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Burn Severity and Postfire Salvage Logging Effects on Vegetation and Soil System in a Short-Term Period in Mediterranean Pine Forests

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Abstract: Wildfires are a natural part of the dynamics of Mediterranean forest ecosystems. The fire patterns in the Mediterranean basin have been altered mainly due to changes in land use and climate change. In 2017, a wildfire in Yeste (Spain) burned 3200 hectares of two Mediterranean pine forests. We investigated the effects of burn severity and postfire salvage logging practices on vegetation and soil properties in four experimental areas distributed within the wildfire perimeter. These areas included unburned, low, high, and high burn severity with salvage logging, all located under *Pinus halepensis* Mill and *Pinus pinaster* Aiton stands. Salvage logging was applied 18 months after the fire. We established 72 circular plots (nine per treatment and pine species). We collected soil samples to analyze physicochemical and biological soil properties, including pH, electrical conductivity (EC), soil organic matter (SOM) content, carbon from microbial biomass (CBM), basal soil respiration (BSR), metabolic quotient (qCO_2), and two enzymatic activities: β-glucosidase (GLU) and phosphatase (PHP). To understand how vegetation changed after fire, we implemented three linear transects per plot to calculate α-diversity indices (richness, Shannon, and Simpson), vegetation coverage (COBV), fraction of bare soil (BSOIL), the number of postfire seedlings (NSeed) and their average height (Hm), and we grouped vegetation into different postfire adaptive strategies: facultative seeder (R+S+), obligate resprouter (R+S−), obligate seeder (R−S+), and non-fire-adapted (R−S−). We ran ANOVA and Tukey's HSD post hoc tests to evaluate the differences between burn severity and salvage logging practices on the variables examined for each pine stand. We used PCA and correlation analysis to identify plant-soil interactions. Our results suggest that *Pinus halepensis* stands were more affected by the wildfire than *Pinus pinaster* stands due to the distinct characteristics of each species (morphology of the leaves, bark thickness, cone structure, etc.) and the significant differences observed in terms of pH, SOM, CBM, qCO_2, GLU, PHP, and Nseed. The proportion of obligate resprouter species was higher in *Pinus halepensis* stands, and the obligate seeder species were higher in *Pinus pinaster* stands. The study highlighted the importance of monitoring burn severity and postfire management practices to promote forest recovery and reduce wildfire risk. Limiting the negative impact of postfire salvage logging practices can enhance the resilience of vulnerable ecosystems.

Keywords: forest management; salvage logging; soils; vegetation; wildfires

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Citation: Peña-Molina, E.; Moya, D.; Fajardo-Cantos, Á.; García-Orenes, F.; Mataix-Solera, J.; Arcenegui, V.; Lucas-Borja, M.E.; de las Heras, J. Burn Severity and Postfire Salvage Logging Effects on Vegetation and Soil System in a Short-Term Period in Mediterranean Pine Forests. *Fire* **2024**, 7, 127. https://doi.org/10.3390/fire7040127

Academic Editor: Grant Williamson

Received: 16 March 2024
Revised: 5 April 2024
Accepted: 8 April 2024
Published: 9 April 2024

1. Introduction

Wildfires are a natural phenomenon in Mediterranean areas [1,2]. However, large wildfires have increased worldwide in recent years due to climate change. There are many examples of bushfires worldwide, like the Canary Islands wildfires in 2019, with more than 12,000 hectares burned; the Amazon Rainforest fires in 2019, which burned more than 800,000 hectares; the California Dixie Fire in 2021, which burned more than 380,000 hectares and more recently, the Australian bushfire season of 2019–2020, where more than 18.6 million hectares were burned. For European countries, the 2022 wildfire season was the second worst on record [3], according to European Forest Fire Information System (EFFIS) data. These high-severity wildfires severely impact the biosphere by causing deaths of species, habitat destruction, and forest loss, among other results [4]. They also decrease air quality and population health and emit large amounts of CO_2 [5]. Due to increasingly hot, dry conditions, the number of these perturbations will continue to increase [6,7], and it will be necessary to improve the application of forward-looking fire management policies. These efforts should include prevention, suppression, and restoration strategies, mainly investing in the early extinction stage [8–10].

In this context, forest management and restoration activities are critical tools for enhanced ecological resilience in fire-prone areas [11–14]. Regeneration following a wildfire is directly related to burn severity [15–18], which is crucial to establishing practical postfire management areas [19] and can be defined as the effect of fire on the environment. It refers to the extent of the immediate fire effects on vegetation (aboveground) and soils (belowground) due to the loss or decomposition of organic matter. The composite burn index (CBI) [20] combines fire severity metrics and ecosystem responses to fire, including substrates (litter, duff, fuel, and soil), herbs, shrubs, trees, and seedling trees. It ranges from 0.0 (unburned) to 3.0 (high-severity) [21]. Burn severity directly impacts both the regeneration of plants and the recovery of the soil following wildfires by limiting natural plant regeneration and reducing soil functionality [22]. According to the review analysis conducted by Agbeshie et al. (2022) [23], soil is the most valuable natural resource. It intervenes in essential processes such as carbon sequestration, nutrient cycling, mineral storage, and plant growth sustainability. Soil organic carbon (SOC), soil reaction (pH), nitrogen (N), phosphorus (P), soil water repellency (SWR), and biological parameters are within the most fire-sensitive soil properties.

There is substantial research on forest management following wildfires and their effects on soil properties and vegetation recovery [16,23–25]. Forest management and restoration practices can help to reduce the impacts of burn severity. Still, it is essential to carefully consider the tradeoffs between economic objectives and fire resilience when managing large-scale forest restoration activities [26,27]. Postfire interventions encompass a range of actions that aim to mitigate the impacts of wildfires. These interventions include implementing soil erosion control measures utilizing natural and artificial materials on various scales, such as erosion barriers and check-dams, which can be deployed at hillslope and stream levels. Additionally, postfire activities may involve establishing tree plantations, salvage logging operations to remove burnt trees, or facilitating natural ecosystem regeneration. Of all the postfire restoration activities, salvage logging is one of the more contentious actions in the scientific community due to its potentially harmful effects on soil and vegetation properties [28–33]. On the one hand, salvage logging is often used to recover part of the economic value of forests and reduce insect outbreaks [34,35]. On the other hand, salvage logging can impede plant cover regeneration [36] and contribute to soil disturbance and erosion [31]. While the impacts mentioned above are typically contingent on specific contextual factors, further research is necessary to assist managers and policymakers worldwide in determining whether salvage logging will promote restoring values and processes in disturbed forests under their particular local conditions [37].

The primary goal of this study was to assess the ecological response of the ecosystem properties following a wildfire in Yeste (Spain) on 27 July 2017, which resulted in the burning of 3200 hectares with varying degrees of burn severity. The specific aims included:

(i) Evaluating the effects of burn severity and the immediate impacts of postfire salvage logging interventions on soil system properties in the designated stands: *Pinus halepensis* Mill and *Pinus pinaster* Aiton;

(ii) Examining vegetation population dynamics by considering two pine stands in the fire-affected perimeter. This analysis assessed the dominant tree species alongside the associated thermo-Mediterranean shrub vegetation.

In summary, this study aimed to evaluate whether salvage logging exacerbates the damage caused by wildfires in terms of soil functionality and vegetation recovery or if salvage logging has no more substantial impact than the degradation caused by wildfires. Our initial hypothesis was that burn severity and salvage logging practices would affect vegetation and soil recovery, and the different pine stands would differ in their response to fire due to their inherent characteristics and strategies in response to fire (*Pinus halepensis* Mill. is more serotinous, and *Pinus pinaster* Aiton regeneration depends more on soil seed bank) [38].

