sustainability

MDPI

Article

Post-Fire Natural Regeneration and Soil Response in Aleppo Pine Forests in a Mediterranean Environment

Pasquale A. Marziliano *, Silvio Bagnato, Elisabetta Emo and Michele Mercuri

Department of Agraria, Mediterranean University of Reggio Calabria, Loc. Feo De Vito, 89124 Reggio Calabria, Italy; silvio.bagnato@unirc.it (S.B.); elisabetta.emo@unirc.it (E.E.); michele.mercuri@unirc.it (M.M.)

* Correspondence: pasquale.marziliano@unirc.it

Abstract

Wildfires are a major ecological disturbance in Mediterranean forests, whose frequency and intensity are increasingly driven by climate change and land-use dynamics. This study investigated post-fire natural regeneration and soil properties in Aleppo pine stands seven years after a high-severity crown fire in southern Italy. Two stand types—pure pine and mixed pine—were compared, differing in fire severity and structural composition. We evaluated seedling density and dendrometric parameters (height and collar diameter), as well as soil parameters (pH, organic matter, and bulk density) to assess their role in post-fire recovery. Regeneration was abundant and composed exclusively of Aleppo pine, with significantly higher seedling density in the pure pine stand, where fire severity was greatest. In mixed pine stand, moderate fire severity combined with interspecific competition limited regeneration density. Deadwood presence enhanced microclimatic conditions favorable to seedling establishment, supporting a post-fire recovery dynamic consistent with self-succession, whereby pre-fire dominant species are favored. Soil analyses revealed higher organic matter content and lower bulk density in the pure stand, which likely facilitated regeneration. Overall, these findings underscore the ecological value of deadwood retention and passive management strategies in fostering spontaneous forest recovery. A better understanding of post-fire regeneration patterns and soil conditions can inform adaptive management approaches to strengthen forest resilience in Mediterranean forests under increasing climate pressure.

Keywords: wildfire; *Pinus halepensis*; deadwood; forest management; Mediterranean

check for updates

Academic Editor: Anna De Marco

Received: 4 August 2025

Revised: 13 September 2025

Accepted: 15 September 2025

Published: 16 September 2025

Citation: Marziliano, P.A.; Bagnato, S.; Emo, E.; Mercuri, M. Post-Fire Natural Regeneration and Soil Response in Aleppo Pine Forests in a Mediterranean Environment. *Sustainability* **2025**, *17*, 8309. https://doi.org/10.3390/su17188309

1. Introduction

The Mediterranean Basin, with its hot, dry summers and mild, wet winters, hosts a wide diversity of ecosystems. These range from dense forests to shrublands, such as maquis and garrigue, coniferous and broad-leaved reforestations, and open woodlands [1,2]. In addition to natural factors, intensive agricultural practices, urban development, and tourism have significantly influenced the ecological dynamics of the region. Despite its rich ecological and cultural heritage, the Mediterranean Basin faces mounting environmental threats, among which forest fires represent a persistent and growing hazard, profoundly reshaping both natural landscapes and human settlements [3,4].

This region has historically been shaped by wildfires, which long played an ecological role in forest regeneration [5–7]. Traditionally, lightning was the main ignition source [8,9]. However, in recent decades, human activity has dramatically altered fire regimes. Urban expansion, rural abandonment and decline of traditional land management have led to fuel accumulation, while the lack of silvicultural interventions has increased fire intensity and spread [9,10]. Consequently, the frequency, scale, and severity of wildfires have escalated, further exacerbated by climate change [1,11,12].

Wildfires now pose an increasingly severe threat to ecological integrity, socioeconomic stability, and public safety across the Mediterranean. They cause biodiversity loss, degradation ecosystem services, and economic damage, and can result in human casualities [13–15]. Southern Europe is particularly vulnerable, with about 80% of Europe's annually burned area concentrated in this region [2]. Extensive forests and recurrent drought conditions promote the rapid spread of large-scale fires, compromising the ecological functions of Mediterranean vegetation [16–18].

Climate change has emerged as a dominant driver of fire regime, intensifying risks through rising temperatures, prolonged droughts, and shifts in vegetation flammability, while also altering plant community compositions [19,20]. The combined effects of climate and human pressures not only increase fire severity but also influence post-fire regeneration trajectories. Understanding these dynamics is crucial for developing management strategies that enhance ecosystem resilience and adapt to evolving disturbance regimes.

Forest type, structure, and composition strongly influence fire vulnerability. Monospecific conifer plantations, particularly when poorly managed, are among the most fire-prone stands [21,22]. In southern Italy, conifer reforestation of the past decades—dominated by Aleppo pine (*Pinus halepensis* Mill), maritime pine (*Pinus pinaster* Aiton) and stone pine (*Pinus pinea* L.)—were established mainly for soil protection [23]. However, their high planting densities, structural homogeneity, and absence of silvicultural management have made them ecologically fragile and fire-prone by weakened [24–26], especially under global change scenarios.

Restoration of fire-affected conifer stands is technically complex and economically costly [27,28]. In Italy, regulatory constraints (Law No. 353/2000) limit the scope of publicly funded post-fire remediation. In this context, a post-fire natural regeneration, particularly when combined with measures such as fencing to prevent grazing, may represent a cost-effective and ecologically sustainable alternative for re-establishing forest structure and function.

Despite the ecological and management relevance of these plantations and the growing frequency of large wildfires, knowledge of the long-term post-fire regeneration of Mediterranean pine forests under different fire severities and stand compositions remains limited. Most studies have focused on short-term responses or on single-species dynamics, while the role of mixed stands, deadwood, and soil properties is still poorly understood. This lack of evidence hampers the development of effective, low-cost restoration strategies in fire-prone landscapes. Against this background, the present study investigates the ecological response—in terms of natural regeneration—of a Mediterranean Aleppo pine forest seven years after a crown fire, focusing on two contrasting stand types: a pure pine forest and a mixed pine–eucalyptus forest. Specifically, we aimed to:

(1) quantify the post-fire natural regeneration in both stand types (seedling abundance, height, collar diameter) and assess whether regeneration reflects auto-successional processes or facilitate the establishment of new species;
(2) evaluate the role of residual necromass (deadwood) in facilitating seedling recruitment;
(3) analyze key soil properties (pH, organic matter content, bulk density) in both forest types, and their influence on regeneration performance.

2. Materials and Methods

2.1. Study Area

The study was conducted in the southernmost part of Sicily, Italy, within the province of Caltanissetta, in the Raffo Rosso State Forest (37°12′52″ N, 14°22′22″ E). The forest extends over approximately 2500 hectares at elevations ranging from 200 to 300 m a.s.l. and is managed by the Department of State Forestry of the Sicilian Region [29].

Reforestation activities were carried out in 1985 using Aleppo pine (*Pinus halepensis*) and *Eucalyptus* spp. Aleppo pine plantations (hereafter referred to as the "pure pine forest") were established at a planting density of 2500 trees per hectare. Eucalyptus groves were managed as coppice, with Aleppo pine planted between the rows (hereinafter referred to as the "mixed pine forest"). After planting, no silvicultural interventions were implemented in either stand type, resulting in dense, continuous canopy structures. The understory vegetation was dominated by *Ampelodesma* and *Hyparrhenia* species.

