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Resilience After Fire in Mediterranean Reforested Areas

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Abstract

Wildfires play a key ecological role in Mediterranean ecosystems but increasing fire frequency and severity, exacerbated by climate change, threaten vegetation integrity, biodiversity, and ecosystem services. Understanding early post-fire recovery trajectories is therefore essential for informing adaptation and restoration strategies. This study examined vegetation recovery in a Mediterranean area three years after a large wildfire, comparing natural holm oak stands and two human-mediated reforestation types: broadleaf and non-native coniferous reforestations. Field surveys were conducted in 117 plots 10 × 10 m across burned and unburned stands to assess total vegetation cover and mean height, and cover and mean height of structural species, complemented by an analysis of the differenced Normalized Burn Ratio (dNBR). Among burned plots, no significant differences were detected among natural holm oak stands, broadleaf reforestations, and conifer reforestations in total vegetation cover, vegetation height, or spectral recovery. In contrast, structural species exhibited distinct recovery patterns: broadleaf reforestations closely resembled natural holm oak stands in terms of the structural species involved, whereas conifer reforestations significantly differed. Whereas recovery in natural stands and broadleaf reforestations was driven by species typical of the potential natural vegetation, regeneration in conifer reforestations was dominated by early successional and fire-resistant species such as *Cytisus villosus* Pourr. and *Pteridium aquilinum* (L.) Kuhn, and conifer seedlings. Overall, these results highlight that broadleaf reforestations may better support trajectories aligned with natural vegetation dynamics, while conifer reforestations may require targeted management to support post-fire vegetation recovery consistent with natural forest recovery trajectories.

Keywords: wildfires; post-fire recovery; Mediterranean forests; vegetation resilience; compositional resilience; reforestations; remote sensing

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1. Introduction

Wildfires represent one of the main ecological processes that shape Mediterranean ecosystems, where vegetation has evolved in the presence of recurrent fire-related disturbances, developing numerous adaptations that favor persistence and regeneration after the fire [1–4]. However, climate change, associated with changes in land use and the increase in the continuity of plant fuels following the abandonment of rural areas, has led to an increase in the frequency, extent and severity of fires in the Mediterranean area, increasing concerns about the conservation of biodiversity, the maintenance of ecosystem functions and the resilience of plant communities [5–9].

The recovery of vegetation after a fire is a fundamental component of the resilience of ecosystems and profoundly influences the structure, composition and functioning of Mediterranean forests in the long term. Recovery processes are governed by numerous interacting factors, including fire severity, local climatic conditions, site characteristics and, above all, the ecological traits of the dominant species [1,10–12]. In particular, Mediterranean woody species show different regenerative strategies, mainly based on the ability to resprout (basal or epicormic resprouting) or to regenerate from seed after the passage of fire (seeding), determining different successional trajectories in the phases following the disturbance [2,5,11,13–15].

Traditionally, post-fire vegetation recovery has been assessed by evaluating the restoration of vegetation cover and structure, as well as changes in remotely sensed spectral indicators [16,17]. However, the rapid recovery of the vegetation structure does not necessarily imply the return of the community to the state before the disturbance. In fact, plant communities showing similar levels of cover may differ in floristic composition, functional strategies and ecological processes that regulate their assemblages [1,16,18,19]. For this reason, resilience assessment requires considering not only the ability of the ecosystem to re-establish a plant structure, but also the ability of the community to recover its compositional identity (compositional resilience) compared to the pre-fire reference condition [11,20].

Mediterranean forests and artificial reforestation can differ profoundly in structure, specific composition, fuel characteristics and regenerative capacities. Natural forests dominated by holm oak (*Quercus ilex* L.) are generally characterized by high resilience to fire, thanks above all to the strong regrowth capacity of the dominant and associated species [15,21,22]. Instead, the post-fire recovery of conifers is reported to be heterogeneous, depending on the species and local ecological conditions. Some species in the Mediterranean area have been found to be well adapted to fire and can recover well after fire [23–25]. Conversely, other species may have a lower recovery capacity, as they may suffer high mortality after fire and their regeneration may depend on seed availability or subsequent colonization by pioneer species [21,26].