2. Materials and Methods

2.1. Study Area

The study area was in the Albacete province (Spain), in the SE region of Spain (Figure 1). On 27 July 2017, a forest fire started in the area known as "La Parrilla", located in the Yeste municipality (Spain). After several days, the fire was finally controlled on 9 August at 5:48 p.m., and 3200 hectares had been burned. On the days when fire continued and was out of control, the atmospheric conditions were characterized by stability and dry air, influenced by the Saharan continental air mass and the high-pressure systems prevailing over the Iberian Peninsula. These conditions were only disrupted by a SW advection episode and the localized low-pressure areas that resulted from heating the air close to the land surface. Given these conditions, the predominant west and northwest wind increased in magnitude and was further aided by local winds. The situation led to higher intensity and faster fire spread on the afternoons of 28 and 30 July, estimated at around 30–35 m/min. The Castilla-La Mancha Regional Forest Service provided all this information. The fire perimeter was calculated using remote-sensing techniques, supported by fieldwork and aerial photographs taken from a helicopter [39]. The burn severity was obtained following [40].

Based on the Köppen-Geiger climate classification [41], the study area has a hot summer Mediterranean climate ("Cs" type). Climate data, including the mean annual precipitation from 400–600 mm and the mean temperatures from 10–14 °C, were obtained from the Agricultural Geographic Information System [42]. The soils in the area were classified as Aridisols and Inceptisols according to the USDA Soil Taxonomy [43]. The natural vegetation community in the study area consisted of forests dominated by *Pinus halepensis* Mill. and *Pinus pinaster* Aiton pine trees, accompanied by various shrub species, including *Quercus coccifera* L., *Pistacia lentiscus* L., *Viburnum tinus* L., *Phyllirea angustifolia* L., *Arbutus unedo* L., *Lonicera implexa* Ait., *Daphne gnidium* L., *Rubia peregrina* L., *Juniperus oxycedrus* L., among others.

This study followed the postfire activities undertaken by the Castilla-La Mancha Regional Forest Service following the 2017 fire. Eighteen months after the wildfire (Figure 2), the Regional Forest Service implemented several postfire emergency actions in the burned area, including stream stabilization and salvage logging. Check-dams were constructed on slopes along primary streams in publicly and privately owned areas to decrease water velocity and promote the accumulation of sediments. The check dams had a width of 6 m on either side of the barracks' axis, measured in a straight line. Within these regions, charred plant material repair constructions were built from fallen, shortened, and fragmented tree trunks. Salvage logging practices consisted of removing tree trunks to reduce the amount of valuable timber lost and prevent insect outbreaks. No salvage logging treatment was conducted in low burn severity areas because the trees remained alive, making it unnecessary to justify extensive treatment. This type of postfire management action is typically implemented in areas of high burn severity to mitigate economic losses, minimize visual impact, prevent tree falls, and reduce the risk and severity of future fires.

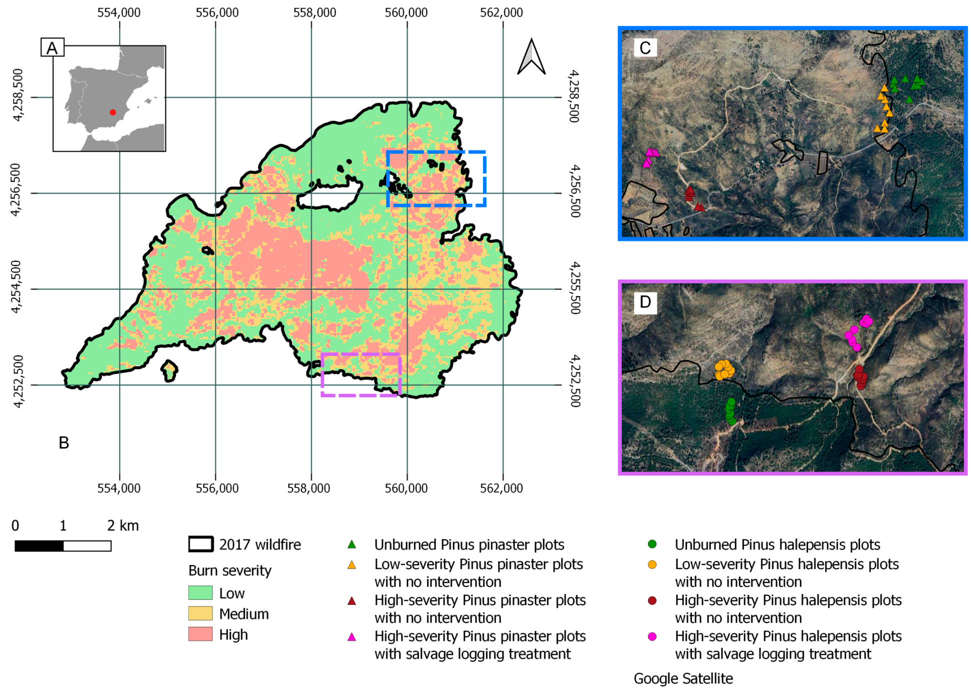

Figure 1. (**A**) Location of the Albacete Province in Spain; (**B**) the study area with the Yeste wildfire (black) and burn severity; (**C**) *Pinus pinaster* Aiton stands; (**D**) *Pinus halepensis* Mill. stands. Plots on each stand are classified as unburned, low-burn severity, high-burn severity, high-burn severity with salvage logging treatment, and background with the Google satellite. The reference coordinate system was ETRS89 (EPSG:25830).

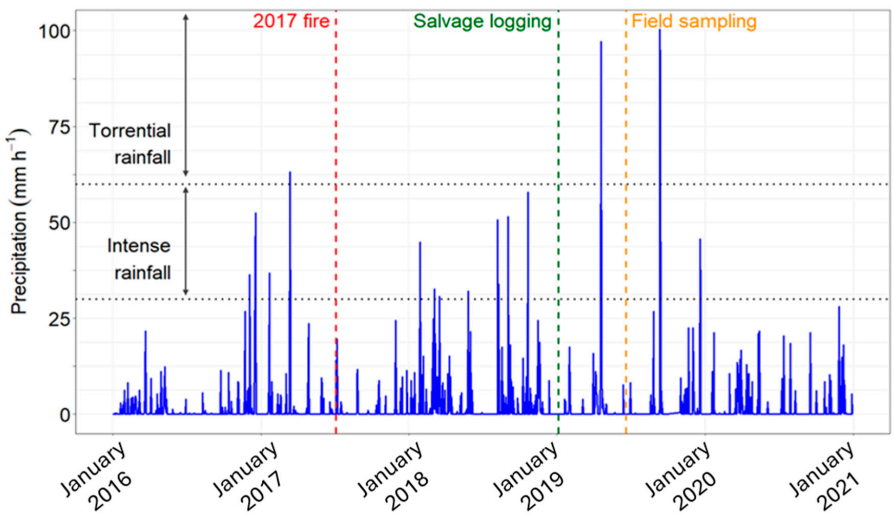

Figure 2. Historical intensity of precipitation (mm h^{-1}) for the research area (Yeste, Spain) from 2016 to 2021 [44]. The year of the fire is marked in red; the salvage logging treatment is colored in green, and the field sampling is in yellow.

Based on burn severity, pine forest (dominated by *Pinus halepensis* or *Pinus pinaster*), and postfire emergency action (salvage logging treatment or no treatment), we monitored several areas:

(1) High-severity plots with no intervention;
(2) High-severity plots with salvage logging treatment;
(3) Low-severity plots with no intervention;
(4) Unburned areas with no intervention at all.

In April 2019, the first torrential rainfall (>60 mm h^{-1}) happened after the salvage logging treatment (Figure 2). Our study was conducted two months later, in the summer of 2019.

2.2. Experimental Design

The experimental areas (unburned, low-severity, high-severity, and high-severity with salvage logging treatment) were replicated at two pine forest sites (*Pinus halepensis* and *Pinus pinaster* stands). In each pine forest, nine plots were established per experimental area. The selected plots shared similar aspects (SE), slopes (20–40%), and soil types (loam). As a result, 72 circular plots of variable size were established (36 plots designated per pine species). The radius of plots was calculated as the ratio of the crown diameter to its base diameter from the pines selected from unburned areas. The base diameter of the *Pinus pinaster* plots was multiplied by 6.755 (R^2 = 99.87%) to acquire the crown diameter in those areas where salvage logging was implemented, while the *Pinus halepensis* plots were multiplied by 2.31 (R^2 = 99.33%). The center of each plot was georeferenced using a high-precision GPS device (Garmin International, Inc., Olathe, KS, USA), with a randomly selected tree serving as the center point.