The region has a hot Mediterranean climate with semi-arid features, characterized by autumn-winter rainfall and a prolonged dry season from May to September. The mean annual precipitation is 354.2 mm, and the mean annual temperature is 17.3 °C. According to the FAO soil classification [30], soils are classified as Vertisols with clay textures.

In August 2016, approximately 50 hectares of forest were affected by wildfire. Fire severity was moderate in the mixed pine forest but reached high severity in the pure pine forest, largely due to the accumulation of dead branches on the forest floor [31]. In the pure pine forest, crown scorch affected up 90% of the canopy, with only a few scattered trees surviving. In the mixed pine forest, crown scorch was less severe (50–70%), while the eucalyptus layer experienced partial shoot burning but little to no damage to stumps. Following the fire, all burned logs were removed from the mixed pine forest, whereas only about 50% were removed from the pure pine forest. The entire burned area was subsequently fenced to exclude grazing and promote natural regeneration.

2.2. Vegetation and Soil Sampling

Post-fire regeneration surveys were conducted in 2023, seven years after the fire, in both stand types. Six linear transects (1 × 20 m) were established: three in the pure pine forest (TP1, TP2, TP3) and three in the mixed pine forest (TE4, TE5, TE6), all located on slopes with similar exposure and soil conditions. Each transect was subdivided into 20 plots 1 m^2 quadrats. In our design, the six transects (TP1–TP3 in the pure pine stand and TE4–TE6 in the mixed stand) were considered as true replicates, while the 1 × 1 m quadrats within each transect were treated as subsamples. Within each quadrat, all naturally regenerated seedlings were counted, and for each seedling, species, height (cm), and collar diameter (mm) were recorded. In addition, for surviving post-fire trees, diameter at breast height (DBH, cm) and total height (m) were measured.

To evaluate soil conditions influencing post-fire regeneration, soil sampling was conducted in 2023 at five points per both stand types (pure and mixed pine forests), positioned near the vegetation transects. At each point, three subsamples were collected at a depth of 0–10 cm using a hand auger and were subsequently pooled to create a composite sample. For each composite sample, the following laboratory analyses were performed: (1) soil pH was measured in a 1:2.5 soil–to-distilled water suspension, following ISO 10390 [32]. Ten grams of air-dried, sieved soil were mixed with 25 mL of distilled water. The supernatant was then analyzed with a calibrated pH meter; (2) Organic matter content (%) was determined by loss-on-ignition (LOI) method. Approximately 10 g of air-dried, sieved soil were first dried at 105 °C for 24 h to obtain dry weight, then combusted at 550 °C for 4 h in a muffle furnace [33]; (3) Bulk density (g/cm^3) was determined using the core method. 100 cm^3 undisturbed soil samples were over-dried at 105 °C for 48 h and weighed to obtain dry mass [34]. These parameters were selected to characterize soil fertility and structure and to assess their potential influence on seedling establishment and early growth in post-fire environments. Soil sampling was limited to the 0–10 cm layer, as this interval represents the most biologically active zone, directly influencing seedling establishment. The upper soil layer is where post-fire changes are most pronounced due to combustion of litter, alteration of organic matter, and surface heating, while deeper horizons are comparatively less affected. By pooling subsamples across 0–10 cm, we obtained an integrated measure of the soil properties most relevant for early regeneration, while minimizing micro-scale variability.

Given the limited number of replicates (N = 5 per stand type), the statistical analysis was restricted to descriptive statistics and bivariate comparisons. More complex models (e.g., mixed-effects regressions) were not applied, as the sample size available did not allow for robust and reliable results.

A map of the study area is provided in Figure 1, showing the extent of the burned area and the location of the two forest stand types (pure pine and mixed pine forest) where sampling was conducted.

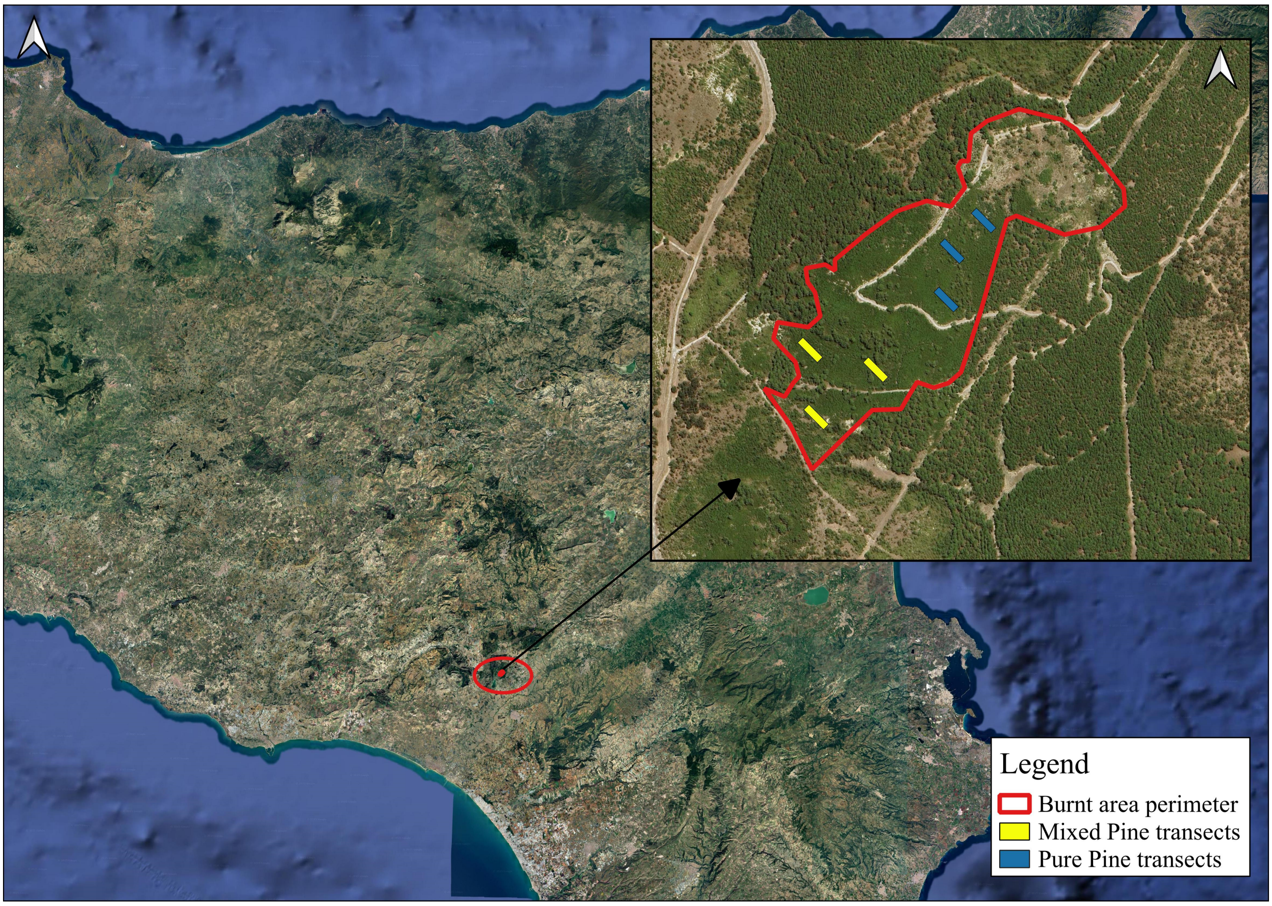


Figure 1. Location of the study area in Sicily (southern Italy). The polygon indicates the perimeter of the area burned. Sampling transects were established within two stand types: pure pine forest (red symbols) and mixed pine forest (yellow symbols).