Despite the extensive literature available on fire ecology in Mediterranean ecosystems, there are still relatively few studies that have directly compared post-fire recovery trajectories between natural forests and different types of reforestation, integrating structural and compositional aspects of vegetation. In addition, studies based solely on remotely sensed data, while crucial for large-scale recovery monitoring, mainly provide information related to the spectral response and structure of vegetation, without allowing a detailed assessment of changes in the specific composition and regenerative strategies of species [1,27]. The floristic-structural field surveys therefore remain essential to identify the ecological mechanisms underlying regeneration and to correctly interpret the observed recovery trajectories [11,17].

In this context, the present study analyzes the post fire vegetation recovery three years after a large fire event, in three different forest types: natural holm oak forests, broadleaf reforestations and coniferous reforestations. We hypothesized that structural recovery could show a rapid convergence between the different forest types in the early stages following the fire, while the floristic composition maintained significant differences due to the different availability of regenerative strategies and different successional paths. In particular, we expected greater compositional resilience in formations dominated by species with high regrowth capacity, such as natural holm oaks, and a greater deviation from reference communities in coniferous reforestation.

Through an integrated approach based on structural and compositional vegetation data, the study aims to: (i) assess post-fire recovery of vegetation structure three years after the fire by comparing burned and unburned plots; (ii) assess whether post-fire structural recovery differs between natural forests and reforestation; (iii) determine whether the composition of post-fire plant communities follows different recovery trajectories among the different forest types; and (iv) quantify the compositional resilience of burned communities compared to the corresponding non-burned reference communities, identifying the species responsible for the main compositional divergences.

2. Materials and Methods

2.1. Study Area, Experimental Design and Data Collection

The study area is located in the upper sector of the Montiferru massif (Figure 1), within a region-owned forest complex predominantly covered by sclerophyllous woodlands dominated by holm oak (*Quercus ilex* L.).

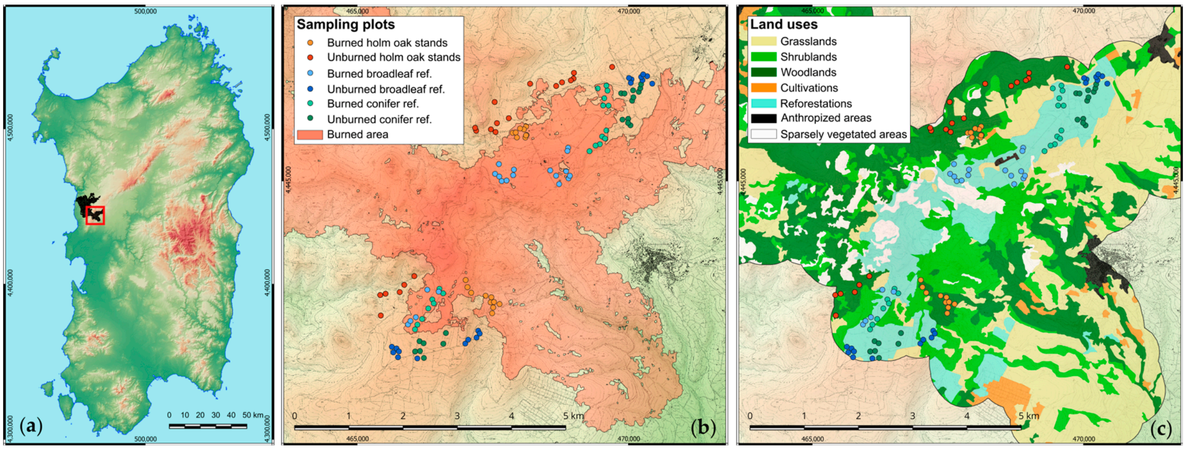

Figure 1. Location of the study area: (**a**) location of the burned area (highlighted in black) in the Sardinia region (Italy); (**b**) sampling plots superimposed on the map of the burned area; and (**c**) sampling plots superimposed on the land-use map. The reference system is WGS84—UTM.