2.3. Soil System Properties

According to earlier research conducted by Moya et al. (2019) and Jiménez-Morillo et al. (2020) [45,46], three soil samples were gathered from each plot in June 2019. Each sample was composed of six subsamples randomly collected from different locations in the plot. After removing surface litter, the top 2–3 cm mineral soil was excavated using a 20 × 20 cm box. Afterwards, subsamples were combined inside a plastic bag and refrigerated at 4 °C until they were sent to be analyzed.

The physicochemical characterization was based on a soil analysis conducted in the summer of 2019 to record texture, pH, electrical conductivity (EC, µS cm^{-1}), and soil organic matter (SOM, %). Since soil quality indicators are sensitive to fire [47,48], the parameters selected in this study include the carbon from the soil microbial biomass (CBM, mg C Kg $soil^{-1}$), basal soil respiration (BSR, mg C-CO_2 Kg $soil^{-1}$ h^{-1}), metabolic quotient (qCO_2, mg C-CO_2 Kg^{-1} biomass C h^{-1}) and two enzymatic activities: β-glucosidase (GLU, µmol p-NP g $soil^{-1}$ h^{-1}), and phosphatase (PHP, µmol p-NP g $soil^{-1}$ h^{-1}). BSR was measured with an automated impedance meter (BacTrac 4200 Microbiological Analyser, Sylab, Austria), using CO_2 emissions by soil microorganisms at 30 °C for 24 h, as detected by indirect impedance measurement. CBM was also measured in the impedance meter as substrate-induced respiration with glucose (3 mg per gram of soil) as carbon substrate according to the Anderson and Domsch (1978) [49] method. The metabolic quotient (qCO_2) was calculated as the ratio BSR:CBM.

2.4. Vegetation Index Calculations

To characterize the existing vegetation, three linear transects were set up from the center of each plot to determine α-diversity with three indices: species richness (S) as the total number of species; species abundance (Shannon Index, H) [50]; and species dominance (Simpson, D) [51]. The first transect was oriented along the maximum slope line, and the remaining two transects were spaced 120 degrees apart from the first one. The intersecting length of each species that perpendicularly touched the line along the linear transects was measured following Canfield's linear transect method [52]. The complete species list is described in Supplementary Materials (Table S1). A visual vegetation cover estimation (COBV, %) and percentage of bare soil (BSOIL, %) were calculated on each plot. COBV was assessed using the improved Braun-Blanquet method [53]. Additionally, three square subplots (1 m^2) were placed in the middle of each transect. At the square subplots (1 m^2), the number of seedlings (NSeed) and their average height (Hm) were counted and measured, respectively.

Using the plant trait database for Mediterranean Basin species (BROT), we classified species according to their fire-adapted traits as facultative seeder (R+S+), obligate resprouter (R+S−), obligate seeder (R−S+), and non-fire-adapted (R−S−) [54]. The visually estimated species coverages for each trait type were merged and averaged.

2.5. Statistical Analyses

Every analysis was conducted utilizing version 4.3.2 of Rstudio [55] with a 95% level of statistical significance. We tested the normality and homoscedasticity assumptions using the Shapiro-Wilk and Levene tests. Data transformations were performed as required. For each pine forest, a one-way analysis of variance (ANOVA) test was conducted to examine the impact of burn severity and salvage logging on the soil properties and vegetation indices. We excluded the pine forest component from the ANOVA tests due to the variation in pine species composition (*P. halepensis* vs. *P. pinaster*), as both species differ in physical, ecological, and biological characteristics and temperaments, which may influence their responses to fire. A Tukey's HSD post hoc test was run to determine which group's means exhibited statically significant differences when comparing one another. We used a principal component analysis (PCA) to describe the variance–covariance structure of the studied variables and correlation analyses to identify the plant–soil interactions. Pearson's correlations were utilized to analyze plant–soil interactions. Additional packages were used to generate the results: 'dplyr' [56] for data manipulation and 'ggplot2' [57] for making graphics and visualizations.

3. Results

3.1. Soil System Properties Analyses

Regarding the pH levels in the *Pinus halepensis* stands, there were no significant variations between the unburned and low-severity plots or between the high-severity and high-severity plots with salvage logging treatment. However, between them (unburned and low-severity vs. high-severity and high-severity with salvage logging treatment), a slight increase in pH (up to 0.2 differential points) was noted as the severity level increased. No significant changes were identified in any case for the *Pinus pinaster* stands.

In EC terms, no significant differences were observed for the *Pinus halepensis* stands. The only significant differences were observed between high-severity with salvage logging treatment and unburned plots in the *Pinus pinaster* stands.

No significant differences were noted for SOM between the high-severity and high-severity with salvage logging treatment plots, but important differences were found between these and the unburned and low-severity plots in the *Pinus halepensis* stands. In addition, a considerable reduction occurred as severity increased. The only significant differences were observed between high-severity and low-severity plots in the *Pinus pinaster* stands. All the results are summarized in Table 1.

Table 1. Physicochemical soil properties (VAR); pH, electrical conductivity (EC, μS cm^{-1}), and soil organic matter (SOM, %); concerning tree species (SP): *Pinus halepensis* Mill. and *Pinus pinaster* Aiton at different levels of burn severity: unburned plots, low-severity plots, high-severity plots, and high-severity plots with salvage logging. Each box includes the mean values ± standard deviations. Groups that do not share a letter differed significantly ($p < 0.05$).

SP	VAR	Unburned	Low-Severity	High-Severity	High-Severity with Salvage Logging Treatment	F	Pr (>F)
Pinus halepensis	pH	8.07 ± 0.07^{b}	8.04 ± 0.05^{b}	8.2 ± 0.01^{a}	8.28 ± 0.01^{a}	14.540	0.013
	EC	195.85 ± 7.28^{a}	246.95 ± 82.05^{a}	148.90 ± 4.94^{a}	154.5 ± 34.64^{a}	2.055	0.249
	SOM	10.09 ± 2.37^{c}	7.24 ± 1.82^{b}	4.17 ± 0.73^{a}	5.24 ± 1.00^{a}	28.520	0.000
Pinus pinaster	pH	8.12 ± 0.15^{a}	7.99 ± 0.08^{a}	7.24 ± 0.94^{a}	7.72 ± 0.31^{a}	14.540	0.013
	EC	174.35 ± 9.82^{a}	118.05 ± 7.42^{ab}	137.30 ± 34.64^{ab}	71.00 ± 5.37^{b}	2.055	0.249
	SOM	6.73 ± 1.37^{ab}	4.79 ± 1.50^{b}	7.26 ± 2.19^{a}	5.50 ± 2.32^{ab}	3.189	0.037

Regarding CBM, no statistically significant differences were noted in the burned (low-severity, high-severity, and high-severity with salvage logging treatment) plots for both *Pinus halepensis* and *Pinus pinaster*. Significant differences appeared only between the unburned plots and all the other groups. No significant differences were observed in any stand for BSR.

Significant changes in GLU were noted between the unburned and low-severity plots compared to the high-severity and high-severity with salvage logging treatment plots in the *Pinus halepensis* stands. No significant variations were observed among the plots in the *Pinus pinaster* stands.

Regarding PHP, a significant reduction occurred as severity increased in the *Pinus halepensis* stands. Although this reduction was still noteworthy in the *Pinus pinaster* stands, it was less pronounced. All the results are summarized in Figure 3.

