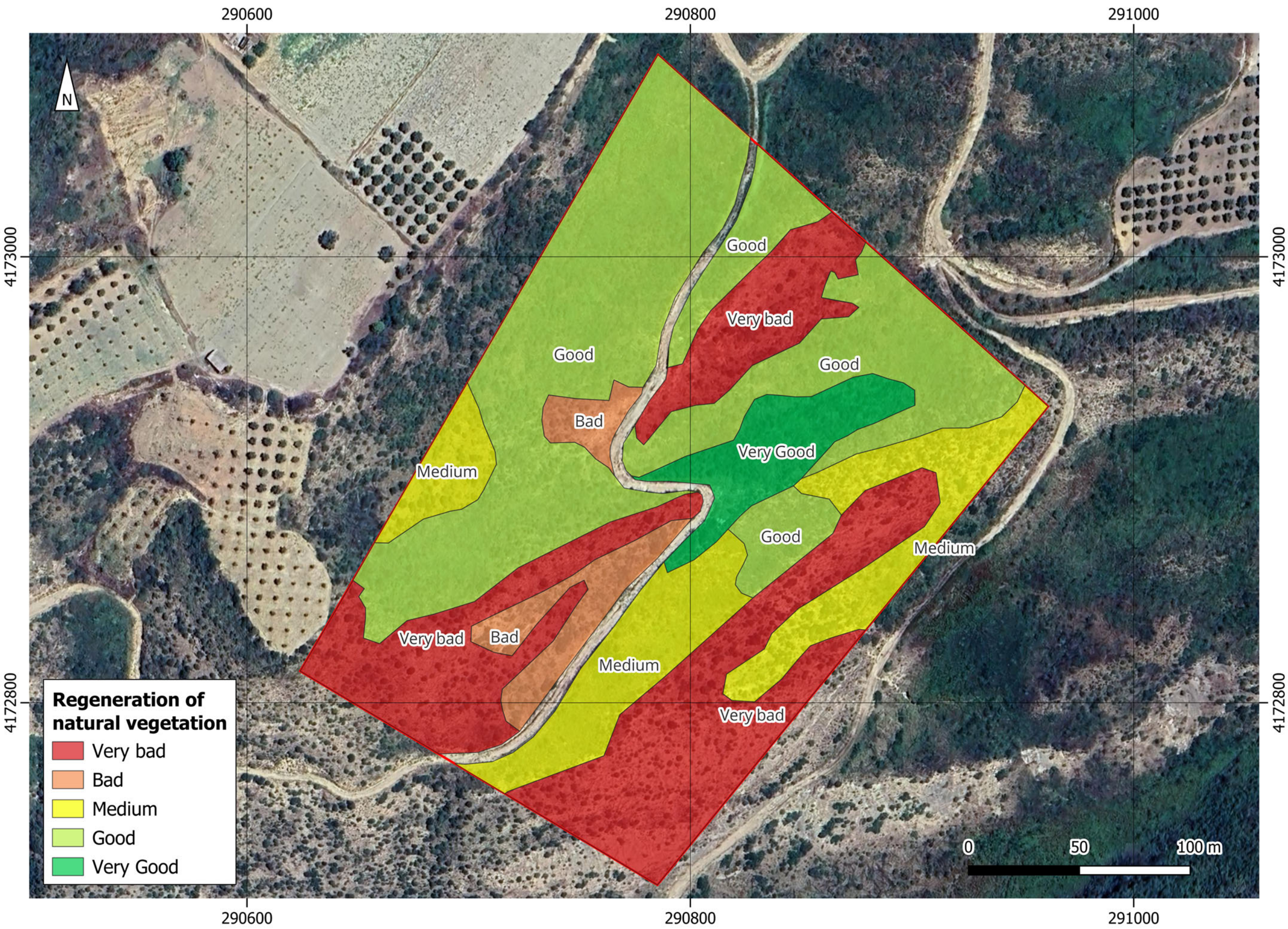

Figure 5. Map showing the degree of regeneration of natural vegetation units in the study area (red outline) (EGSA87 Greek Geodetic Reference System).

Table 1. Field survey findings at the ten center plots of the sampling sites in the study area.

Plot number	X (GGRS 87)	Y(GGRS 87)	Elevation (m)	Slope (%)	Aspect	% Branches/Trunks	% Rocks/Stones	Pine Individuals	Total Vegetation Cover (%)	*Arbutus unedo* (% Cover)	*Pistacia lentiscus* (% Cover)	*Erica* sp. (% Cover)	*Quercus coccifera* (% Cover)	*Olea europaea* (% Cover)	*Phillyrea latifolia* (% Cover)	*Cercis siliquastrum* (% Cover)	*Cistus* sp. (% Cover)	*Arundo plinii* (% Cover)	*Asphodelus* sp. (Number of Individuals)	Herb Layer (% Cover)	Legumes (% Cover)	Poaceae (% Cover)
1	290809	4173018	235	10%	SE	15	10	0	100%	15	0	0	0	0	2	1	0	85	0	90	5	85
2	290774	4172965	237	15%	E	12	5	0	70%	20	0	0	0	0	1	0	2	0	0	50	5	45
3	290761	4172893	245	45%	NE	5	5	0	70%	0	10	0	1	10	0	0	1	0	0	55	2	40
4	290787	4172877	245	35%	SE	7	15	0	55%	0	0	0	0	5	1	0	5	0	0	40	15	25
5	290762	4172845	248	30%	E	17	5	0	70%	0	0	0	0	1	30	0	1	45	0	40	5	35
6	290740	4172818	250	25%	E	21	5	0	70%	0	0	0	0	2	1	0	30	0	0	40	10	30
7	290732	4172803	250	30%	E	11	20	0	55%	2	0	0	0	5	10	0	20	0	0	35	15	20
8	290715	4172786	250	20%	SE	21	2	0	70%	5	0	0	0	5	5	0	15	2	0	55	10	20
9	290706	4172769	250	15%	S	17	5	0	75%	0	0	0	0	5	5	0	5	45	0	60	5	55
10	290706	4172764	245	70%	S	25	5	0	90%	1	0	0	0	5	5	1	5	30	0	75	10	70