2.3. Statistical Analysis

Both independent-sample *t*-tests and Mann–Whitney U-tests were used to assess differences in regeneration density and dendrometric parameters between forest types. The *t* test is a parametric test known to be more statistically powerful; on the other hand, the Mann–Whitney U-test is non-parametric and requires almost no assumptions. Applied statistic textbooks [35–37] usually recommend using both tests in order to truly verify the estimates. Finally, we calculated the regression lines between (i) abundance of natural regeneration and seedling diameter, (ii) abundance of natural regeneration and seedlings height. For these analyses, both for diameters and heights, data from both stand types were used together. Soil parameters were compared between forest types using independent sample *t*-tests and Mann–Whitney U-tests. All statistical tests used a significance threshold of $p < 0.05$. All data were analyses using the R programming language (version 4.3.2).

3. Results

The biometric data of post-fire natural regeneration, recorded seven years after the fire, are shown in Table 1. Natural regeneration was abundant and consisted exclusively of Aleppo pine, with no other woody species observed. Density of natural regeneration was significantly higher in the pure pine forest, which experienced high fire severity, averaging 36.5 seedlings per m^2, compared to 23.7 seedlings per m^2 in the mixed pine forest, which was subjected to moderate fire severity (Figure 2). These differences were statistically significant, as confirmed by both the independent sample test (Table 2).

Table 1. Dendromeric parameters of post-fire natural regeneration in Aleppo pure and mixed pine forest, seven years after the fire. Diameter at collar is the average diameter, expressed in mm, of the seedlings recorded in each transect. Seedlings height is the average height, expressed in cm, of the seedlings recorded in each transect. In each column the second value represents the standard deviation.

Transect	Number of Seedlings (N° m^{-2})	Diameter at Collar (mm)	Height (cm)
TP1	37.1 ± 12.3	8.8 ± 2.7	119.3 ± 31.4
TP2	39.5 ± 15.6	7.6 ± 1.9	126.5 ± 14.8
TP3	32.8 ± 7.2	9.8 ± 3.3	149.8 ± 35.1
Mean pure pine forest	36.5 ± 12.4	8.8 ± 2.8	131.8 ± 30.9
TE4	20.3 ± 9.9	14.0 ± 5.3	126.4 ± 21.8
TE5	26.0 ± 9.6	12.8 ± 3.0	136.8 ± 15.9
TE6	24.8 ± 11.4	12.6 ± 2.6	137.6 ± 14.8
Mean mixed pine forest	23.7 ± 10.6	13.1 ± 3.8	133.5 ± 18.2

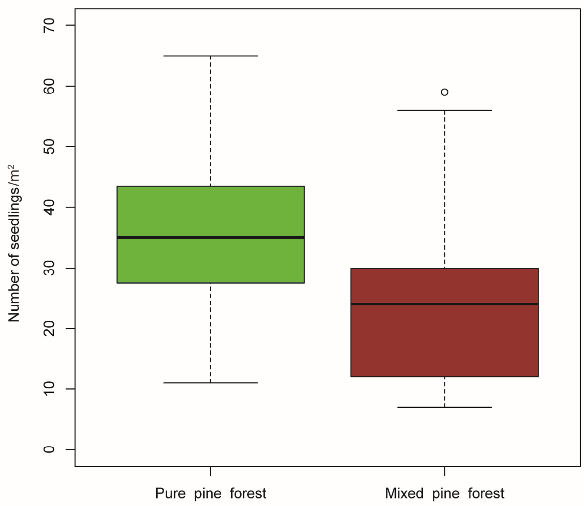
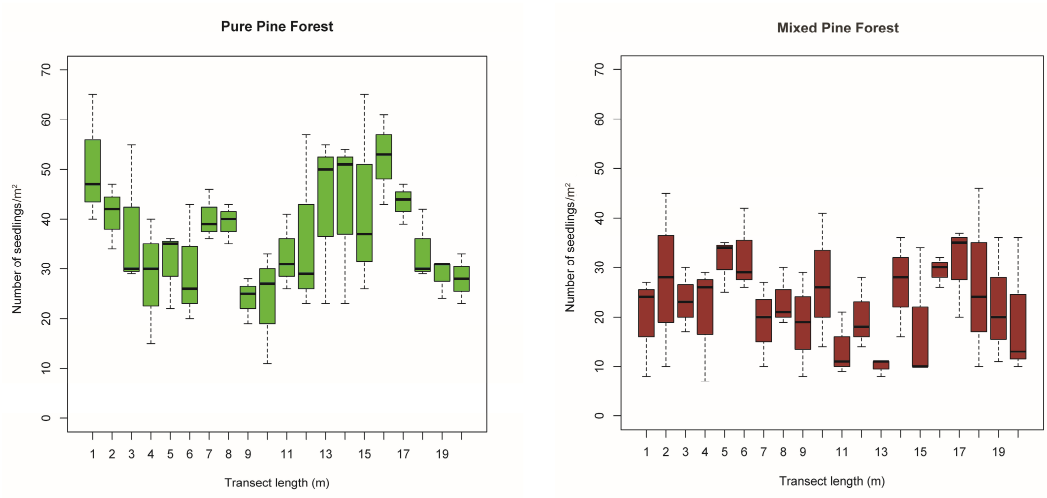


Figure 2. Variability and median values of number of seedlings m^{-2} recorded in the Pure pine forest and Mixed pine forest, represented as box-plot distributions. In the box plot, the horizontal line is the median and open circles are outliers. Statistical significance of differences between stand types is reported in Table 2.

Table 2. Significance of the variables estimation differences between pure pine stand and mixed pine stand, assessed by the Independent-sample *t*-tests (T) and Mann–Whitney U-tests (Z). N indicates the number of replicates: transects for vegetation variables (N = 3 per stand) and composite soil samples for soil variables (N = 5 per stand).

Independent Comparison	T	*p*-Value (T)	Z	*p*-Value (Z)
Number of seedlings (N = 3)	6.425	<0.001	5.440	0.001
Diameter at collar (N = 3)	7.108	<0.001	6.219	<0.001
Height seedling (N = 3)	1.483	0.141	0.286	0.775
pH (N = 5)	2.787	0.012	2.458	0.014
Organic matter content (N = 5)	4.743	<0.001	3.213	0.001
Bulk density (N = 5)	5.359	<0.001	3.478	<0.001

For each square meter (individual 1 m^2 squares), Figure 3 shows the variability in seedling density recorded in the three transects for each type of pine forest. In the pure pine forest (Figure 3a), seedling density peaked in areas where dead logs were present on the forest floor, particularly near the beginning and around the 15 m mark of the transects. By contrast, the mixed pine forest (Figure 3b) showed a more uniform seedling distribution along the transects, with maximum density occurring around 6 m (approximately 32 seedlings m^{-2}). Notably, no coarse woody debris was observed in the mixed forest.