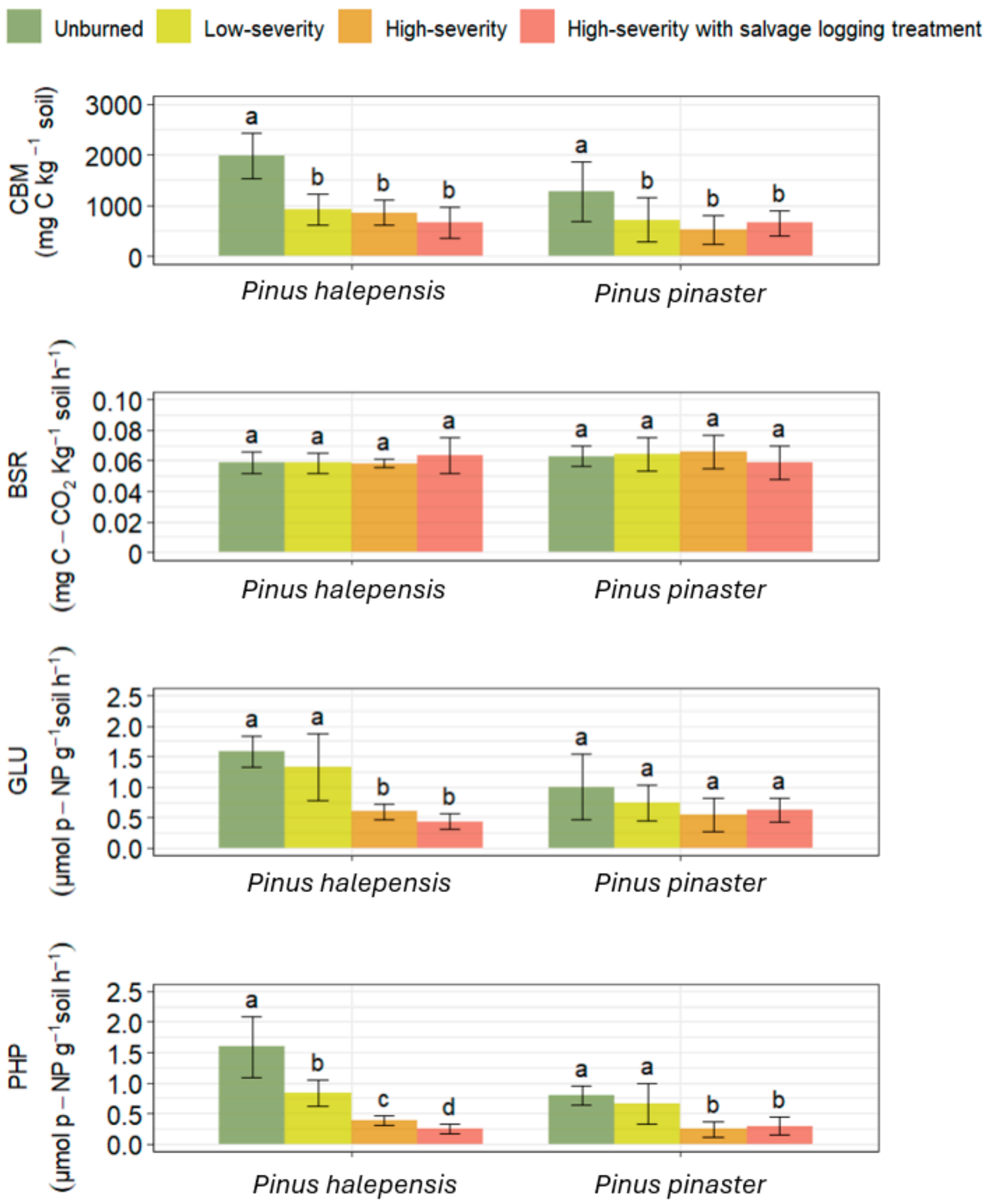

Figure 3. Soil biological properties for the unburned, low-severity, high-severity, and high-severity with salvage logging treatment sites. The significant differences between treatments (HSD, $p < 0.05$) are indicated by letters above the group label. Having the same letter in the group label suggests a similar response of means. The hanging bars in the graph correspond to standard deviations.

In *Pinus halepensis* stands, qCO_2 showed a positive trend as burn severity increased (Figure 4). In *Pinus pinaster* stands, qCO_2 increased with burn severity, but only the unburned and high-severity plots showed significant differences.

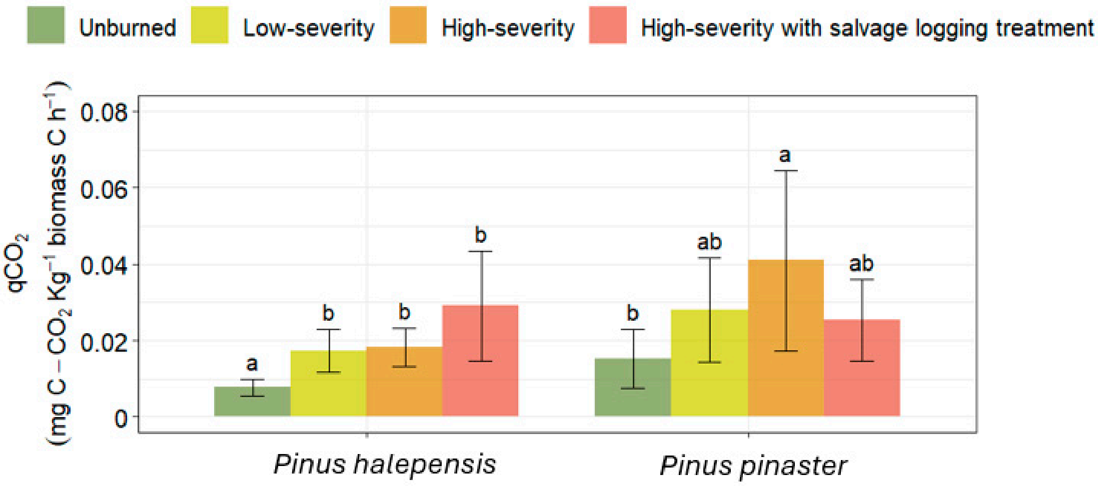

Figure 4. Metabolic quotient (qCO_2, mg C-CO_2 Kg^{-1} biomass C h^{-1}) for the unburned, low-severity, high-severity, and high-severity with salvage logging treatment sites. The significant differences between treatments (HSD, $p < 0.05$) are indicated by letters above the group label. Having the same letter in the group label suggests a similar response of means. The hanging bars in the graph correspond to standard deviations.

3.2. Vegetation Index Analyses

The COBV was higher in the unburned and low-severity plots than in the high-severity and high-severity with salvage logging treatment plots (Table 2). However, significant differences were observed only between the unburned and low-severity plots compared to the high-severity with salvage logging treatment plots in the *Pinus halepensis* stands. The unburned plots in the *Pinus pinaster* stands exhibited statistically significant differences compared to all the other locations.

Table 2. Vegetation variables (VAR): plant coverage (COBV, %), bare soil (BSOIL, %), vegetation richness (S), number of pine seedlings (NSeed), and average height (Hm, m) concerning tree species (SP): *Pinus halepensis* Mill. and *Pinus pinaster* Aiton at different levels of burn severity: unburned plots, low-severity plots, high-severity plots, and high-severity plots with salvage logging. Each box includes the mean values ± standard deviations. Groups that do not share a letter differ significantly ($p < 0.05$).