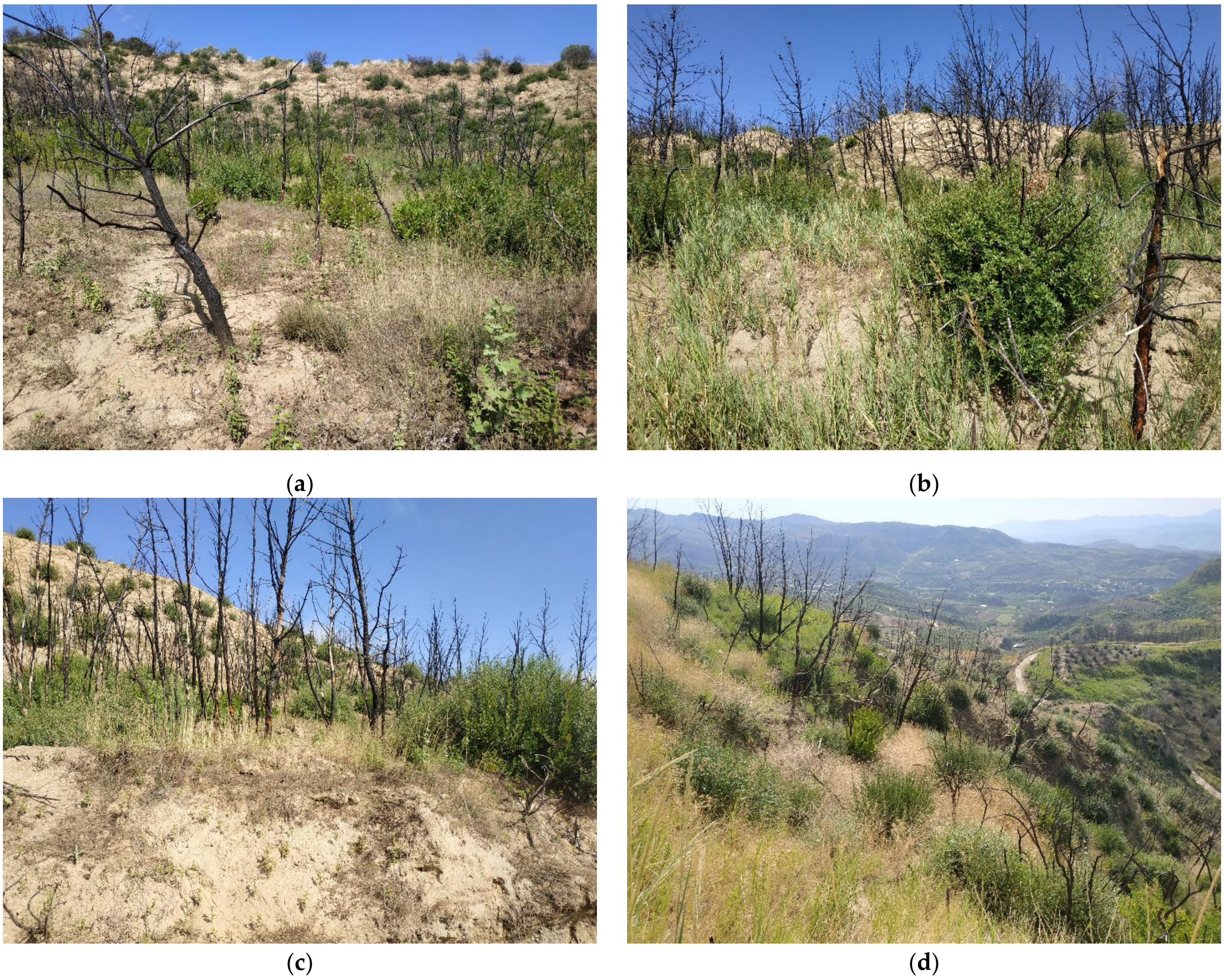

Figure 6. Representative images from the study area, (a) plot site 2, (b) plot site 5, (c) plot site 8, (d) plot site 10.

3.2. Soil Analysis

3.2.1. Sedimentological Characteristics

According to the results of the sedimentological analyses, the minority of the soil samples are classified as sandy loam and silty clay loam, while the majority of them being classified as loam and silt loam. The fractions of sand, silt, and clay were plotted in a ternary diagram according to the USGS and ASTM-D2487 standard. They displayed little variation of the grain size among the soil samples (Figure 7). The sand percentages ranged from 14.76% to 71.11%, with an average of 35.01%, with higher values at the southern section of the region. The concentrations of the silt fraction ranged from 21.68% to 62.34%, with an average of 44.96%, noting a normal distribution in the area. The clay percentages ranged from 4.39% to 43.43%, with an average of 20.63%, with higher concentrations recorded at the northern section of the area.

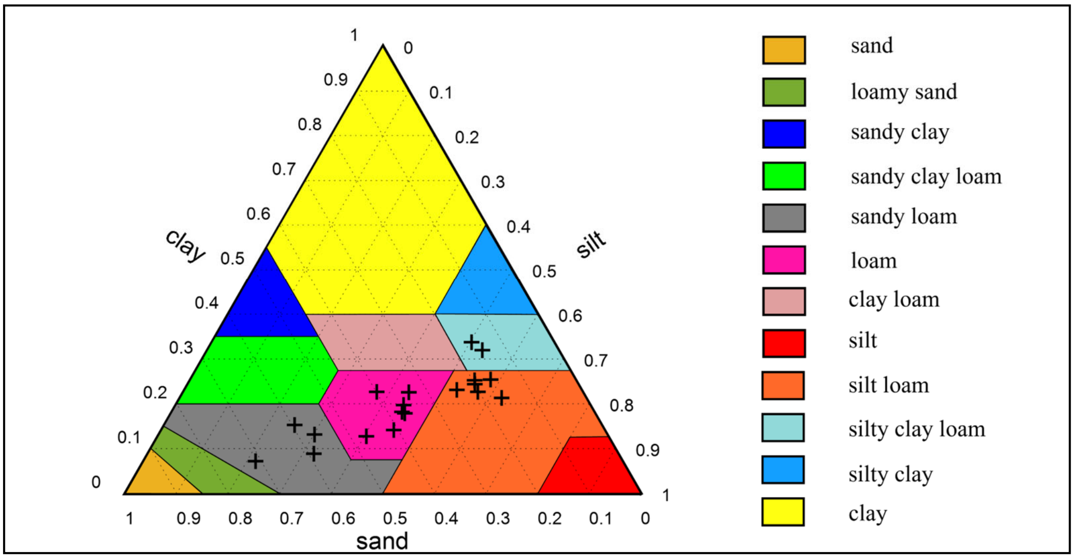

Figure 7. Sediment classification of the soil samples (+: indicates a soil sample).

3.2.2. Mineralogy of Soils

In all the studied samples, SiO_2 minerals (especially quartz), carbonates (mainly calcite), feldspars, and clay minerals were identified in various ratios. Specifically, the values of quartz ranged between 38 and 57%, with an average of 48%. Calcite ranged from 2 to 25%, with an average value of 13%, while the values of the feldspar group ranged from 7 to 26%, with an average of 4%. Clay minerals represent the final mineralogical group, with values ranging from 4 to 43%, with an average of 21%. In Figure 8, the spatial distribution and composition (%) of the samples are depicted.

All the studied samples contained high concentrations of quartz, indicating no correlation between the material type and its spatial distribution (Figure 8b). The calcite concentrations showed an increasing pattern in the southern part of the studied area, contrary to the northern part, where concentrations were significantly low. The only exception was site R, at the northernmost sampling area, which was more enriched in quartz and clay minerals (Figure 8a,b).

From the feldspars group, albite and oligoclase were the dominant minerals, whereas anorthite was observed only in the central part of the area and particularly in sites 4, 6, and 7 (Figure 8c–e). The presence of albite showed no correlation between the material's composition and its spatial distribution, as the values fluctuated around 12% (Figure 8c). On the other hand, the oligoclase values tended to be lower in the eastern part of the studied area, although the values did not deviate greatly from the average concentration of 6% (Figure 8d). The westernmost site (site 7) had the lowest concentration of anorthite (3%) compared to sites 4 and 6, which had concentrations of 19% and 12%, respectively (Figure 8e).

Regarding the clay minerals, montmorillonite (smectite), kaolinite, and illite were identified in the studied area and represented the secondary minerals (Figure 8f–h). In particular, the northern and northeastern part of the area concentrated the highest values of smectite and illite over the southern part, where lower concentrations prevailed (Figure 8f,g). Kaolinite was found in seven sites, with the western and northern part of the area having the highest concentrations and the central and southern part having the lowest (Figure 8h).