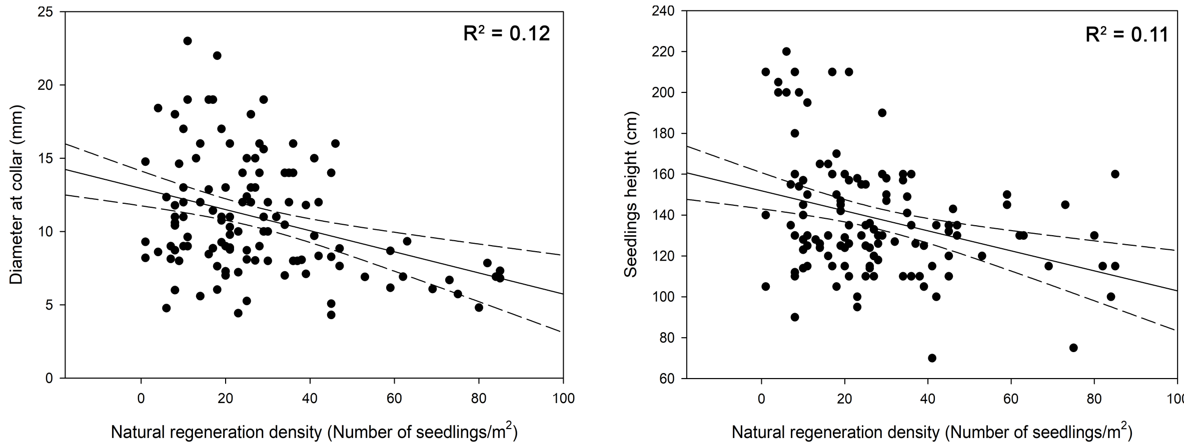


(**a**) (**b**)

Figure 3. Variability and median values of number of seedlings m^{-2} in each square meter along the transect of Pure pine forest (**a**) and Mixed pine forest (**b**), represented as box-plot distributions. In the box plot, the horizontal line is the median.

Regarding seedling growth, the mixed pine forest showed greater collar diameter and mean height compared to the pure pine forest (Table 1). Significant differences were observed for collar diameter between the two stands (Table 2), whereas differences in height were not statistically significant. The larger diameters in the mixed pine forest are likely due to lower regeneration density and reduced competition.

Figure 4 shows the regression lines of the relationship between post-fire natural regeneration density and seedling dendrometric parameters (collar diameter and height). In both cases the regression is significant, suggesting that increased seedling density is associated with reduced growth. These results imply that intense post-fire regeneration leads to stronger competition for resources, thereby limiting seedling development.



(**a**) (**b**)

Figure 4. Relationship between number of seedlings per m^2 (post-fire natural regeneration) and diameter at collar (**a**) and seedling height (**b**). Data from both stand types were pooled to show the relationship between seedling growth and regeneration density. R^2 is the determination coefficient.

Soil analysis revealed significant differences between the two stand types (Table 2). The pure pine forest exhibited a lower pH (mean = 6.23 ± 0.22) compared to the mixed pine forest (mean = 6.49 ± 0.19), suggesting slightly more acidic conditions (Figure 5). Organic matter content was significantly higher in the pure pine forest (2.08 ± 0.28%) than in the mixed pine forest (1.58 ± 0.17%). In contrast, bulk density was lower in the pure pine forest (1.25 ± 0.05 g/cm^3) compared to the mixed pine forest (1.35 ± 0.04 g/cm^3), indicating better soil porosity and structure in areas with denser regeneration.

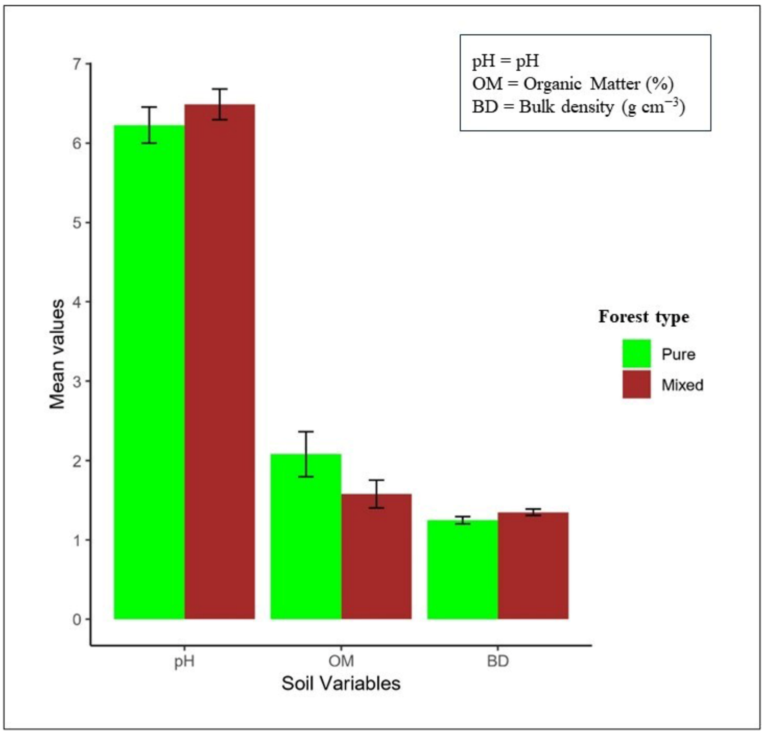


Figure 5. Comparison of soil properties in pure and mixed Aleppo pine stands, seven years after fire. Bars represent mean values ± standard deviation. Statistical test results (*p*-values) are reported in Table 2. At each stand type, five composite soil samples were obtained (one per sampling point), each derived from three subsamples. The soil variables were measured on these composite samples, resulting in five replicates per stand type (N = 5).

4. Discussion

This study confirms that post-fire vegetation dynamics in Aleppo pine dominated forests generally do not favor the establishment of new species. Instead, these dynamics promote ecological processes such as auto-succession [38], leading to a gradual return to pre-fire community composition. These observations are consistent with previous studies [39,40] and align with the "initial floristic composition" model, whereby pre-fire species dominate and perpetuate self-succession. Recent works further emphasize that Mediterranean post-fire trajectories are often constrained by pre-fire species pools and local climatic conditions, with drought emerging as a key driver limiting recruitment success [41,42].

Our results showed higher post-fire regeneration density in the pure pine forest. The lower density observed in the mixed pine forest likely reflects the partial survival of the pre-existing understory, specifically *Ampelodesma* and *Hyparrhenia*, whose stumps persisted after moderate-severity fire and exerted competitive pressure on pine seedling establishment. Similar patterns have been reported in other Mediterranean contexts, where competitive interactions with resprouting grasses can suppress pine recruitment [43]. In the pure pine forest, the highest regeneration density appears closely linked to the presence of fallen deadwood, which likely facilitated seedling establishment by enhancing microclimatic conditions, providing a nutrient source through slow decomposition, and mitigating water stress by shading seedlings [44,45].

Conversely, trees removal (salvage logging), currently one of the most common post-fire interventions, can hinder natural regeneration [46]. In our study area, leaving dead trees on site did not negatively affect post-fire regeneration; rather, seedling density was particularly high in the pure pine stand, reaching approximately 33 seedlings per m^2. Similar observations have been reported elsewhere in Southern Italy, where delayed deadwood removal led to higher seedling densities compared to early removal [47], and in Estonia, where clearing burned areas significantly reduced post-fire regeneration in a managed *Pinus sylvestris* forest compared to uncleared areas [48]. These findings suggest that retaining deadwood on site enhances microhabitat conditions for seedling establishment, whereas salvage logging may disrupt successional pathways by introducing a secondary disturbance that interacts negatively with the initial fire [49]. The facilitative role of necromass is further supported by studies showing increased seedling establishment with advancing wood decay and soil accumulation around logs, contributing to creating microsites favorable to seedling recruitment [50–53].