SP	VAR	Unburned	Low-Severity	High-Severity	High-Severity with Salvage Logging Treatment	F	Pr (>F)
Pinus halepensis	COBV	137.02 ± 41.73^{a}	134.64 ± 50.41^{a}	100.06 ± 34.49^{ab}	88.13 ± 33.31^{b}	4.951	0.006
	BSOIL	0 ± 0^{b}	3.60 ± 5.59^{b}	35.42 ± 14.65^{a}	39.55 ± 19.30^{a}	35.730	0.000
	S	5.56 ± 1.19^{a}	5.08 ± 1.17^{a}	5.81 ± 1.80^{a}	6.33 ± 2.61^{a}	0.276	0.842
	NSeed	0 ± 0^{b}	1 ± 1^{b}	1 ± 1^{b}	3 ± 2^{a}	6.590	0.0009
	Hm	0 ± 0^{b}	5.69 ± 3.23^{b}	15.20 ± 8.69^{a}	13.60 ± 5.84^{a}	15.53	0.0000
Pinus pinaster	COBV	214.2 ± 32.55^{a}	77.78 ± 40.71^{b}	104.02 ± 49.93^{b}	73.09 ± 24.55^{b}	11.480	0.000
	BSOIL	0.79 ± 2.05^{b}	0 ± 0^{b}	13.59 ± 17.13^{b}	44.01 ± 14.75^{a}	35.760	0.000
	S	7.42 ± 1.25^{a}	6.44 ± 2.57^{a}	5.72 ± 2.03^{a}	5.72 ± 1.42^{a}	1.367	0.271
	NSeed	0 ± 0^{a}	1 ± 1^{a}	1 ± 1^{a}	1 ± 1^{a}	1.140	0.3430
	Hm	0 ± 0^{c}	5.67 ± 7.16^{bc}	16.20 ± 14.00^{a}	15.10 ± 6.18^{ab}	6.898	0.0007

At all the sites and for the pine tree species, the unburned and low-severity plots had a lower proportion of BSOIL than the high-severity and high-severity with salvage logging treatment plots.

In S terms, there were no significant variations among sites, regardless of the pine tree species. According to the vegetation indices calculations, no index showed substantial differences, irrespective of the pine tree species (Table 2).

The NSeed was significantly higher in the high-severity with salvage logging treatment plots in *Pinus halepensis* stands, while it was not markedly higher in *Pinus pinaster* stands. In both stands, unburned plots did not show pine tree regeneration. Similarly, the Hm increased with burn severity, which was higher in high-severity plots than in high-severity with salvage logging treatment, low-severity, and unburned plots. High-severity plots offered significant differences from the unburned and low-severity plots, but no significant differences were detected between the high-severity and high-severity with salvage logging treatment plots. With regard to diversity indices, no significant differences were found in any case, regardless of pine species or area (Figure 5).

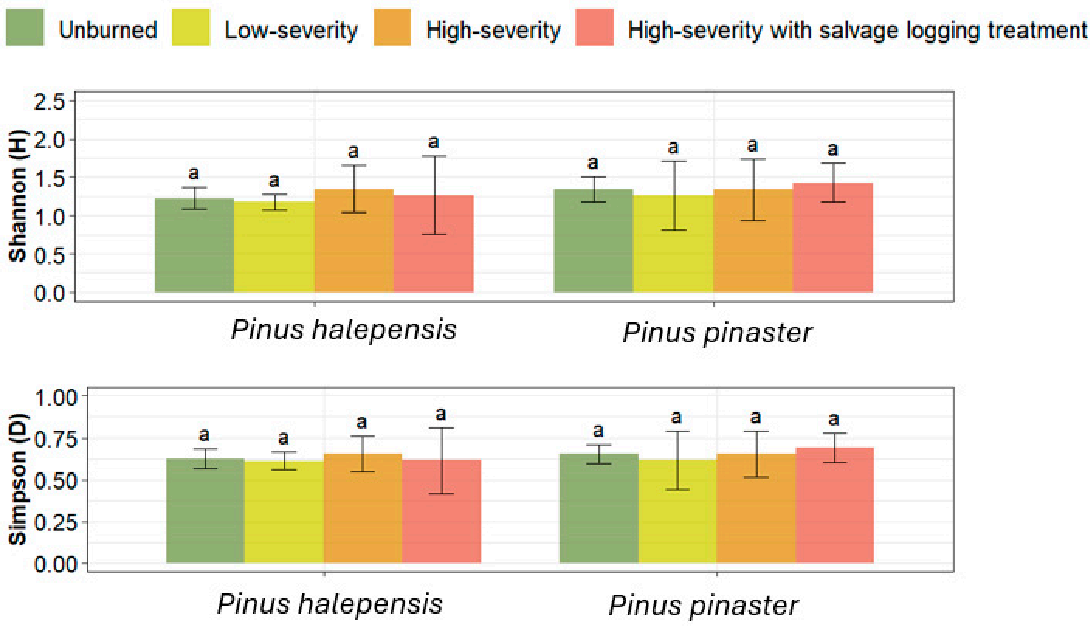

Figure 5. Vegetation indices for the unburned, low-severity, high-severity, and high-severity with salvage logging sites. The significant differences between treatments (HSD, $p < 0.05$) are indicated by letters above the group label. Having the same letter in the group label suggests a similar response of means. The hanging bars in the graph correspond to standard deviations.

Species were classified based on their specific reactions to fire (Figure 6 and Table 3). After the fire, there was a higher proportion of resprouter species (R+S−) in the *Pinus halepensis* stands compared to the *Pinus pinaster* stands. For the *Pinus halepensis* stands, the only significant differences were noted between the low-severity and high-severity plots, in which the proportion of obligate seeders (R−S+) increased (from 22.56% to 53.29%, respectively) and the ratio of facultative seeders decreased from 32.38% to 10.44%, respectively. In the *Pinus pinaster* stands, the proportion of non-fire-adapted traits (R−S−) was significantly higher in the low-severity plots (8%) than for the rest of the zones (0.92% for unburned, 0.49% for high-severity, 1.62% for high-severity with salvage logging treatment). In addition, the proportion of obligate seeders (R−S+) was lower in all fire-affected plots compared to the unburned plots, with a statistically significant reduction. No significant differences were found in the proportion of facultative seeders (R+S+).

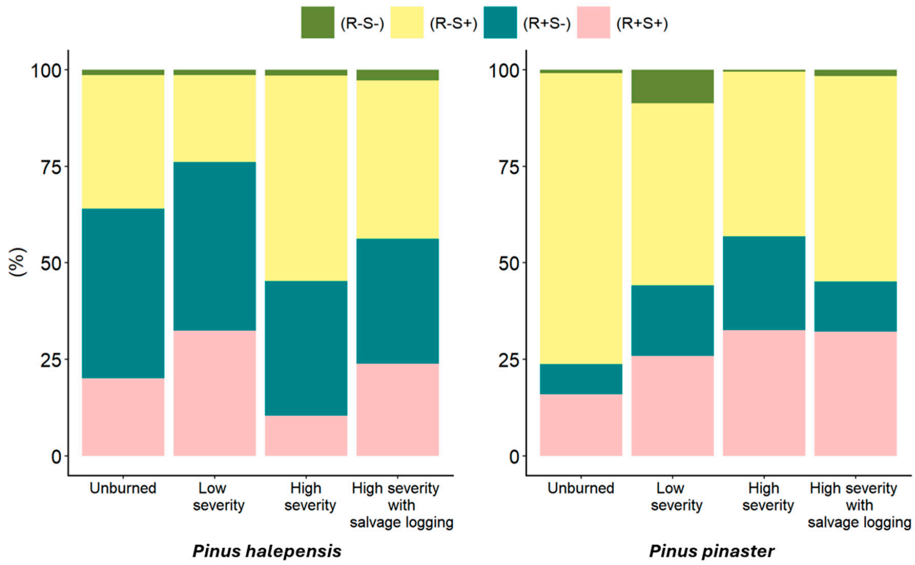

Figure 6. Average coverages according to the postfire trait adaptive strategy: facultative seeder (R+S+), obligate resprouter (R+S−), obligate seeder (R−S+), and non-fire-adapted (R−S−) in the study area: unburnt plots, low-severity plots, high-severity plots, and high-severity plots with salvage logging treatment.

Table 3. Average coverages according to the postfire trait adaptive strategy: facultative seeder (R+S+), obligate resprouter (R+S−), obligate seeder (R−S+), and non-fire-adapted (R−S−) in the study area: unburned plots, low-severity plots, high-severity plots, and high-severity plots with salvage logging treatment. Each box includes the mean values ± standard deviations. Groups that do not share a letter differ significantly ($p < 0.05$).