From a geological perspective, the Montiferru massif is mainly composed of trachytes, phonolites, and alkaline basalts, although local lithological variations reflect the complex volcanic evolution of the region. The massif is characterized by extensive basaltic lava flows and deeply incised volcanic deposits resulting from an older volcanic cycle dating from the Oligocene–Miocene and a younger one spanning the Pliocene–Quaternary. The study area is predominantly characterized by andesitic rocks and includes the highest elevations of the massif, extending above 800 m a.s.l. and encompassing its highest peak, Mount Urtigu (1050 m a.s.l.).

In July 2021, a large portion of the massif was severely affected by a large wildfire that burned between 23 and 28 July, impacting more than 12,000 ha [28] (Figure 1a). The study was conducted in the area affected by the fire and, specifically, mainly within region-owned forest complexes. Three main forest types representative of different ecological and management conditions were analyzed: natural holm oak forests, broadleaf reforestation and coniferous reforestation.

Natural forests were mainly represented by sclerophyllous woodlands dominated by holm oak (*Quercus ilex* L.), attributable to the *Saniculo europaeae–Quercetum ilicis* association, together with mixed deciduous oak forests [29]. The broadleaf reforestations are primarily composed of *Q. ilex* and other Mediterranean sclerophyllous species; deciduous oaks and mixed plantations with conifers have also been used sporadically. Coniferous reforestations include the introduction of different species for forestry or experimental purposes, including *Pinus pinaster* Aiton, *Pinus nigra* J.F.Arnold, *Pinus radiata* D.Don., *Abies alba* Mill., and *Cedrus atlantica* (Endl.) G.Manetti ex Carrière. The broadleaf and coniferous reforestations were established between the 1970s and 1980s and, based on the available information, no regular management actions have been documented, except for sporadic replacement of conifers with native species in mixed plantations. Because no complete catalogue of the historical reforestation interventions and management activities was available, this information was reconstructed from interviews with local forest operators and field observations.

The selection of the sampling areas was carried out through the integration of cartographic data, photointerpretation and direct field checks. In particular, a land use map [30] updated through photointerpretation of recent orthophotos and field inspections was used to identify the three forest types considered in this study. Moreover, the map developed by Rossetti et al. [28], which assessed the burned area and fire severity classes using spectral indices, were used to identify the areas affected by the fire. The burned areas were identified within the perimeter of the 2021 fire, while corresponding non-burned control areas were selected outside, within a buffer between 100 and 500 m from the fire perimeter. This criterion was adopted both to exclude possible direct effects of the fire on the control areas, and to reduce the spatial variability. All the selected sites were located at altitudes above 700 m a.s.l. and characterized by environmental conditions that were as comparable as possible in terms of aspect and slope.

Within the selected areas, random sampling points were generated with a density of 1 point per hectare, imposing a minimum reciprocal distance of 50 m in order to reduce the spatial dependence between observations. Plots falling within areas with uncertain reforestation type or clear evidence of mixed introductions were excluded from the study. The sampling points were subsequently reached in the field by a GNSS receiver with support for GPS and Galileo systems. At each point, a survey of the vegetation was carried out within a square plot of 10 × 10 m.

A total of 117 plots were analyzed, distributed among the six combinations of forest type and fire condition: 19 plots in burned holm oak forests, 20 in burned broadleaf reforestation, 20 in burned coniferous reforestation, 20 in unburned holm oak forests, 19 in unburned broadleaf reforestations and 19 in unburned coniferous reforestations (Figure 1b,c).