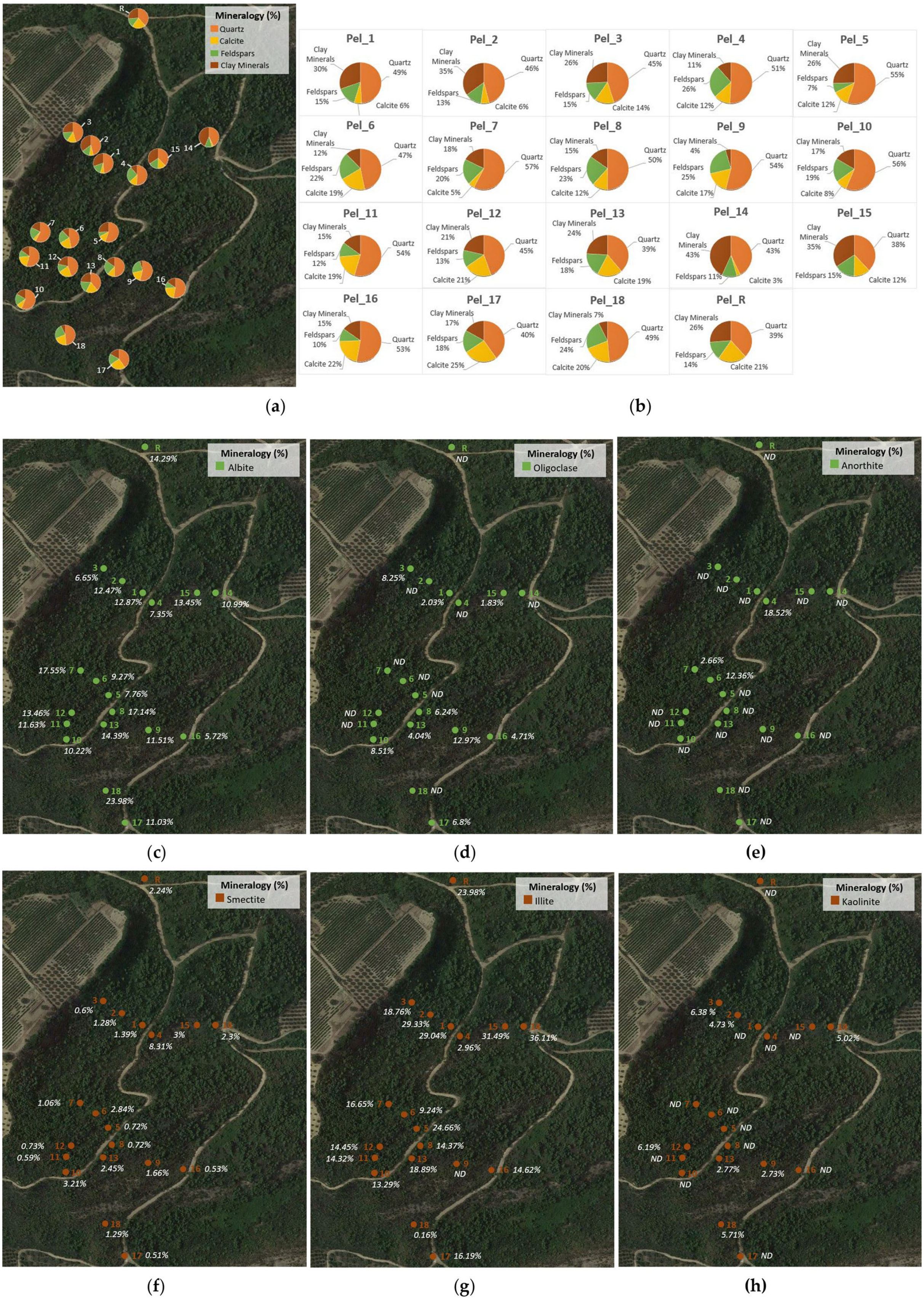

Figure 8. Spatial distribution and illustration of sample mineralogical contents in the studied area (**a**). Detailed mineralogical composition of each sample (%) (**b**), distribution of albite (**c**), oligoclase (**d**), anorthite (**e**), smectite (**f**), illite (**g**), and kaolinite (**h**).

3.2.3. Geochemistry of Soils

The results of the geochemical analyses showed that the TN values ranged from 0.09–0.48 mg/g, with an average of 0.30 mg/g. The TOC values ranged from 0.28–0.83%, with an average value of 0.60%, and the TP values ranged from 0.02–0.26 mg/g, with average value of 0.14 mg/g. The values of electrical conductivity ranged from 0.05–0.12 mS/cm, with an average of 0.07 mS/cm, while the values of pH ranged from 7.5 to 9.07, with an average of 8.74. These values are consistent with the values reported by the Land Use/Land Cover Area Frame Survey (LUCAS) project for sampling and analysis of the main properties of topsoil in 23 Member States of the European Union [43].

The concentrations of total organic carbon appeared to be higher in the southern and northern parts of the study area, while the lower concentrations were spotted in the central part. Similarly, the highest total nitrogen concentrations were observed in the northern and northeast parts, unlike the lower concentrations, which were found in the central part of the area. The pH concentrations displayed an increase from the northern and southern parts of the region towards its center, while the electrical conductivity values appeared to be higher in the northern parts and lower in the southern part of the study area (Figure 9).