Recent literature consistently indicates that post-fire salvage logging can impair natural regeneration, alter successional trajectories, and negatively affect ecosystem processes [54–57]. Therefore, unless specific management objectives require it (e.g., public safety or infrastructure protection), retaining necromass on-site represents a viable and ecologically beneficial strategy. Strategic use of deadwood as a facilitator of post-fire regeneration should be considered a key component of sustainable forest management. The abundant natural regeneration observed in the pure pine forest highlights the dual role of fire as both a destructive force and a catalyst for ecological renewal [58–60].

Table 1 indicates that seedling height and collar diameter were inversely related to fire severity; seedlings in the mixed pine forest, subject to moderate fire, achieved greater height and collar diameter over time. This trend likely reflects reduced intraspecific competition due to lower seedling density. Similar trends have been reported in Southern Europe [23,47] and in mixed conifer forests in the Blue Mountains, USA, where high severity fire reduced seedling height [61]. While some studies attribute seedling growth directly to fire severity [62], others highlight that seedling size post-fire is influenced by a more complex interaction involving fire intensity, soil properties, species traits, climate, and interspecific interactions [25,63,64]. Recent findings in Mediterranean systems show that regeneration responses are modulated by both fire severity and the position of populations within their climatic niche, with peripheral sites being more vulnerable to recruitment failure [65]. These findings indicate that post-fire seedling development varies depending on local biotic and abiotic conditions, particularly during early successional stages [23]. A clear understanding of these ecological processes is essential for designing effective post-disturbance management strategies that enhance resilience in Mediterranean pine ecosystems, together with our ability to mitigate the impacts of future wildfires on these forest systems, especially in a scenario driven by climate change [66].

Soil characteristics may also have contributed to the contrasting regeneration dynamics observed between the two stands. The higher organic matter content and lower bulk density in the pure pine forest likely improved water retention, nutrient availability, and root penetration, creating more favorable conditions for seedling establishment. Probably, these factors play a critical role in post-fire environments, where early soil recovery and microclimate stabilization strongly influence vegetation resilience [67–70]. The slightly more acidic pH observed in the pure pine forest may reflect enhanced rates of organic matter decomposition and the accumulation of necromass resulting from the absence of salvage logging. This interpretation is consistent with previous studies showing that coarse woody debris promotes microsite diversity, increases soil heterogeneity and facilitates seedling recruitment by buffering temperature and moisture extremes [45,49–51]. Conversely, the mixed pine forest exhibited lower organic matter and higher bulk density, suggesting a more compacted soil structure, possibly due to reduced biomass input and the absence of decomposing wood. In addition, competitive pressure from fire-resilient grasses such as *Ampelodesma* and *Hyparrhenia* may have further inhibited pine seedling recruitment. Similar findings have been observed in Mediterranean post-fire environments, where aggressive herbaceous regrowth suppresses tree regeneration [71,72]. Overall, these soil-related factors appear to mediate post-fire vegetation dynamics and should be considered in the design of post-disturbance management strategies.

Overall, post-fire regeneration in Mediterranean pine forests is strongly influenced by the interplay of fire severity, soil conditions, and biotic interactions. Inappropriate management can delay recovery, reduce biodiversity, and compromise stand resilience Severe fires can degrade soils [25], increase erosion, and eliminate seed banks, all of which hinder natural regeneration. Moreover, climate change is altering wildfire timing, frequency and intensity, posing additional challenges to forest recovery. These findings highlight the need for adaptive management strategies that consider both ecological processes and changing environmental conditions to enhance resilience in Mediterranean pine ecosystems [41,42].

Finally, given the limited number of replicates, our analysis was restricted to descriptive statistics and bivariate comparisons. Although more advanced approaches, such as mixed-effects regression models, could provide a deeper understanding of the combined influence of soil variables on regeneration, the available sample size did not allow for their robust application. Future research with larger datasets should adopt multivariate frameworks to better capture the complex interactions between soil properties and vegetation dynamics in post-fire environments.

While our study focuses on Aleppo pine-dominated Mediterranean forests, similar ecological processes have been observed in other forest types. In boreal conifer forests, such as *Pinus sylvestris* stands in Latvia, delayed removal of deadwood after high-severity fires was found to enhance natural regeneration, whereas immediate salvage logging hindered seedling establishment [73]. In temperate mixed forests of Quercus-Fagus or Pinus-Quercus in North America and Europe, post-fire regeneration patterns are strongly influenced by competition from resprouting understory vegetation and by fire severity, with high-severity events reducing seedling growth and survival [74,75]. In xerophytic conifers of the Palouse region of eastern Washington State, the presence of post-fire necromass facilitates microsite creation, improves soil moisture, and enhances seedling establishment, highlighting the general role of necromass across various ecosystems [76]. Similarly, in a black pine mixed with manna ash forest plantation in Central Italy, the presence of downed logs in post-fire areas stabilizes soil temperature and maintains higher soil moisture, creating favorable conditions for seedling recruitment [77]. These comparisons indicate that, although species composition, climatic conditions, and soil characteristics modulate regeneration dynamics, the facilitative effects of deadwood and the influence of pre-existing vegetation are recurrent patterns in post-fire forest ecosystems globally.

5. Conclusions

This study provides new insights into post-fire regeneration dynamics and soil conditions in Aleppo pine forests of southern Italy, seven years after a high-severity crown fire. Natural regeneration was abundant, particularly in pure pine stands where higher fire severity and partial deadwood retention favored seedling establishment by creating more suitable microclimatic conditions and reducing herbaceous competition. Higher organic matter content and lower bulk density in these stands further supported root development and water retention, highlighting the important role of soil properties in post-fire recovery.

Despite the limited spatial and temporal scope of this study, the results offer important implications for forest management. They show that site-specific strategies considering fire severity and soil conditions can effectively promote natural regeneration while minimizing intervention costs, in line with sustainable forest management principles. Nevertheless, the observed ecological responses varied with stand type and fire severity, underlining the importance of local assessments. Retaining residual necromass and allowing natural recovery not only supports seedling establishment but also maintains soil fertility and enhances long-term ecosystem resilience, key aspects of sustainable ecosystem stewardship. Overall, adaptive, evidence-based post-fire strategies can reconcile fire management with biodiversity conservation and sustainable resource use in Mediterranean pine forests. Future research should integrate long-term monitoring and functional soil indicators to better elucidate post-fire successional trajectories, particularly under the combined pressures of climate change and increasing fire frequency.