Within each plot, the main structural parameters and species composition were surveyed, including the overall average percentage cover and the average height of the vegetation. For species-specific data, as in the previous studies [28,31], the structural species were considered [32–34]. For the reforested areas, the species that had been planted were also surveyed. Moreover, two mesophilic species of conservation interest (*Taxus baccata* L. and *Ilex aquifolium* L.), already present in the study area, have been considered as indicators of the system's recovery capacity towards pre-fire conditions. For species-specific data, adult living plants and post-fire regenerative structures were distinguished when they could be reliably identified in the field. Percentage cover and height of living adult trees were recorded separately from those of basal resprouts or seedlings. These categories represent structural stages or regeneration forms of the same *taxon* and were used to characterize post-fire vegetation structure. Pines individuals were retained at the genus level because reliable species-level identification of field seedlings was not always possible. A standardized field data-sheet was used to record both general plot information and species-specific structural attributes. Considering the practical challenges in the field, as already tested in previous surveys, each survey was carried out by three surveyors, and the value reported for each parameter was the average of the different evaluations. Field surveys were carried out during late spring 2024, corresponding to the period of maximum vegetative development, in order to ensure optimal detectability of the surveyed species.

As a complementary approach to the field-based assessment, post-fire vegetation spectral recovery was evaluated. Sentinel-2 Level-2A imagery were used to minimize

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atmospheric effects. Single-date anniversary-paired images were selected to maximize temporal comparability between the pre-fire and three-year post-fire observations. Images without cloud cover acquired on 30 July 2021, representative of the condition immediately following the fire, and on 31 July 2024, corresponding to the recovery phase three years after the event, were used. The late-July acquisition dates also allowed to capture vegetation conditions during the dry summer period, when the herbaceous layer is generally senescent and the spectral response is expected to be dominated by the woody vegetation component.

For both dates, the Normalized Burn Ratio (NBR) was calculated according to the formula:

$$NBR = (NIR - SWIR)/(NIR + SWIR), \quad (1)$$

where NIR and SWIR are, respectively, the reflectance in the near-infrared and short-wave infrared bands.

The change in NBR between the post-fire condition and three years after the fire was then calculated as the differenced Normalized Burn Ratio, as follows:

$$dNBR_{3yr} = (NBR_{2021} - NBR_{2024}) \times 1000. \quad (2)$$

Importantly, the 2021 NBR used in this calculation represents the immediate post-fire condition and not the pre-fire condition. Accordingly, negative dNBR values indicate an increase in NBR between the immediate post-fire condition and three years after the fire, consistent with an increase in vegetation spectral response during the recovery period.

For each sampling plot, the average value of $dNBR_{3yr}$ was extracted within a circular area of 20 m radius centered on the point, in order to obtain an integrated measure of the response of the vegetation in the area surrounding the field survey. All sampling plots were located within the same Sentinel-2 scene and were therefore evaluated under the same acquisition conditions for each date. Interannual environmental variability cannot be completely excluded, but the adopted design minimizes spatial and acquisition-related differences within the study area and is appropriate for the relative comparison of forest types exposed to the same wildfire and local environmental conditions.

2.2. Statistical Analyses

The analytical workflow followed a stepwise deepening approach. First, burned and unburned plots were compared using overall vegetation structural indicators to quantify the general effect of fire after three years. Once the overall fire effect was established, subsequent analyses were restricted to burned plots to determine whether post-fire recovery differed among forest types without the strong burned–unburned contrast obscuring among-forest-type patterns. These analyses were progressively refined from overall structural variables to species-level community composition and structure. Finally, burned plots were compared with their corresponding unburned reference communities to quantify compositional resilience. All analyses were conducted in R software, version 4.6.1 [35] using the packages *emmeans 2.0.3* [36], *rstatix 0.7.3* [37], *vegan 2.7.5* [38], *indicspecies 1.8.0* [39], and *ggplot2 4.0.3* [40].

2.2.1. Preliminary Assessment of Post-Fire Recovery of Overall Vegetation Structure After 3 Years

To assess post-fire recovery of overall vegetation structure, burned and unburned plots were compared focusing on vegetation cover, mean vegetation height, and the differenced Normalized Burn Ratio three years after the fire ($dNBR_{3yr}$), using Kruskal–Wallis tests due to deviations from normality and homoscedasticity.