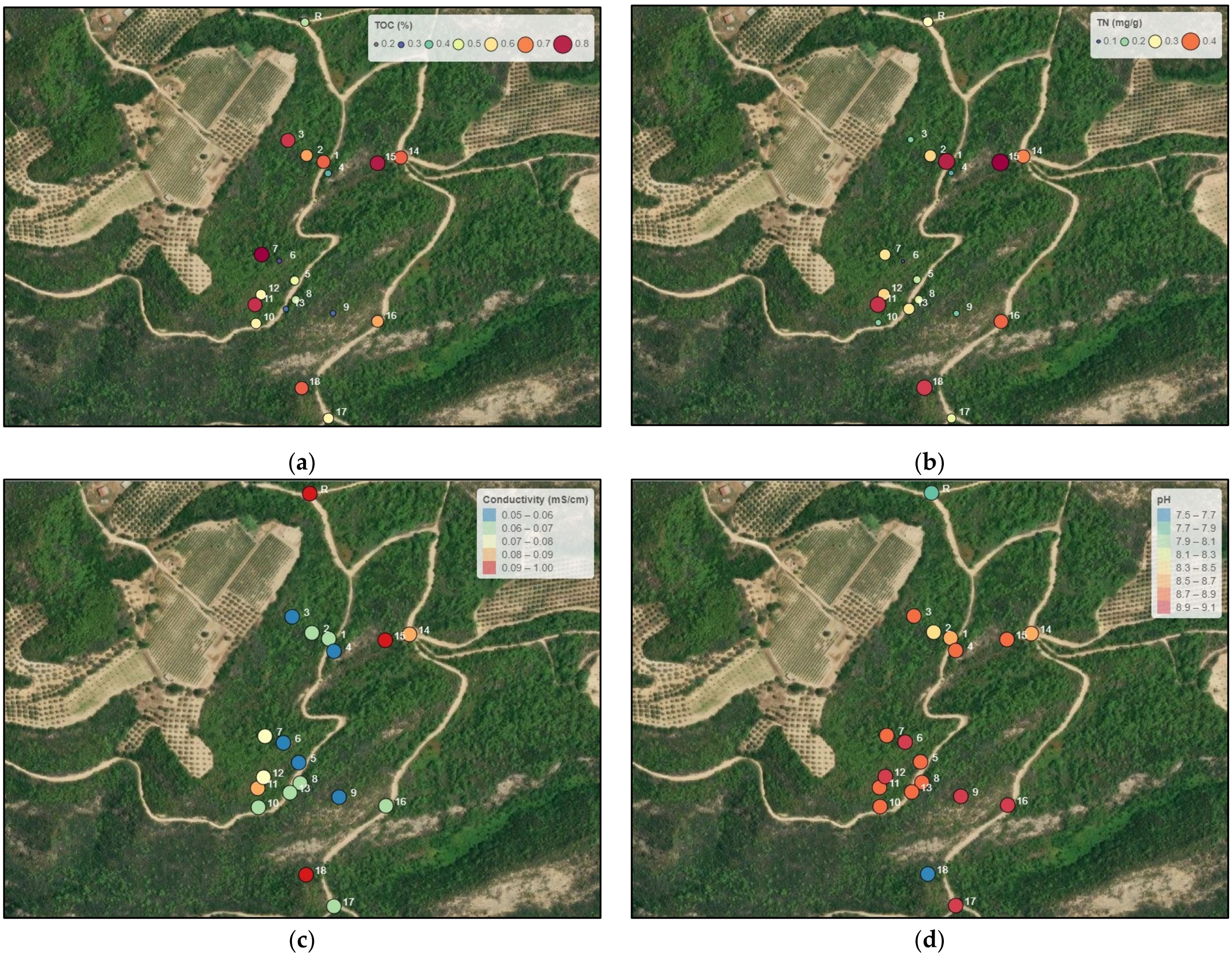

Figure 9. Distribution in TOC (**a**), TN (**b**), EC (**c**), and pH (**d**) of the studied soil samples.

The concentrations of the potassium in the soil samples ranged from 4700 to 12,700 ppm, with a mean value of 9900 ppm. The concentrations of calcium approximately ranged from 18,600 to 111,600 ppm, with a mean value of 63,900 ppm. The values of magnesium ranged from 14,900 to 18,800 ppm, and the values of silicium ranged from 198,300 to 278,800 ppm, with mean values of 16,700 and 234,900 ppm, respectively.

The spatial distributions derived from the geochemical analyses showed opposite trends for the potassium and calcium values (Figure 10a,b). Specifically, the concentrations of potassium showed an increase from the southwestern to the northeastern parts of the area, in contrast with the calcium concentrations, which tended to be higher from the northwestern to the southeastern parts of the region. The opposite trend was observed in the distributions of the magnesium and silicium concentrations (Figure 10c,d). The values of magnesium showed a distinct increase from the southwestern to the eastern parts of the region, contrary to the values of silicium, which showed an increase from the northeastern to the southwestern parts, respectively.

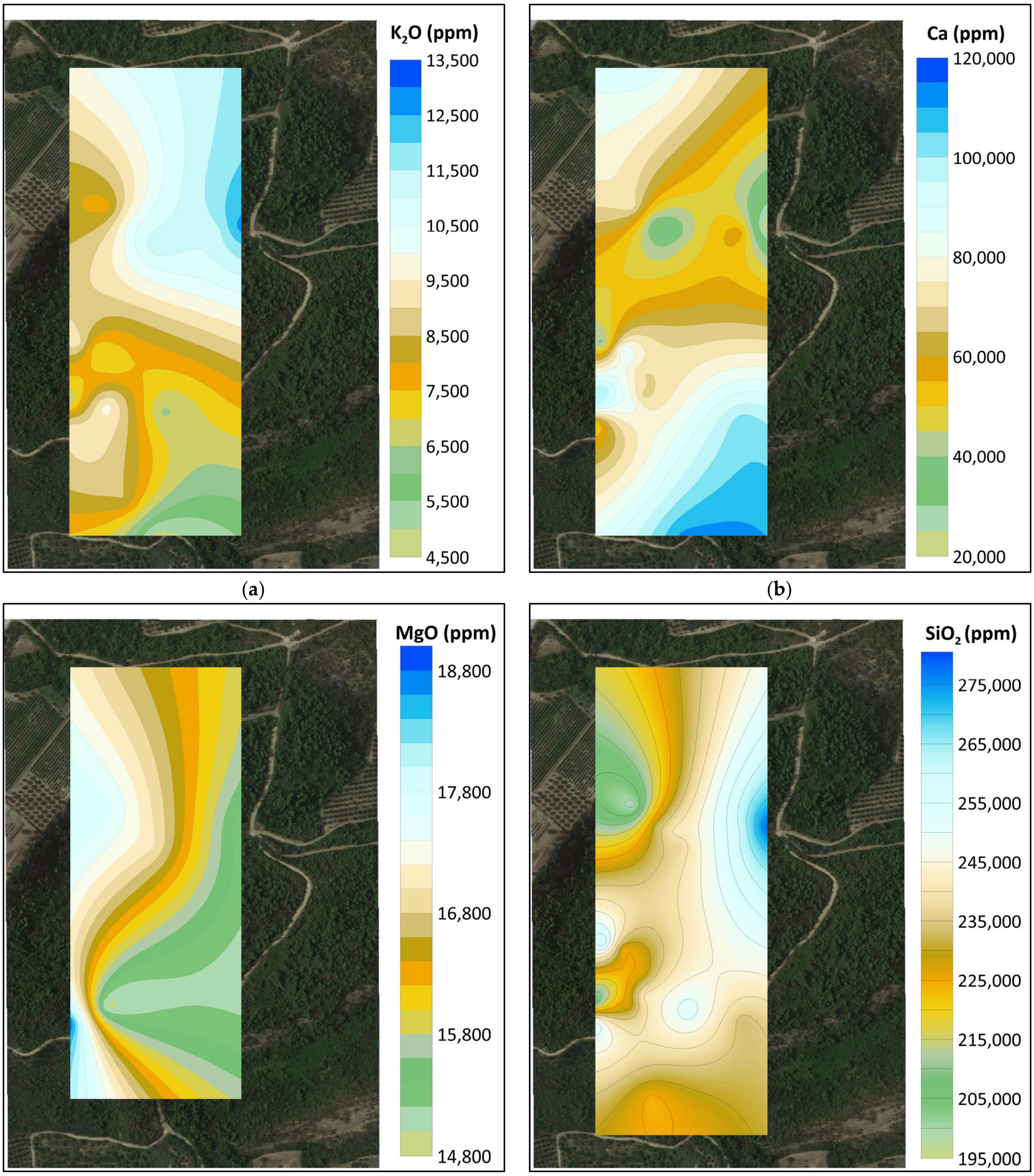

Figure 10. Distribution in K (**a**), Ca (**b**), Mg (**c**), and Si (**d**) of the studied soil samples.

In the soil samples of the studied area, the manganese values ranged from 612 to 1204 ppm, with a mean value of 900 ppm. The iron values ranged from 9528 to 27,500 ppm, with a mean value of 18,400 ppm. The values of Fe and Mn in the studied area showed lower concentrations compared to the values reported for forest soils [47]. The concentrations of lead and phosphorus ranged from 15 to 21 and 383 to 707 ppm, with mean values of 17 and 477 ppm, respectively.

The results of the geochemical analyses for heavy metals showed a similar distribution over a wider area. The highest values of manganese were found in the northeastern parts of the area and were lower in the southwestern part. Likewise, the values of iron displayed the same variation (Figure 11a,b). Concerning the lead concentrations, they showed an increase from the easternmost to the westernmost parts of the study area, contrary to the phosphorus concentrations, which showed the opposite trend (Figure 11c,d).