Author Contributions: Conceptualization, P.A.M.; methodology, P.A.M.; investigation, P.A.M., S.B., E.E. and M.M.; resources, P.A.M.; writing—original draft preparation, P.A.M.; writing—review and editing, P.A.M., S.B., E.E. and M.M.; supervision, P.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Next Generation EU—Italian NRRP, Mission 4, Component 2, Investment 1.5, call for the creation and strengthening of 'Innovation Ecosystems', building 'Territorial R&D Leaders' (Directorial Decree n. 2021/3277)—Project Tech4You—Technologies for climate change adaptation and quality of life improvement, n. ECS0000009, CUP: C33C22000290006. This work reflects only the authors' views and opinions; neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lange, M.A. Climate Change in the Mediterranean: Environmental Impacts and Extreme Events. *IEMed. Mediterr. Yearb.* **2020**, *2020*, 30–45.
2. Salis, M.; Del Giudice, L.; Alcasena-Urdiroz, F.; Jahdi, R.; Arca, B.; Pellizzaro, G.; Scarpa, C.; Duce, P. Assessing Cross-Boundary Wildfire Hazard, Transmission, and Exposure to Communities in the Italy-France Maritime Cooperation Area. *Front. For. Glob. Change* **2023**, *6*, 1241378. [CrossRef]
3. Guiot, J.; Cramer, W. Climate Change: The 2015 Paris Agreement Thresholds and Mediterranean Basin Ecosystems. *Science* **2016**, *354*, 465–468. [CrossRef] [PubMed]
4. Moreno, M.; Bertolín, C.; Arlanzón, D.; Ortiz, P.; Ortiz, R. Climate Change, Large Fires, and Cultural Landscapes in the Mediterranean Basin: An Analysis in Southern Spain. *Heliyon* **2023**, *9*, e16941. [CrossRef] [PubMed]
5. Fernandes, P.M.; Monteiro-Henriques, T.; Guiomar, N.; Loureiro, C.; Barros, A.M.G. Bottom-Up Variables Govern Large-Fire Size in Portugal. *Ecosystems* **2016**, *19*, 1362–1375. [CrossRef]
6. dos Santos, S.M.B.; Bento-Gonçalves, A.; Franca-Rocha, W.; Baptista, G. Assessment of Burned Forest Area Severity and Postfire Regrowth in Chapada Diamantina National Park (Bahia, Brazil) Using dNBR and RdNBR Spectral Indices. *Geosciences* **2020**, *10*, 106. [CrossRef]
7. Rodrigues, M.; Cunill Camprubí, À.; Balaguer-Romano, R.; Coco Megía, C.J.; Castañares, F.; Ruffault, J.; Fernandes, P.M.; Resco de Dios, V. Drivers and Implications of the Extreme 2022 Wildfire Season in Southwest Europe. *Sci. Total Environ.* **2023**, *859*, 160320. [CrossRef]
8. Fournier, T.; Fèvre, J.; Carcaillet, F.; Carcaillet, C. For a Few Years More: Reductions in Plant Diversity 70 Years After the Last Fire in Mediterranean Forests. *Plant Ecol.* **2020**, *221*, 559–576. [CrossRef]
9. Abrhám, J.; Soukupova, J.; Prochazka, P. Wildfires and Tourism in the Mediterranean: Balancing Conservation and Economic Interests. *BioResources* **2025**, *20*, 500–526. [CrossRef]
10. Dupuy, J.L.; Fargeon, H.; Martin-StPaul, N.; Pimont, F.; Ruffault, J.; Guijarro, M.; Hernando, C.; Madrigal, J.; Fernandes, P. Climate Change Impact on Future Wildfire Danger and Activity in Southern Europe: A Review. *Ann. For. Sci.* **2020**, *77*, 35. [CrossRef]
11. Fernandez-Anez, N.; Krasovskiy, A.; Muller, M.; Vacik, H.; Baetens, J.; Hukić, E.; Kapovic Solomun, M.; Atanassova, I.; Glushkova, M.; Bogunović, I.; et al. Current Wildland Fire Patterns and Challenges in Europe: A Synthesis of National Perspectives. *Air Soil Water Res.* **2021**, *14*, e117862212110281. [CrossRef]
12. Miebach, A.; Power, M.J.; Resag, T.R.; Netzel, T.; Colombaroli, D.; Litt, T. Changing Fire Regimes During the First Olive Cultivation in the Mediterranean Basin: New High-Resolution Evidence from the Sea of Galilee, Israel. *Glob. Planet. Change* **2022**, *210*, 103774. [CrossRef]
13. Keeley, J.E.; Bond, W.J.; Bradstock, R.A.; Pausas, J.G.; Rundel, P.W. *Fire in Mediterranean Ecosystems: Ecology, Evolution and Management*; Cambridge University Press: New York, NY, USA, 2012.
14. Molina-Terrén, D.M.; Xanthopoulos, G.; Diakakis, M.; Ribeiro, L.; Caballero, D.; Delogu, G.M.; Viegas, D.X.; Silva, C.A.; Cardil, A. Analysis of Forest Fire Fatalities in Southern Europe: Spain, Portugal, Greece and Sardinia (Italy). *Int. J. Wildland Fire* **2019**, *28*, 85–98. [CrossRef]
15. Forzieri, G.; Girardello, M.; Ceccherini, G.; Spinoni, J.; Feyen, L.; Hartmann, H.; Beck, P.S.A.; Camps-Valls, G.; Chirici, G.; Mauri, A.; et al. Emergent Vulnerability to Climate-Driven Disturbances in European Forests. *Nat. Commun.* **2021**, *12*, 1081. [CrossRef] [PubMed]
16. Galizia, L.F.; Curt, T.; Barbero, R.; Rodrigues, M. Understanding Fire Regimes in Europe. *Int. J. Wildland Fire* **2022**, *31*, 56–66. [CrossRef]
17. San-Miguel-Ayanz, J.; Durrant, T.; Boca, R.; Maianti, P.; Liberta, G.; Oom, D.; Branco, A.; De Rigo, D.; Ferrari, D.; Roglia, E.; et al. *Advance Report on Forest Fires in Europe, Middle East and North Africa 2022*; EUR 31479 EN; Publications Office of the European Union: Luxembourg, 2023.
18. Sanesi, G.; Lafortezza, R.; Colangelo, G.; Marziliano, P.A.; Davies, C. Root System Investigation in Sclerophyllous Vegetation: An Overview. *Ital. J. Agron.* **2013**, *8*, e17. [CrossRef]
19. Salesa, D.; Baeza, M.J.; Santana, V.M. Fire Severity and Prolonged Drought Do Not Interact to Reduce Plant Regeneration Capacity but Alter Community Composition in a Mediterranean Shrubland. *Fire Ecol.* **2024**, *20*, 61. [CrossRef]
20. Moreira, F.; Ascoli, D.; Safford, H.; Adams, M.A.; Moreno, J.M.; Pereira, J.M.C.; Catry, F.X.; Armesto, J.; Bond, W.; González, M.E.; et al. Wildfire Management in Mediterranean-Type Regions: Paradigm Change Needed. *Environ. Res. Lett.* **2020**, *15*, 011001. [CrossRef]
21. Cos, J.; Doblas-Reyes, F.; Jury, M.; Marcos, R.; Bretonnière, P.A.; Samsó, M. The Mediterranean Climate Change Hotspot in the CMIP5 and CMIP6 Projections. *Earth Syst. Dyn.* **2022**, *13*, 321–340. [CrossRef]
22. Marziliano, P.A.; Lombardi, F.; Cataldo, M.F.; Mercuri, M.; Papandrea, S.F.; Manti, L.M.; Bagnato, S.; Alì, G.; Fusaro, P.; Pantano, P.S.; et al. Forest Fires: Silvicultural Prevention and Mathematical Models for Predicting Fire Propagation in Southern Italy. *Fire* **2024**, *7*, 278. [CrossRef]