SP	VAR	Unburned	Low-Severity	High-Severity	High-Severity with Salvage Logging Treatment	F	Pr (>F)
Pinus halepensis	(R−S−)	1.38 ± 2.56 ^{a}	1.36 ± 1.70 ^{a}	1.48 ± 4.54 ^{a}	2.81 ± 4.58 ^{a}	0.142	0.934
	(R−S+)	34.60 ± 16.99 ^{ab}	22.56 ± 13.78 ^{b}	53.29 ± 21.48 ^{a}	41.02 ± 17.86 ^{ab}	3.955	0.0166
	(R+S−)	43.88 ± 18.70 ^{a}	43.70 ± 17.40 ^{a}	34.79 ± 23.18 ^{a}	32.30 ± 16.21 ^{a}	0.823	0.491
	(R+S+)	20.14 ± 16.46 ^{ab}	32.38 ± 11.66 ^{a}	10.44 ± 7.85 ^{b}	23.87 ± 17.65 ^{ab}	4.379	0.0108
Pinus pinaster	(R−S−)	0.92 ± 1.43 ^{b}	8.69 ± 8.00 ^{a}	0.49 ± 1.10 ^{b}	1.62 ± 3.88 ^{b}	5.424	0.0039
	(R−S+)	75.34 ± 9.99 ^{a}	47.18 ± 19.52 ^{b}	42.71 ± 21.11 ^{b}	53.24 ± 19.25 ^{b}	5.53	0.0036
	(R+S−)	7.79 ± 5.66 ^{a}	18.29 ± 17.89 ^{a}	24.21 ± 24.35 ^{a}	12.99 ± 8.66 ^{a}	2.29	0.0971
	(R+S+)	15.95 ± 10.49 ^{a}	25.84 ± 13.34 ^{a}	32.59 ± 20.45 ^{a}	32.15 ± 19.07 ^{a}	0.862	0.471

3.3. Plant–Soil Interactions

Soil and vegetation parameters were subjected to a PCA to decrease dimensionality and retain the maximum amount of their variability, which enhanced data visualization and exploration by minimizing the number of variables involved. The dimensions were reduced to five components (with eigenvalues over 1). However, for the biplot component, we opted for a simplified model (Figure 7). The first component (Dim1) exhibited 27.5% explanatory power for variability, whereas the second component (Dim2) provided 20.6%. The variables that contributed the most to the Dim1 axis were PHP, GLU, EC, CBM, and SOM (0.867, 0.825, 0.824, 0.816, and 0.825, respectively). Conversely, H, D, S, and COBV contributed more to the Dim2 component by showing cosine squares of 0.917, 0.884, 0.882, and 0.463, respectively.

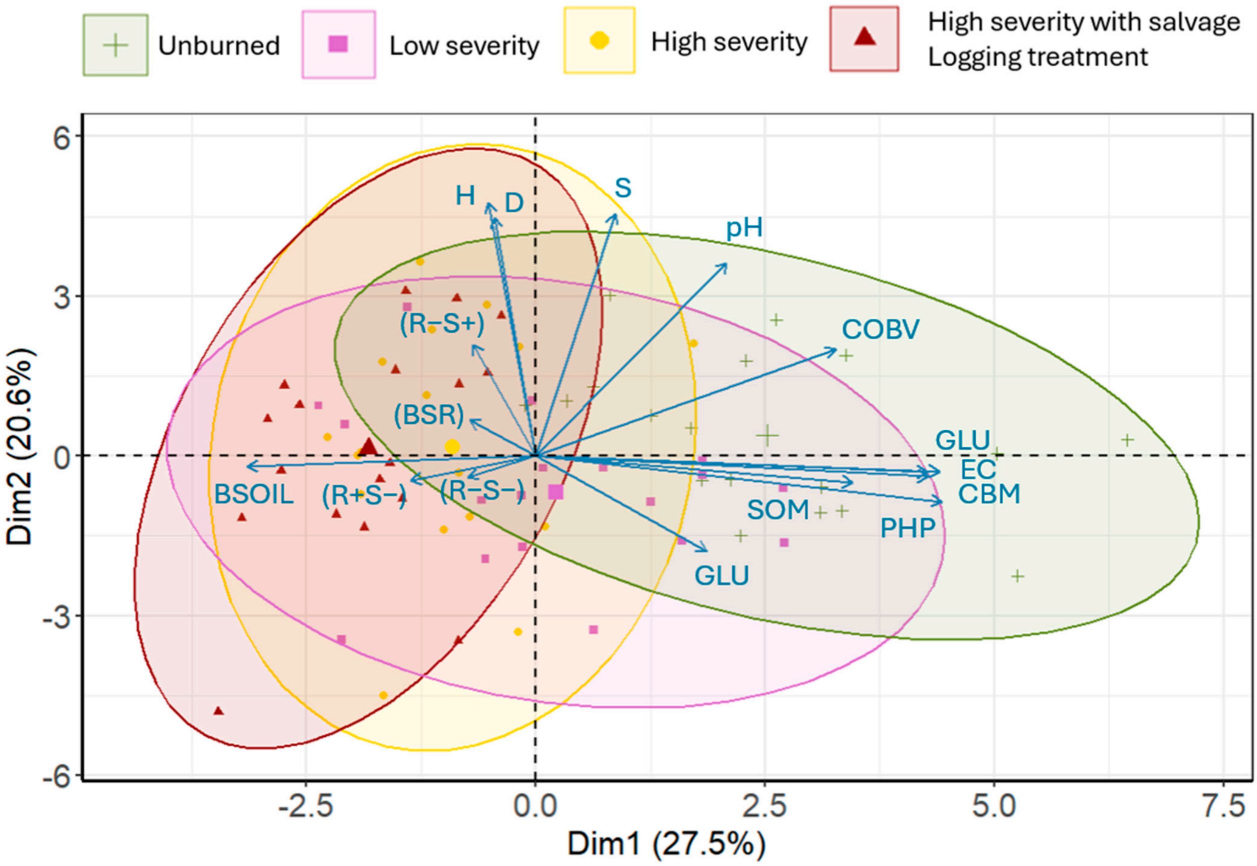

Figure 7. The principal component analysis (PCA) biplot diagram in the *Pinus halepensis* and *P. pinaster* stands. S: species richness; H: Shannon Index; D: Simpson Index; (R−S−): non-fire-adapted trait; (R+S−): obligate seeder; (R−S+): obligate resprouter; (R+S+): facultative seeder; BSOIL: bare soil; COBV: vegetation coverage; CBM: carbon from soil microbial biomass; BSR: basal soil respiration; SOM: soil organic matter; GLU: β-glucosidase enzymatic activity; PHP: phosphatase enzymatic activity.

In *Pinus halepensis* stands, solid and significant correlations (r > 0.5 ***, where *** denotes a significance level of 0.99) were identified on pH, EC, GLU, PHP, SOM, qCO_2, BSOIL, and COBV. The pH was strongly correlated with BSOIL (r = 0.85) and negatively with EC (r = −0.92), GLU (r = −0.82), PHP (r = −0.72), and SOM (r = −0.68) (Figure 8A). Concerning the biological soil properties, the CBM was strongly correlated with PHP, GLU, and SOM (r ≥ 0.7) and negatively correlated with qCO_2. The enzymatic activities were significantly correlated with BSOIL and qCO_2 (r > 0.5). Regarding the vegetation properties, the S, H, and D were correlated to each other (r > 0.7). The obligate seeders (R−S+) were negatively correlated with obligate resprouter species (R+S−), COBV, and EC, and positively correlated with pH. No significant correlation was found between the rest of the physicochemical, biochemical soil properties, or vegetation indices.

The results were less significant in *Pinus pinaster* stands (Figure 8B). The pH was strongly correlated with PHP (r = 0.69). The EC was negatively correlated with BSOIL (r = −0.72) and positively correlated with COBV (r = 0.69). The CBM was correlated with other biological soil properties (GLU, PHP, and qCO_2) but not with BSR. The GLU was also correlated with COBV (r = 0.53). Regarding vegetation indices, S, H, and D were strongly correlated with each other (r > 0.65). The obligate seeders (R−S+) were correlated with COBV (r = 0.57) and negatively correlated with obligate resprouter species (R+S−), as shown in *Pinus halepensis* stands.