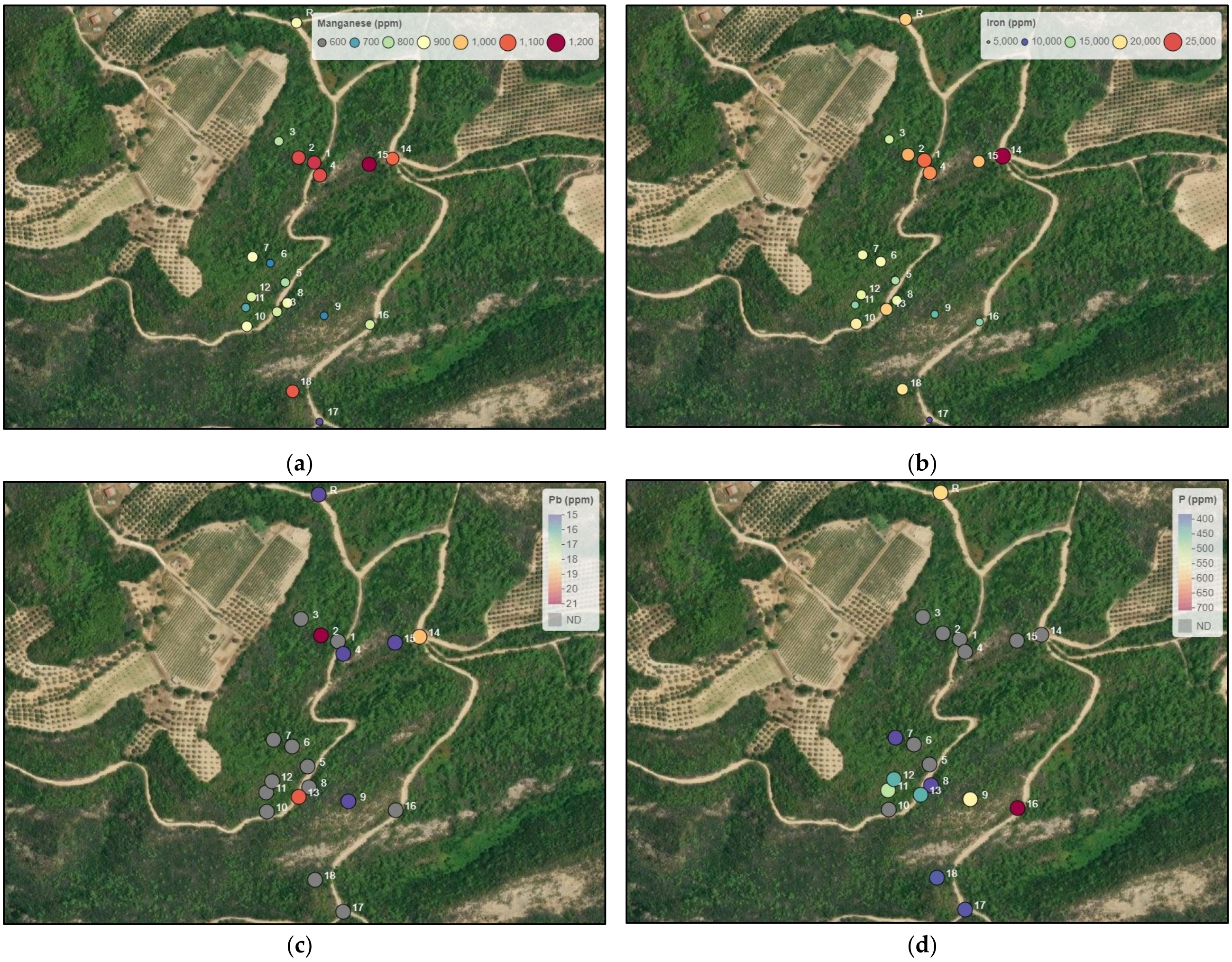

Figure 11. Distribution of Mn (**a**), Fe (**b**), Pb (**c**), and P (**d**) of the studied soil samples.

Correlation matrices (Pearson) of all the examined geochemical and mineralogical parameters were calculated. The statistical analysis of the data showed a positive correlation between Mn, Fe, and K. A strong positive correlation was depicted between TOC and TN, while Fe showed a strong negative correlation with calcium and a strong positive correlation with Mn (Figure 12).

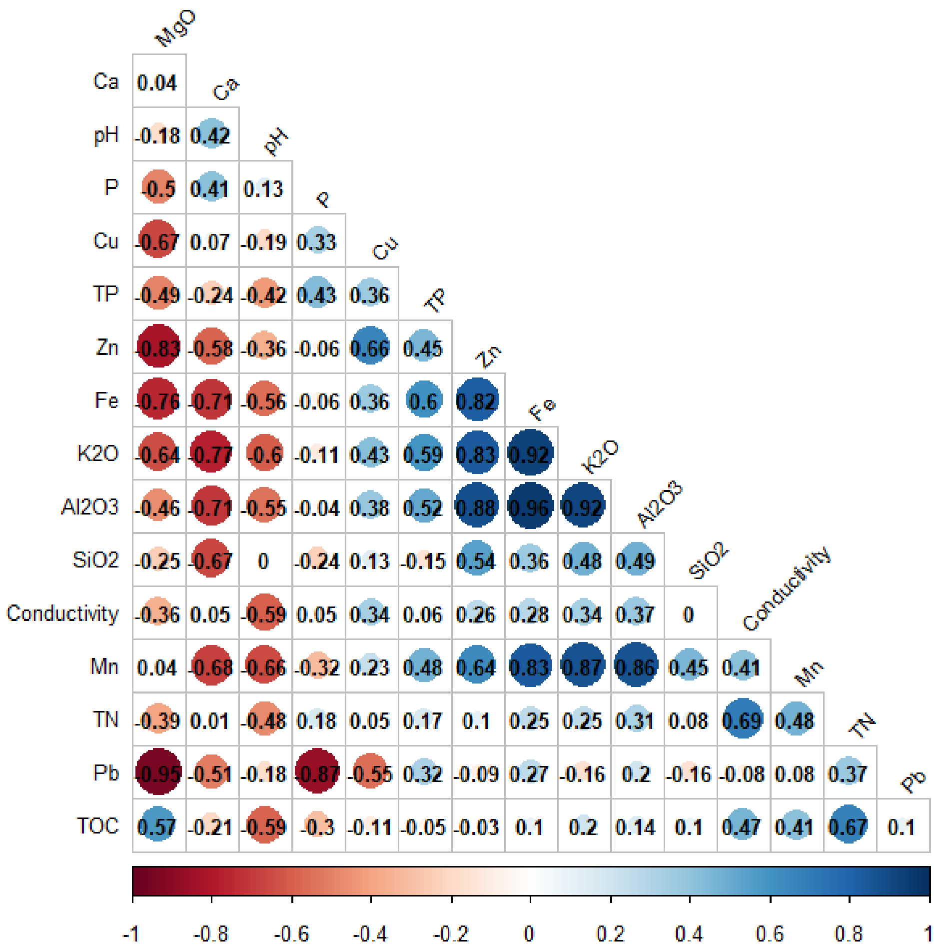

Figure 12. Correlation matrix (Pearson) of the studied soil samples.