Post-fire recovery analyses were then restricted to burned plots. Differences among forest types were evaluated using Kruskal–Wallis tests. Distributions of vegetation cover, mean height, and $dNBR_{3yr}$ were visualized using violin plots, boxplots, and jittered observations to represent data distribution, central tendency, and variability across forest types.

2.2.2. Assessing Post-Fire Community Compositional and Structural Dynamics

Because the primary aim of this analysis was to compare the post-fire recovery state among forest types three years after the disturbance, compositional comparisons among forest types were restricted to burned plots. Unburned plots were retained as reference communities and subsequently used to quantify the post-fire resilience as described in the next section.

To assess whether post-fire vegetation differed among the three forest types, community composition and vegetation structure were analyzed separately. For community composition, species cover was used. Data were Hellinger-transformed to reduce the influence of dominant taxa while preserving Euclidean relationships among samples. For vegetation structure, species-specific cover and height were used together as measures of horizontal and vertical occupation of space. Because cover and height variables were measured on different scales, each variable was standardized separately using z-score standardization across all 59 burned plots. No transformation was applied before standardization.

Differences among forest types were tested using permutational multivariate analysis of variance (PERMANOVA) based on Euclidean distances with 999 permutations. When significant differences were detected, similarity percentage analysis (SIMPER) was used to identify the species contributing most to pairwise dissimilarities among forest types. Indicator Species Analysis (IndVal) was performed to identify taxa significantly associated with each forest type or combinations of forest types. Finally, community patterns were visualized using non-metric multidimensional scaling (NMDS), with group confidence ellipses and species vectors representing the taxa contributing most strongly to community differentiation.

2.2.3. Assessing Post-Fire Vegetation Resilience

To evaluate post-fire resilience, each burned plot was compared with the corresponding unburned reference community of the same forest type. Resprouts and seedlings were assigned to their corresponding species so that the analysis reflected floristic composition rather than structural differences among regeneration strategies. Species cover data were first Hellinger-transformed, and the centroid of the unburned plots was calculated separately for each forest type. Compositional deviation was then quantified as the Euclidean distance between each burned plot and the centroid of its corresponding unburned community. Lower distances indicate higher compositional resilience, whereas larger distances indicate greater divergence from the pre-fire community.

Differences in compositional deviation among forest types were assessed using the non-parametric Kruskal–Wallis test, followed by Dunn's multiple comparison test with Bonferroni correction to obtain more conservative p-values. To complement significance testing, effect sizes were quantified using the rank-biserial correlation (r_{rb}), providing a standardized measure of the magnitude of pairwise differences.

To identify the species responsible for post-fire compositional changes within each forest type, separate SIMPER analyses were performed comparing burned and unburned communities of holm oak forests, broadleaf and conifer reforestations. These analyses allowed identification of the taxa contributing most to the observed deviation from the corresponding reference communities.

This approach was intended to quantify the degree of recovery towards the forest-type-specific reference condition, rather than to test a differential fire effect among forest types.

To complement the reference-based resilience analysis, a two-dimensional non-metric multidimensional scaling (NMDS) ordination was performed on the complete dataset, including both burned and unburned plots. Species cover data were Hellinger-transformed and Bray–Curtis dissimilarities were used for the ordination. To visualize compositional displacement between fire conditions within each forest type, centroids were calculated for each forest type × fire-status combination, and vectors were drawn connecting the corresponding unburned and burned centroids. These vectors were used to illustrate the direction of compositional displacement from the unburned reference condition to the burned condition and were not interpreted as temporal trajectories at the plot level.

3. Results

3.1. Assessing Post-Fire Recovery of Overall Vegetation Structure After 3 Years

The analyses on the full dataset comparing burned and unburned plots confirmed the strong and expected differences on both structural and spectral vegetation attributes. Kruskal–Wallis tests indicated significant differences between burned and unburned conditions in terms of vegetation cover, mean vegetation height, and $dNBR_{3yr}$ (Table 1).