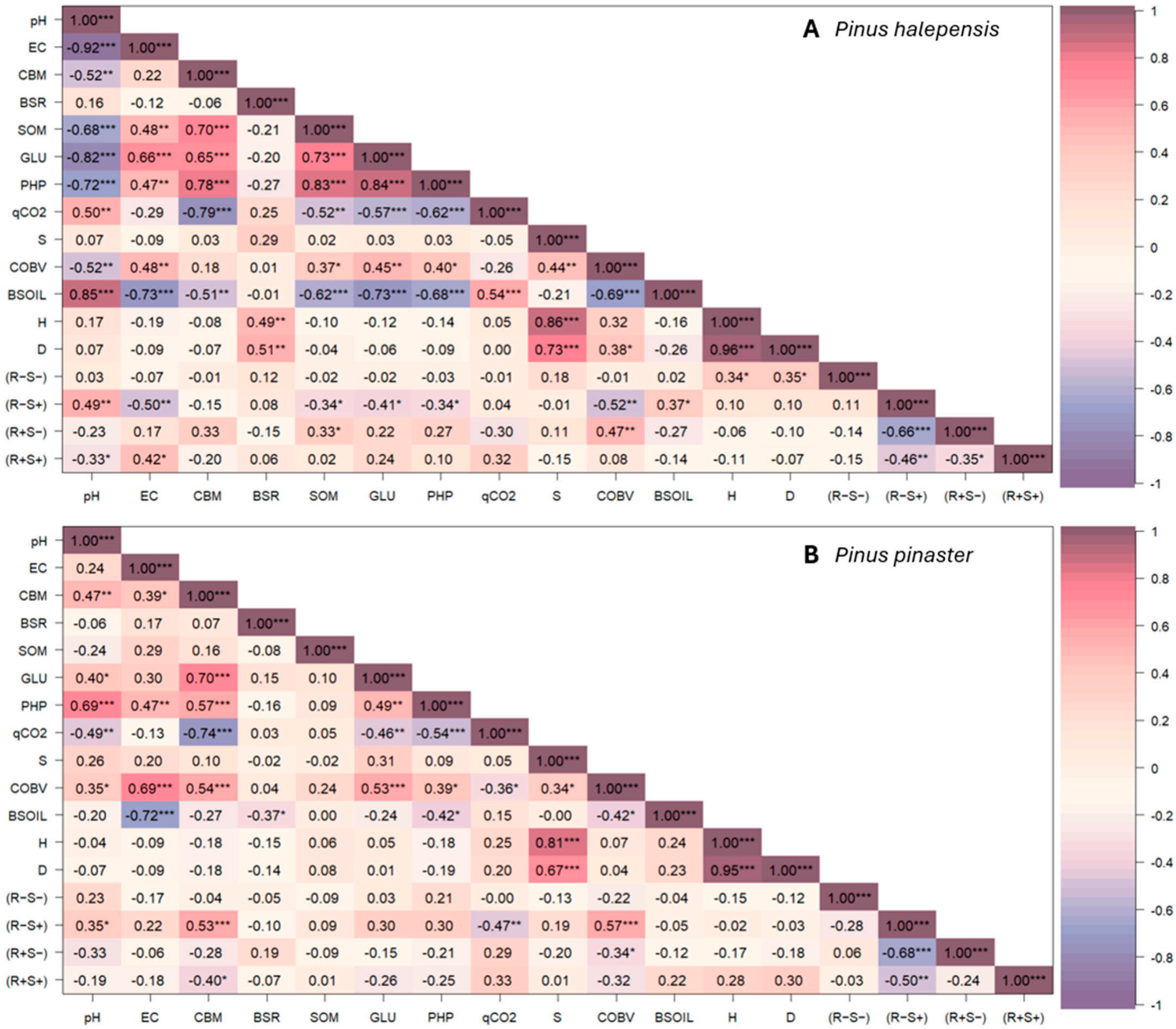

Figure 8. Correlation matrix among physicochemical, biological, and vegetation properties for the unburned, low-severity, high-severity, and high-severity with salvage logging plots in *Pinus halepensis* Mill. stands (**A**) and *Pinus pinaster* Aiton stands (**B**) (n = 36). Significant correlations are represented with asterisks. Abbreviations: electrical conductivity (EC); organic matter (SOM, %); carbon from the soil microbial biomass (CBM, mg C Kg soil^{-1}); basal soil respiration (BSR, mg C-CO_2 Kg soil^{-1} h^{-1}), metabolic quotient (qCO_2, mg C-CO_2 Kg^{-1} biomass C h^{-1}); β-glucosidase (GLU, µmol p-NP g soil^{-1} h^{-1}); phosphatase (PHP, µmol p-NP g soil^{-1} h^{-1}); species richness (S); Shannon Index (H); Simpson index (D); vegetation cover estimation (COBV, %); percentage of bare soil (BSOIL, %); facultative seeder (R+S+); obligate resprouter (R+S−); obligate seeder (R−S+); and non-fire-adapted (R−S−). The symbols *, **, and *** refer to the levels of statistical significance of 0.90, 0.95, and 0.99, respectively.

4. Discussion

4.1. Effects of Wildfire and Salvage Logging on Soil Properties

The physicochemical soil properties exhibited minimal variation, slightly intensified by salvage logging, especially in the *Pinus halepensis* stands. The pH showed a positive relation with the degree of burn. This was attributed to oxides, basic cations, and carbonates in ashes, which abound following wildfires in high-severity areas [23]. Raising pH levels can reduce nutrient accessibility (i.e., phosphorus) for plants. Still, in our case, the difference in pH for *Pinus halepensis* stands was minimal, and no substantial alterations in pH were detected in the *Pinus pinaster* stands. Other studies have also revealed that pH was not affected by burning and salvage logging [58].

In contrast to the *Pinus pinaster* stands, EC showed no significant changes in any case in the *Pinus halepensis* stands, where the salvage logging effect significantly lowered the EC values (from 174.35 to 71.00 µS cm^{-1}). These results are consistent with Muñoz-Rojas et al. (2016) [59], where EC values significantly decreased with time (5 years after the fire).

As other authors have pointed out [38,47,58], SOM content is one of the most critical soil quality indicators because of its plant growth-related functions (water retention, nutrient exchange, soil structure). In the *Pinus halepensis* stands, SOM content showed significant differences between the unburned plots and the other burn severities. As burn severity increased, the reduction in SOM content became more noticeable, and salvage logging amplified this effect. The decrease in SOM content was less relevant in the *Pinus pinaster* stands, possibly due to soil erosion. However, the salvage logging values lowered in the *Pinus pinaster* stands and showed significant differences with the unburned plots. In this case, salvage logging should not be applied if regeneration can be compromised.

The major effects of fire were observed principally in the microbiological soil properties. CBM was lowered at all the sites regardless of the pine tree stand being affected by the fire. Decreased microbial activity is attributed to the high sensitivity of microorganisms to heat from forest fires. The duration and intensity of wildfires can strongly impact soil microbiology [31,47]. In contrast, BSR (related to microbial activity) remained similar between the unburned and burned plots (low-severity, high-severity, and high-severity with salvage logging treatment). This phenomenon is important because a reduction in CBM while BSR remains constant indicates that microorganisms are experiencing stress and exhibiting higher respiration rates [47]. These findings are supported by Figure 4, which showed that both severity and salvage logging increased $qCO_{2,}$ especially in *Pinus halepensis* stands.

Of all the enzymatic activities, PHP and GLU showed significant reductions as severity increased, especially in the *Pinus halepensis* stands. These enzymatic activities are crucial for catalyzing biological processes [47]. According to other authors [22,23], these declines in GLU and PHP may be linked with reduced microbial activity (CBM).