The above statistical analysis revealed a negative correlation between pH and electrical conductivity, as well as the existence of a negative correlation between Mg and Fe, K, and Pb. On the contrary, the correlation of TOC with Mg and electrical conductivity seems to be quite positive, as well as the correlation of Si with K and Fe. Noteworthy is the strong negative correlation between Pb and P.

4. Discussion

Greece, akin to many nations in the Mediterranean region, has a longstanding historical association with wildfires. The occurrence, current presence, and future persistence of forest fires pose substantial challenges concerning the preservation of natural resources. Nevertheless, the frequency of these incidents has notably surged in recent years. Current forecasts suggest that the broader Mediterranean area will encounter notable difficulties in the forthcoming years due to climate change [48].

4.1. Restoration Potential

The study area was historically characterized by the presence of Aleppo pine forests (*Pinus halepensis*), along with a diverse understory of sclerophyllous, broadleaved species. However, it has experienced forest fires at various points in history, notably the severe mega-fire of Ilia and the Peloponnese in 2007, prior to the recent fire in 2021. Following the 2007 mega-fire, the pine forest exhibited a natural recovery process, leading to the establishment of healthy stands. Nevertheless, the landscape underwent significant transformations following the 2021 forest fire. Based on the double-burnt within the last 15 years status of the site, the three-year period field surveys, and a comprehensive assessment of the study area and its surroundings, it is deduced that the likelihood of the site reverting back to its original pine forest state is highly improbable (e.g., [48,49]). Moreover, the documented low cover of legumes, which plays a crucial role in post-fire restoration [50], is considered as inadequate. Post-fire sites of *Pinus halepensis* forests usually host a large contribution of legumes to vegetation cover and biomass, especially at the early post-fire period [26], which was the period when the present study's field surveys were applied, a condition that was absent in the study area.

It is essential to highlight that a pertinent study recommends the implementation of artificial reforestation measures for areas affected by multiple fires over the past two decades, with special reference to the (wider) study area [51], emphasizing the significance of addressing the repercussions of recurrent forest fires, potentially exacerbated by climate variations and anthropogenic factors. Therefore, prioritizing conservation strategies focused on nature restoration, the preservation of natural resources, and the sustainable provision of ecosystem services is imperative in light of the escalating frequency of consecutive wildfires [48].

4.2. Attributes and Functions of Soil

The soil survey assessment identified good soil conditions for natural vegetation recovery [52], thus providing the adequate conditions for any selected landscape restoration strategy (i.e., reforestation or natural vegetation regeneration of the recorded species and their communities). This is documented by the fact that most of the soil samples are classified as loam and silt loam, while the rest of them are classified as sandy loam and silty clay loam. While based on the geological map of the area (Figure 2) and the nature of the parent material, samples with higher percentages of clay (with >40%) were expected. The occurrence of wildfires in the area decreased the clay fraction while enhancing the sand fraction due to the exposure of the soil to extreme temperatures, as also referred to in the literature [16]. For example, the quartz content of the samples from the burned area were higher than the quartz content of the reference sample (R), which came from the unburned area in our study. Thus, at temperatures above 400 °C, the clay content decreases and the silt and sand content increases [52,53].

However, various scholars have come to different conclusions about the temperature limit (e.g., they put it lower or higher than 400 °C), but it is generally believed that kaolinite in soil dissolves to form Al and Si compounds under high temperatures. These compounds melt and agglomerate during the cooling process and typically cause soil particle composition changes [52,54]. The clay fraction ranged from 4.39% to 43.43%, with an average of 20.63%, and higher concentrations existed in the northern section of the area. The silt fraction ranged from 21.68% to 62.34%, with an average of 44.96%. The presence of clay minerals in relatively low amounts (like in our case, around 20%) favors the vegetation, since clay minerals adsorb water molecules and make them available for vegetation. Additionally, the cation exchange capacity of clay minerals is high, making a wide range of cations available for vegetation [18]. If the presence of clay minerals was too low, that would not be possible. On the other hand, if the presence of clay minerals was too high (especially montmorillonite), then the conditions would not be good for vegetation, since montmorillonite (the rock that contains montmorillonite in amounts higher than 80% is called bentonite) is an expandable clay mineral. When it loses water, it becomes hard like a cement and impermeable and destroys plants, especially their roots [55].

A differentiation among the southern and northern parts of the study area and the potential relationships between samples were further explored with the use of a hierarchical cluster analysis (HCA). Samples were categorized into clusters according to their squared Euclidean distance, and the results are presented in Figure 13. The dendrogram shows a dissimilarity between the sample sites, let alone the differentiation between the northern and the southern parts of the study area. As a result, we can distinguish three main clusters. The first cluster (C1) contains samples 3, 5, 12, 17, 11, 16, 6, 9, 7, 8, and 10, the second cluster (C2) contains samples 18, 4, 13, 1, 2, 14, and 15, and the third cluster (C3) is defined by the presence of the sample R, the reference material from the unburned site (Figure 13).

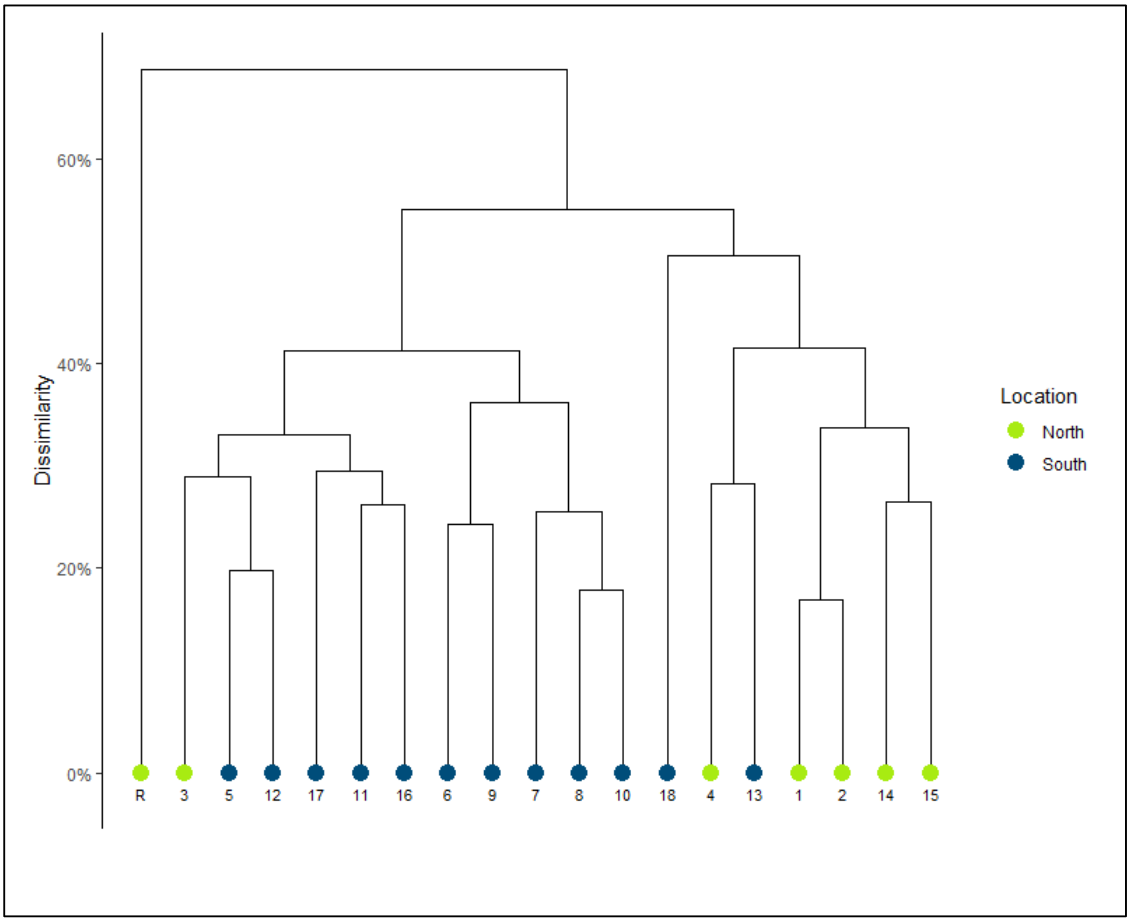

Figure 13. Dendrogram of HCA for the soil samples.