23. Bombino, G.; D'Agostino, D.; Marziliano, P.A.; Pérez Cutillas, P.; Praticò, S.; Proto, A.R.; Manti, L.M.; Lofaro, G.; Zimbone, S.M. A Nature-Based Approach Using Felled Burnt Logs to Enhance Forest Recovery Post-Fire and Reduce Erosion Phenomena in the Mediterranean Area. *Land* **2024**, *13*, 236. [CrossRef]
24. Coello, J.; Cortina, J.; Valdecantos, A.; Varela, E. *Forest Landscape Restoration Experiences in Southern Europe: Sustainable Techniques for Enhancing Early Tree Performance*; FAO: Rome, Italy, 2015; Volume 66.
25. Romeo, F.; Marziliano, P.A.; Turrión, M.B.; Muscolo, A. Short-Term Effects of Different Fire Severities on Soil Properties and Pinus halepensis Regeneration. *J. For. Res.* **2020**, *31*, 1271–1282. [CrossRef]
26. Iovino, F.; Nicolaci, A.; Marziliano, P.A.; Pignataro, F.; Sanesi, G. Lessons Learned from the Past: Forestry Initiatives for Effective Carbon Stocking in Southern Italy. *Ann. Silvic. Res.* **2021**, *46*, 99–111.
27. Proto, A.R.; Bernardini, V.; Cataldo, M.F.; Zimbalatti, G. Whole Tree System Evaluation of Thinning a Pine Plantation in Southern Italy. *Ann. Silvic. Res.* **2020**, *45*, 44–52.
28. de Pagter, T.; Lucas-Borja, M.E.; Navidi, M.; Carra, B.G.; Baartman, J.; Zema, D.A. Effects of Wildfire and Post-Fire Salvage Logging on Rainsplash Erosion in a Semi-Arid Pine Forest of Central Eastern Spain. *J. Environ. Manag.* **2023**, *329*, 117059. [CrossRef] [PubMed]
29. La Mantia, T.; Da Silveira, B.R.; Badalamenti, E.; Calabria, S.; Giardina, G.; La Mela Veca, D.S.; Laschi, A.; Maetzke, F.; Palazzolo Fara, L.M.; Sala, G. Risultati di Azioni di Rimboschimento in Diversi Contesti Pedoclimatici Siciliani. In *Alberi-Foreste-Biodiversità: Dal New Green Deal alla Farm to Fork Strategy, Proceedings of the XIII Congresso SISEF, Orvieto, Italy, 30 May–2 June 2022*; Paris, P., Calfapietra, C., Motta, R., Travaglini, D., Bucci, G., Eds.; Abstract-Book Posters; SISEF: Viterbo, Italy, 2022; p. 30.
30. FAO. *World Reference Base for Soil Resources: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2014.
31. D'Angelo, N.; Albano, A.; Gilardi, A.; Adelfio, G. Spatio-Temporal Modelling of Fires in Sicily. In *Methodological and Applied Statistics and Demography II. SIS 2024*; Pollice, A., Mariani, P., Eds.; Springer: Cham, Switzerland, 2024. [CrossRef]
32. *ISO 10390:2005*; Soil Quality—Determination of pH. International Organization for Standardization: Geneva, Switzerland, 2005.
33. Nelson, D.W.; Sommers, L.E. Total Carbon, Organic Carbon, and Organic Matter. In *Methods of Soil Analysis. Part 3—Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America and American Society of Agronomy: Madison, WI, USA, 1996; pp. 961–1010. [CrossRef]
34. Blake, G.R.; Hartge, K.H. Bulk Density. In *Methods of Soil Analysis. Part 1—Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; American Society of Agronomy and Soil Science Society of America: Madison, WI, USA, 1986; pp. 363–375. [CrossRef]
35. Zar, J.H. *Biostatistical Analysis*, 3rd ed.; Prentice Hall Inc.: Englewood Cliffs, NJ, USA, 1996; p. 718.
36. Montgomery, D. *Introduction to Statistical Quality Control*, 4th ed.; John Wiley & Sons: New York, NY, USA, 2001; p. 795.
37. Soliani, L. *Statistica Applicata [Applied Statistics]*; UNI.NOVA: Parma, Italy, 2008; p. 694.
38. Naveh, Z. The Evolutionary Significance of Fire in the Mediterranean Region. *Science* **1975**, *188*, 1007–1012. [CrossRef]
39. Harvey, B.J.; Holzman, B.A. Divergent Successional Pathways of Stand Development Following Fire in a California Closed-Cone Pine Forest. *J. Veg. Sci.* **2014**, *25*, 88–99. [CrossRef]
40. Wilson, J.B. Does the Initial Floristic Composition Model of Succession Really Work? *J. Veg. Sci.* **2014**, *25*, 4–5. [CrossRef]
41. Blanco-Rodríguez, M.Á.; Ameztegui, A.; Gelabert, P.; Rodrigues, M.; Coll, L. Short-term recovery of post-fire vegetation is primarily limited by drought in Mediterranean forest ecosystems. *Fire Ecol.* **2023**, *19*, 68. [CrossRef]
42. Peris-Llopis, M.; Vastaranta, M.; Saarinen, N.; González-Olabarria, J.R.; García-Gonzalo, J.; Mola-Yudego, B. Post-fire vegetation dynamics and location as main drivers of fire recurrence in Mediterranean forests. *For. Ecol. Manag.* **2024**, *568*, 122126. [CrossRef]
43. Mendez-Cartin, A.L.; Coll, L.; Valor, T.; Torné-Solà, G.; Ameztegui, A. Post-fire growth of Pinus halepensis: Shifts in the mode of competition along a precipitation gradient. *For. Ecol. Manag.* **2024**, *554*, 121693. [CrossRef]
44. Borghetti, M.; Colangelo, M.; Ripullone, F.; Rita, A. Ondate di Siccità e Calore, Spunti per una Selvicoltura Adattativa. *For.-J. Silvic. For. Ecol.* **2021**, *18*, 49.
45. Steinebrunner, F.; Tischer, A.; Medicus, T.; Huth, F.; Bernhardt-Römermann, M. The effects of deadwood on tree regeneration and microsites: A systematic review. *For. Ecol. Manag.* **2025**, *596*, 123096. [CrossRef]
46. Lindenmayer, D.B.; Noss, R.F. Salvage Logging, Ecosystem Processes, and Biodiversity Conservation. *Conserv. Biol.* **2006**, *20*, 949–958. [CrossRef]
47. Maiullari, G.; Leone, V.; Lovreglio, R. Post-Fire Regeneration in Artificial Stands of Pinus halepensis Miller. *L'Italia For. E Mont.* **2005**, *6*, 287–702.
48. Parro, K.; Metslaid, M.; Renel, G.; Sims, A.; Stanturf, J.A.; Jõgiste, K.; Köster, K. Impact of Postfire Management on Forest Regeneration in a Managed Hemiboreal Forest, Estonia. *Can. J. For. Res.* **2015**, *45*, 1192–1197. [CrossRef]
49. Marcolin, E.; Marzano, R.; Vitali, A.; Garbarino, M.; Lingua, E. Post-Fire Management Impact on Natural Forest Regeneration through Altered Microsite Conditions. *Forests* **2019**, *10*, 1014. [CrossRef]