4.2. Effects of Wildfire and Salvage Logging on Vegetation Indices

Regeneration is favored in both pine forests by high burn severity. According to the Shannon (H) and Simpson (D) indices, there were no significant differences, and salvage logging did not increase the negative impacts of wildfire. Salvage logging implied more remarkable regeneration in the *Pinus halepensis* plots, although salvage logging did not significantly influence the regeneration in the *Pinus pinaster* plots. According to the results, the high-severity plots favored pine regeneration, possibly due to poor competition and the fact that nutrients, water, and light were more available, as reported by Erdozain et al. (2023) [60]. These results favored seedling development and growth. The number of regenerated seedlings was also more prominent in the *Pinus halepensis* stands than those dominated by the *Pinus pinaster* stands in all the studied cases. This could be because *Pinus halepensis* is more heliophilous than *Pinus pinaster* and regenerates better when exposed to more sunlight [61]. In addition, the aerial seed bank, protected by serotinous pine cones, is usually more abundant in *Pinus halepensis* stands [16,17,62]. For both habitats (*Pinus halepensis* and *Pinus pinaster* stands), the results showed that high-severity implied lower COBV and a higher percentage of BSOIL but no differences in richness. These results are similar to those of other studies [63], which report no significant differences.

Regarding fire-adapted traits, our results showed that the proportion of resprouting species was higher in *Pinus halepensis* stands, while the proportion of obligate seeder species was higher in *Pinus pinaster* stands. Burn severity favored seedling dispersion in *Pinus halepensis* stands, while obligate seeder species in *Pinus pinaster* stands were reduced. Resprouting from remaining vegetative structures is the primary method of surviving following a wildfire [64]. As severity increased, *Pinus halepensis* stands showed no significant changes in (R−S−) proportions. However, there were differences in *Pinus pinaster*, with low-severity plots exhibiting the most significant proportions. R+S+ was minimized in high-severity plots at *Pinus halepensis* stands. In contrast, in *Pinus pinaster* stands, the (R+S+) proportion increased in tandem with the severity. Salvage logging in *Pinus pinaster* stands exacerbated this effect. According to Moya et al. (2020) [63], obligate seeders effectively deal with intense fires in these Mediterranean environments. In addition, resprouter species occurrence in all conditions suggests an effective technique beyond fire adaptation. Our results showed that pine forests respond positively to severe fires even in salvage logging areas, leading to more remarkable regeneration in areas with high burn severity. This was particularly evident in the case of *Pinus halepensis* stands. Therefore, in addition to the fire intensity, the morphological and temperamental differences between the two pine species may also impact the recovery capacity after a fire [38]. These different responses in regeneration patterns could be related to the pine serotiny level of each species. According to Cruz et al. (2019) [65], the researchers identified a significant correlation between the serotiny level and the tree's age. If crown fires occur at a greater frequency, species resistant to fire and adapted for success in fire-prone environments could be at risk unless they adapt correspondingly [66].

In addition, salvage logging increases the possibility of mortality due to increased exposure to sunlight and direct seedling damage from mechanical treatments, which leaves more soil exposed. Furthermore, dead canopies can raise soil moisture and enhance seedling water availability while lowering soil temperature and solar radiation [67]. More studies would be necessary to analyze whether areas with recurrent fires (like the wildfire of 1994) occurring in intervals less than 25 years can affect these values.

4.3. Effects of Wildfire and Salvage Logging on Plant–Soil Interactions

The PCA results showed that the high-variance components captured significant data patterns and could extract the most relevant information. Among all the variables analyzed, the most significant ones always include PHP, GLU, EC, CBM, SOM, and COBV. These values were concentrated in non-burned areas (Dim1), while species richness and diversity indices (S, H, and D) were focused on areas with high-severity and salvage logging (Dim2). These results are consistent with those of Agbeshie et al. (2022) [23], which emphasizes that wildfires negatively affect physicochemical and biological soil properties.

The correlation matrix results provided crucial information on how soil properties relate to each other and the biodiversity present in the ecosystem. These results included pH, qCO_2, BSOIL, and the variables identified before in the PCA (EC, GLU, PHP, SOM, and COBV). In the *Pinus halepensis* stands, COBV is related to pH, EC, SOM, GLU, PHP, and S. As mentioned before, SOM is one of the soil properties most sensitive to fire [47], and it is related to CBM and enzyme properties (PHP and GLU). In turn, CBM is related to qCO_2, a ratio that can be used to identify the stress level of soil microorganisms [68]. In contrast, in the *Pinus pinaster* stands, SOM showed no significant relationship with any other soil property or vegetation index. We also observed important relationships between COBV, EC, CBM, GLU, and PHP. It was demonstrated that burn severity negatively impacted enzymatic activities and CBM [69].

Based on these results, analyzing how enzymatic activities (PHP and GLU) relate to recalcitrance SOM compounds would be valuable, as it could reduce soil functionality and compromise vegetation recovery. Understanding the long-term interactions between soil properties, plant biodiversity, and vegetation indices can improve the development of more effective and sustainable management strategies, the preservation of biological diversity, and the promotion of ecosystem restoration.

5. Conclusions

This study provides insights into how burn severity and salvage logging postfire management affect soil physicochemical and microbiological responses and vegetation recovery after wildfires in the short term. The high burn severity negatively impacted the ecosystem functions of soil and plant coverage. This study also demonstrated that some ecological properties recovered without being affected by salvage logging (species richness, abundance, or dominance). As burn severity increased, the decrease in SOM content became more prominent, and salvage logging exacerbated this impact. Furthermore, organisms remaining after the fire have shown elevated stress levels, particularly in areas with high burn severity and salvage logging practices. Highlighting the importance of studying the responses of different pine species to wildfires is vital for enhancing our understanding of the diverse effects observed on soil and vegetation recovery.

Nevertheless, it is essential to acknowledge the limitations of the current research before concluding. The study is constrained by the singular fire event in Yeste (Spain), which restricts the generalizability of the findings to regions with different environmental conditions and pine species. Moreover, the analysis examines the immediate impacts (18 months following the fire and salvage logging), which may not provide a comprehensive understanding of the long-term restoration of pine forest ecosystems. Specific effects, such as changes in species composition and vegetation diversity, may only become apparent later. Another challenge is that factors like fauna, complex interactions between organisms, and genetic effects may significantly influence postfire recovery beyond that of soil and vegetation characteristics. These challenges highlight the necessity of adopting a holistic and long-term approach when examining soil functionality and vegetation restoration in Mediterranean ecosystems impacted by forest fires.

In conclusion, it is imperative to continue researching the long-term effects of wildfires on Mediterranean forest ecosystems to enhance our understanding and conservation efforts.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fire7040127/s1, Table S1: Inventory of species within the study area.

Author Contributions: Conceptualization, E.P.-M. and D.M.; methodology, E.P.-M., D.M. and Á.F.-C.; validation, E.P.-M. and Á.F.-C.; formal analysis, E.P.-M.; investigation, E.P.-M. and Á.F.-C.; resources, J.d.l.H.; data curation, E.P.-M.; writing—original draft preparation, E.P.-M.; writing—review and editing, E.P.-M., D.M., J.M.-S., F.G.-O., V.A. and M.E.L.-B.; visualization, E.P.-M. and Á.F.-C.; supervision, D.M., J.M.-S., F.G.-O., V.A., M.E.L.-B. and J.d.l.H.; project administration, J.d.l.H.; funding acquisition, J.d.l.H. All authors have read and agreed to the published version of the manuscript.

Funding: Esther Peña is supported by a doctoral fellowship from the Internal Research Plan of the University of Castilla-La Mancha, co-financed by the European Social Fund (2020-PREDUCLM-16032). This study was also funded by the Spanish Institute for Agricultural Research and Technology (INIA) with National Research Project "VIS4FIRE": Integrated vulnerability of forest systems to wildfire: implications for forest management tools (RTA2017-0042-C05-05) and regional funds from the "Junta Comunidades Castilla-La Mancha (PRESFIRE: SBPLY/19/180501/000130/1)", MCIN/AEI/10.13039/501100011033 "ERDF a way of making Europe" (ENFIRES: PID2020-116494RR-C43).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors thank Helen Warburton for revising the English language and express their gratitude to the anonymous reviewers, whose helpful suggestions and comments improved the quality of the manuscript.

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

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