For the geochemical analysis, a principal component analysis (PCA) was performed. The PCA clearly shows the differentiation between the northern and the southern parts of the study area. The factors show increasing values to the northern parts of the study area, except for the factors of pH and Ca concentrations, which increase their values in the southern parts of the area (Figure 14).

The present mineralogical and geochemical compositions of the samples analyzed and the presence of carbonate and clay minerals in the studied area were found in amounts that are good for natural recovery. The ability of the clay minerals to interact with organic matter and control the nutrients' availability in soil is the key component for potential plant regeneration. The presence of clay minerals favors the vegetation due to hydration and ion exchange. In addition, nitrogen, phosphorus, potassium, and micronutrient availability are limiting factors for plants recovery [18]. Our study indicates a better regeneration degree for most of the northern part of the studied area (Figure 5). This concedes with the mineralogical and geochemical properties of the studied area (Figures 13 and 14).

Minerals including quartz, calcite, feldspars (albite, anorthite, oligoclase), and clay minerals (smectite, kaolinite, illite) were detected in all the studied samples. Due to the identical mineralogical footprints, it is unlikely that the samples can be categorized according to their spatial distribution. The differentiating aspect among them depends entirely on whether kaolinite, anorthite, or oligoclase are present or absent and where the concentrations of quartz, calcite, and clay minerals in general are higher. In particular, kaolinite could determine the effect of the wildfire in the area, as the mineral exhibits structural damage when it is heated above 550 °C [47]. Thus, the absence of the mineral in certain sites indicates that either the temperature in the studied area exceeds 550 °C, completely impairing kaolinite, or the soil never hosted this mineral. Conversely, kaolinite's presence could be attributed to the limited duration of the fire in the specific site, or the temperature did not exceed 550 °C. All the samples were enriched in quartz, as it is a stable mineralogical phase until temperatures of 600 °C [16], with almost equal or even higher concentrations than the reference unburned samples. In combination with the presence of kaolinite, this can be evidence that no temperatures higher than 600 °C took place in most of the area. Thus, in the areas that lack kaolinite mineral, higher temperatures may be reached, causing a difficulty in forest natural regeneration.

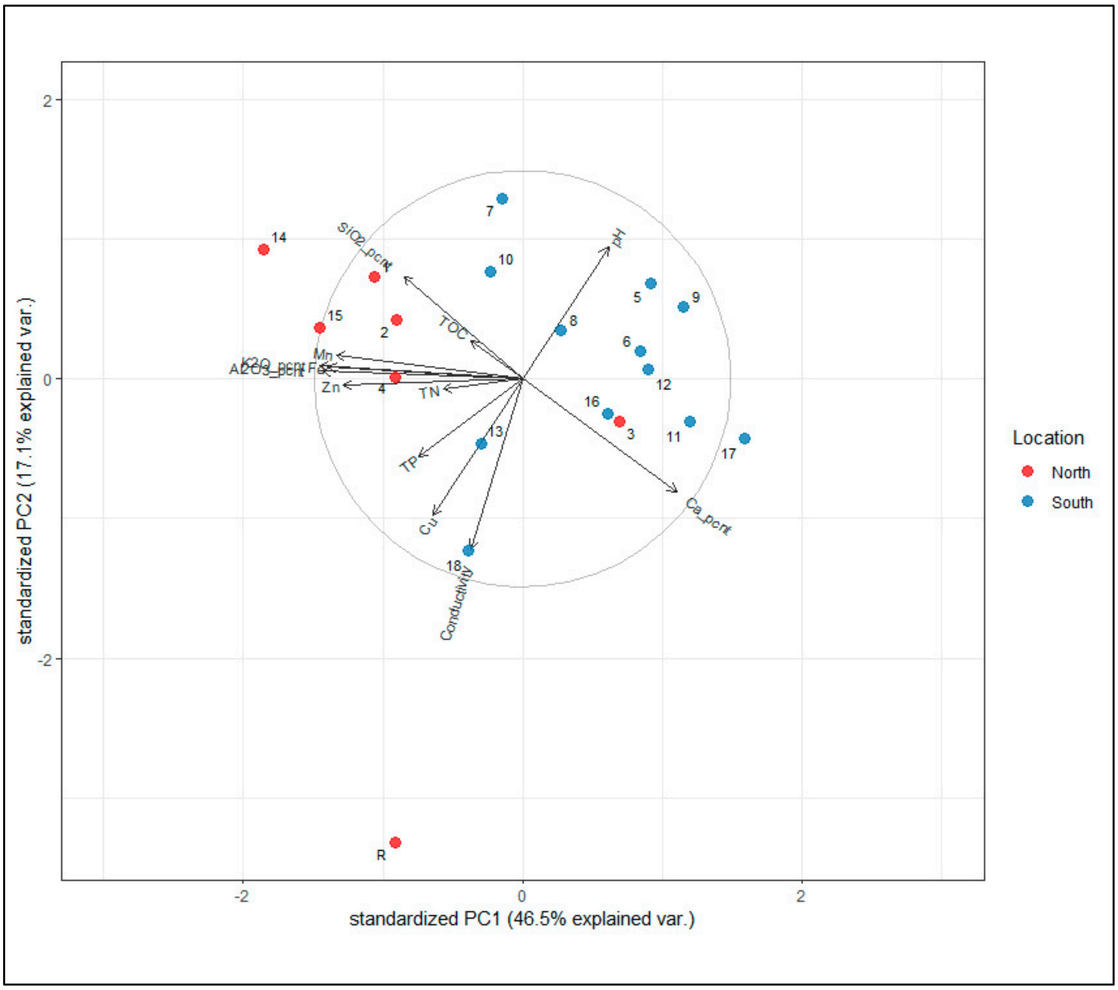

Figure 14. Principal Component Analysis (PCA) for the geochemical parameters of soil samples.