50. Bujoczek, L.; Bujoczek, M.; Banaś, J.; Zięba, S. Spruce regeneration on woody microsites in a subalpine forest in the western Carpathians. *Silva Fenn.* **2015**, *49*, 1337. [CrossRef]
51. Rammig, A.; Fahse, L.; Bebi, P.; Bugmann, H. Wind disturbance in mountain forests: Simulating the impact of management strategies, seed supply, and ungulate browsing on forest succession. *For. Ecol. Manag.* **2007**, *242*, 142–154. [CrossRef]
52. Lingua, E.; Marques, G.; Marchi, N.; Garbarino, M.; Marangon, D.; Taccaliti, F.; Marzano, R. Post-Fire Restoration and Deadwood Management: Microsite Dynamics and Their Impact on Natural Regeneration. *Forests* **2023**, *14*, 1820. [CrossRef]
53. Peña-Molina, E.; Moya, D.; Merino, A.; Fajardo-Cantos, A.; Díaz-Montero, A.; García-Orenes, F.; Lucas-Borja, M.E.; de las Heras, J. Fire and salvage logging increased recalcitrant soil organic matter and reduced soil functionality in Mediterranean pine forests. *For. Ecol. Manag.* **2024**, *573*, 122344. [CrossRef]
54. Donato, D.C.; Fontaine, J.B.; Campbell, J.L.; Robinson, W.D.; Kauffman, J.B.; Law, B.E. Post-wildfire logging hinders regeneration and increases fire risk. *Science* **2006**, *311*, 352. [CrossRef]
55. Marzano, R.; Garbarino, M.; Marcolin, E.; Pividori, M.; Lingua, E. Deadwood anisotropic facilitation on seedling establishment after a stand-replacing wildfire in Aosta Valley (NW Italy). *Ecol. Eng.* **2013**, *51*, 117–122. [CrossRef]
56. Thorn, S.; Bässler, C.; Svoboda, M.; Müller, J. Effects of natural disturbances and salvage logging on biodiversity. Lessons from the Bohemian Forest. *For. Ecol. Manag.* **2017**, *388*, 113–119. [CrossRef]
57. Leverkus, A.B.; Rey Benayas, J.M.; Castro, J.; Boucher, D.; Brewer, S.; Collins, B.M.; Donato, D.; Fraver, S.; Kishchuk, B.E.; Lee, E.J.; et al. Salvage logging effects on regulating and supporting ecosystem services—A systematic map. *Can. J. For. Res.* **2018**, *48*, 983–1000. [CrossRef]
58. Bodí, M.B.; Cerdda, A.; Mataix-Solera, J.; Doerr, S. A review of fire effects on vegetation and soil in the Mediterranean basin. *Bol. Asoc. Geogr. Esp.* **2012**, *58*, 439–441.
59. Riba, M.; Retana, J. Fire effects on pine reproductive ecology mediated by vegetation structure. *For. Ecol. Manag.* **2008**, *255*, 117–125.
60. Souza-Alonso, P.; Saiz, G.; García, R.A.; Pauchard, A.; Ferreira, A.; Merino, A. Post-fire ecological restoration in Latin American forest ecosystems: Insights and lessons from the last two decades. *For. Ecol. Manag.* **2022**, *509*, 120083. [CrossRef]
61. Andrus, R.A.; Droske, C.A.; Franz, M.C.; Hudak, A.T.; Lentile, L.B.; Lewis, S.A.; Morgan, P.; Robichaud, P.R.; Meddens, A.J.H. Spatial and temporal drivers of post-fire tree establishment and height growth in a managed forest landscape. *Fire Ecol.* **2022**, *18*, 29. [CrossRef]
62. Keeley, J.E.; Fotheringham, C.J.; Baer-Keeley, M. Factors affecting plant diversity during post-fire recovery and succession of Mediterranean-climate shrublands in California, USA. *Divers. Distrib.* **2005**, *11*, 525–537. [CrossRef]
63. Bond, W.J.; Midgley, G.F. Ecology of sprouting in woody plants: The persistence niche. *Trends Ecol. Evol.* **2001**, *16*, 45–51. [CrossRef]
64. Tilman, D. Community invasibility, recruitment limitation, and grassland biodiversity. *Ecology* **1997**, *78*, 81–92. [CrossRef]
65. Elvira, N.J.; Lloret, F.; Margalef-Marrase, J.; Borrego, R.D.; Batllori, E. Position in the climatic niche modulates post-fire performance of Pinus halepensis regeneration. *For. Ecol. Manag.* **2025**, *580*, 122516. [CrossRef]
66. Ermitão, T.; Gouveia, C.M.; Bastos, A.; Russo, A.C. Recovery Following Recurrent Fires Across Mediterranean Ecosystems. *Glob. Change Biol.* **2024**, *30*, e70013. [CrossRef]
67. Certini, G. Effects of fire on properties of forest soils: A review. *Oecologia* **2005**, *143*, 1–10. [CrossRef]
68. Naveh, Z. The role of fire in the Mediterranean: Human-environment interactions. In *Fire and the Environment*; Goldammer, J.G., Moreno, J., Eds.; SPB Academic Publishing: The Hague, The Netherlands, 1994; pp. 163–173.
69. Mataix-Solera, J.; Cerdà, A.; Arcenegui, V.; Jordán, A.; Zavala, L.M. Fire effects on soil aggregation: A review. *Earth-Sci. Rev.* **2009**, *92*, 141–163. [CrossRef]
70. García-Carmona, M.; García-Orenes, F.; Arcenegui, V.; Mataix-Solera, J. The Recovery of Mediterranean Soils After Post-Fire Management: The Role of Biocrusts and Soil Microbial Communities. *Span. J. Soil Sci.* **2023**, *13*, 11388. [CrossRef]
71. Trabaud, L. Postfire plant community dynamics in the Mediterranean Basin. In *Plant–Animal Interactions in Mediterranean-Type Ecosystems*; Arianoutsou, M.J., Groves, R.H., Eds.; Springer: Dordrecht, The Netherlands, 1994; pp. 1–15.
72. Retana, J.; Espelta, J.M.; Habrouk, A.; Ordóñez, J.L.; de Solà-Morales, F. Regeneration patterns of three Mediterranean pines and forest changes after a large wildfire in northeastern Spain. *Ecoscience* **2002**, *9*, 89–97. [CrossRef]
73. Kārkliņa, A.; Brūmelis, G.; Dauškane, I.; Elferts, D.; Freimane, L.; Kitenberga, M.; Lībiete, Z.; Matisons, R.; Jansons, Ā. Effect of salvage-logging on post-fire tree establishment and ground cover vegetation in semi-natural hemiboreal forests. *Silva Fenn.* **2020**, *54*, 10334. [CrossRef]
74. Hutto, R.L. The ecological importance of severe wildfires: Some like it hot. *Ecol. Appl.* **2008**, *18*, 1827–1834. [CrossRef]
75. Neary, D.G.; Ryan, K.C.; DeBano, L.F. *Wildland Fire in Ecosystems: Effects of Fire on Soils and Water*; General Technical Reports 2005; RMRS-GTR-42-vol. 4; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2005; 250p. [CrossRef]

76. Swanson, M.E.; Franklin, J.F.; Beschta, R.L.; Crisafulli, C.M.; Della Sala, D.A. Experimental downed woody debris-created microsites enhance tree survival and growth in extreme summer heat. *Front. For. Glob. Change* **2023**, *6*, 1224624. [CrossRef]
77. Taccaliti, F.; Marzano, R.; Santoro, M. Soil temperature and moisture near downed trees and logs: Implications for post-fire regeneration. *Fire Ecol.* **2025**, *21*, 365. [CrossRef]