The presence of kaolinite is more common in the northwest part of the study area, while the other tested clay minerals were also concentrated in the north part of the burned area, with a higher presence in the eastern part, i.e., smectite and illite. The total organic compounds were also more common in the northern part of the area, where clay minerals were present. This positive correlation can be explained by the ability of clay minerals to strongly interact with organic compounds through a wide range of interactions such as adsorption, intercalation, or cation exchange [18]. The total organic compounds are correlated with organic matter which remains in the area as residual ash, even if it is burned. Such residual ash is composed of trace elements required by plants for their normal growth processes. Thus, organic matter contains necessary elements for the regeneration of forests and strongly interacts with clay minerals. Due to the property of the cation exchange of clay minerals, K_2O, MgO, and SiO_2 were positively correlated with the presence of illite and smectite. As K and Mg ions exist in the structure of illite and Mg in the structure of smectite in an exchangeable from, they are easily released in the relevant environment, given higher concentrations. Similarly, Fe and Mn were more frequent in the places with higher clay mineral concentrations. Moreover, the presence of clay minerals in soils has the ability to enhance the soil fertility by controlling nutrient supplies and availability. The main mechanisms for such control are the sequestration and stabilization of organic matter as well as the microaggregate formation, which subsequently controls the soil physical properties by influencing the soil microbial activity and the soil acidity [56]. It is characterized as the most critical mechanism for the role of clay minerals in the soil fertility [18]. Several studies verified the influence of clay minerals on N, P, and K retention and the availability in soil, which is in agreement with the results of the present research based on the correlation of K with clay minerals (Kome et.al., 2019 [18] and references within).

The calcite concentrations were found to be higher in the southernmost point of the area, overcoming the values of the unburned reference sample in most of the cases. This can be explained by the remain of calcium carbonate released by ash after the combustion of organic matter [57]. TN shows its affiliation with the organic fraction of the investigated samples due to the strong positive correlation with TOC. In the areas with a higher concentration of calcite, there is a positive correlation, with higher pH values as well as with the availability of Ca, which can be explained by the nature of calcium carbonate and the release of Ca ions to the neighbor soils. As calcite presents a lower EC than quartz and clay, there is a negative correlation of calcite and EC in the southern part of the investigated area [58,59].

4.3. Post-Fire Management Reccomendations

The restoration of Mediterranean ecosystems impacted by forest fires, and especially mega-fires, is crucial for the upcoming years, focusing on ecosystem restoration and ecosystem services amelioration, especially under the spectrum of climate change. Our study findings support that vegetation regeneration of the area is possible; however, the restoration of the previously established forest will require specific actions in order to succeed. Moreover, the recovery of the *Pinus halepensis* forest is crucial at the national and EU level, since it is included in Annex I (Natural habitat types of community interest whose conservation requires the designation of special areas of conservation) of Dir. 92/43/EEC [60]. Additionally, the recently adopted EU Nature Restoration Law [61] urges member states to restore ecosystems in their territory and submit national restoration plans. Towards achieving this goal and working to fulfill this obligation, it is suggested that relevant efforts could be guided by five fundamental principles, which serve as consecutive and/or supplementary measures, and as outlined below.

(a) Rapid ecological assessment: A prompt evaluation of the burned area is essential to determine the fire severity and the likelihood of ecosystem recovery. Utilizing tools like the European Forest Fire Information System (EFFIS) and Sentinel-2 satellite imagery is crucial for categorizing the burned area based on fire severity and evaluating regeneration potential (e.g., through cone counting and estimating macchia species coverage [62]). Conducting a rapid ecological assessment is pivotal for comprehending the extent and intensity of fire-induced damage and for organizing restoration endeavors. Tüfekcioğlu et al. [62] performed a swift assessment in the Marmaris region of the Mediterranean basin after a fire in 2021. They employed EFFIS and Sentinel-2 satellite imagery to categorize the burned area according to fire severity, revealing regeneration potential by counting pine cones and estimating macaque species coverage. This methodology is applicable within two months post-fire, offering a cost-efficient approach for local managers and decision makers.

(b) Natural regeneration and assisted restoration: Depending on the fire severity and ecological attributes of the burned area, it is advisable to combine natural regeneration with assisted recovery methods. These methods may involve allowing some areas to naturally regenerate, placing cone-bearing branches to encourage regrowth, additional seeding, and artificial regeneration through seedling planting post-tiering and cultivation activities [62]. The transition from reforesting with a single pine species to more varied restoration techniques reflects the progression of management strategies after Mediterranean fires. Vallejo and Alloza [63] elaborate on the shift towards incorporating greater plant species diversity in reforestation efforts and a broader spectrum of restoration measures. This diversification aims to enhance ecosystem resilience and mitigate the risk of recurrent fires. A study from Greece exemplifies the systematic approach to reforestation and restoration of burned lands, developed by Tzamtzis et al. [48]. This underscores the significance of considering forest species' regeneration potential, fire history, and affected areas' slope (inclination).

(c) Short- to long-term restoration approaches: The implementation of a phased restoration strategy is essential, beginning with short-term measures to address soil degradation post-fire and excessive runoff. Restoration efforts should prioritize the rehabilitation of key species in the short and medium run, with a clear long-term goal of restoring the integrity of reference ecosystems and their associated services while concurrently mitigating fire risks [64]. The case study of Mount Athos in Greece offers insights into the prolonged vegetation dynamics post-fire. Research by Xofis et al. [65] examined the vegetation dynamics over a period of 30 years since the last fire, revealing that forest communities displayed rapid recovery, maintaining their original composition and structure. In contrast, maquis communities required several years to regain their pre-fire characteristics. This study underscores the necessity of a phased restoration approach that considers the varying recovery rates of distinct plant communities and the potential influence of climate change on these dynamics.

(d) Highlighting ecosystem elements and natural processes: It is crucial to underscore the significance of post-fire biological remnants, such as burnt wood, and to advocate for natural processes as essential components supporting forest regeneration. This strategy aims to diminish anthropogenic impacts on ecosystems and may prove more efficient and economical compared to intensive intervention measures. The advancing comprehension of fire ecology and restoration science has led to a heightened emphasis on promoting natural processes and ecosystem components in post-fire environments. Duguy et al. [66] emphasize the formulation of novel protocols integrating scientific insights from fire ecology and recovery. These protocols strive to pinpoint fire-prone forests and shrublands through a Geographic Information Systems-based methodology, concentrating on vegetation resilience and the risk of post-fire erosion to steer restoration endeavors.

(e) The evaluation of climate conditions and categorization of drought: An important focus should be placed on recognizing the essential role that the duration of drought plays in the process of vegetation recovery subsequent to wildfires. The effects of drought are especially pronounced at the boundaries of the dry season continuum, impacting the post-fire ecological restoration. Additionally, the restoration of plant cover is influenced by fire severity and topographical features, with their effects exhibiting variability across different levels of drought severity [67]. The influence of climate, specifically the duration of drought, on the recuperation of vegetation following a fire is a pivotal concern within Mediterranean ecosystems. Tüfekcioğlu et al. [62] formulated strategies for restoration founded on the capacity for regeneration and the intensity of burning while considering the indigenous climatic circumstances. This methodology highlights the significance of tailoring restoration endeavors to the particular ecological and climatic parameters of the impacted region.

5. Conclusions

This study provides a local (fine) scale assessment of a double-burnt Aleppo pine (*Pinus halepensis*) forest in W. Peloponnisos, Greece, in terms of natural regeneration and soil properties. The results reveal that natural regeneration of the Aleppo pine forest is absent, while the succession process of natural vegetation (sclerophyllous, broadleaved shrubs) has begun to take its place in spatial terms throughout the areas. The soil conditions are considered adequate for landscape restoration, regardless the method that will be used (i.e., natural vegetation succession or artificial regeneration of the Aleppo pine forest). However, considerations should be taken into account for measures and actions based on local conditions as well as on the potential impacts of climate change. Specific measures and actions are provided for mitigation and adaptation actions. This study provides a combined assessment of vegetation and soil analysis and can be used to support scientifically based decisions for the wider area restoration as well as for similar cases throughout the Mediterranean basin.

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