Table 1. Kruskal–Wallis tests for differences between burned and unburned conditions for vegetation cover, mean height and $dNBR_{3yr}$.

Variable	χ^2	df	p
Cover	31.20	1	**<0.001**
Height	88.32	1	**<0.001**
$dNBR_{3yr}$	87.00	1	**<0.001**

χ^2 = Chi-Square value; df = degrees of freedom. Bold p-values indicate statistically significant differences ($p < 0.05$).

Because these results confirmed strong contrasts on vegetation structure among burned and unburned plots, subsequent analyses focused exclusively on burned plots to assess whether the magnitude and nature of post-fire recovery differed among forest types.

3.2. Post-Fire Structural Recovery Among Forest Types

Having established the overall structural differences between burned and unburned vegetation, we next asked whether the three forest types differed in their post-fire structural recovery. To avoid the dominant burned–unburned difference masking among-forest-type variation, this analysis was restricted to burned plots.

When considering only burned plots, no significant differences were detected among forest types (holm oak stands, broadleaf and conifer reforestations) in terms of vegetation cover, mean vegetation height, or $dNBR_{3yr}$ (Table 2).

Table 2. Kruskal–Wallis tests for differences among vegetation types for vegetation cover, mean height and $dNBR_{3yr}$.

Variable	χ^2	df	p
Cover	5.479	2	0.065
Height	0.733	2	0.693
$dNBR_{3yr}$	3.369	2	0.186

χ^2 = Chi-Square value; df = degrees of freedom.

Graphical analysis of vegetation cover, mean height, and $dNBR_{3yr}$ further supported the statistical results. Figure 2 reveals strong overlap in the distribution of values across forest types. All three variables showed high intra-group variability and no clear separation among holm oak stands, broadleaf and conifer reforestations. This pattern was consistent across all structural and spectral indicators, reinforcing the absence of statistically detectable differences in post-fire overall structural recovery.

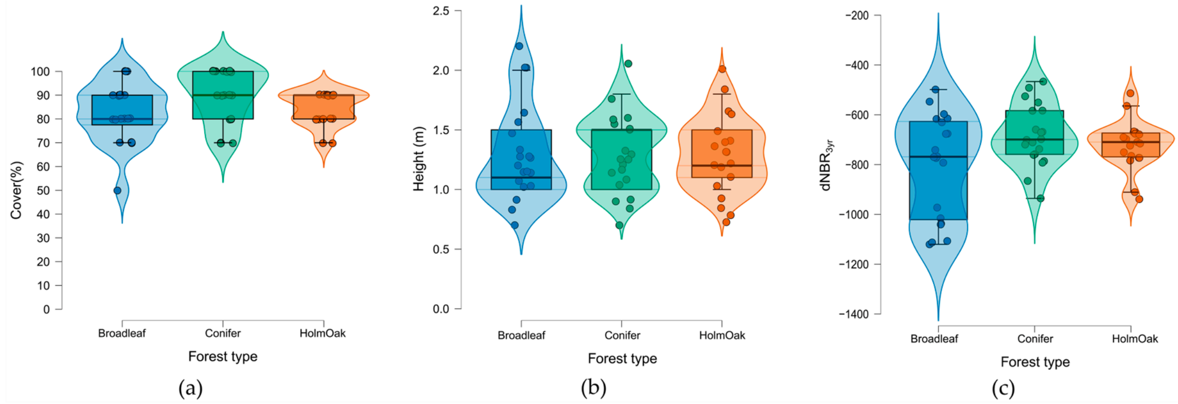

Figure 2. Distribution of post-fire vegetation structural attributes among the three forest types: (**a**) total vegetation cover, (**b**) mean vegetation height and (**c**), and $dNBR_{3yr}$. Forest types are broadleaf reforestations (Broadleaf), conifer reforestations (Conifer), and natural holm oak stands (HolmOak). Violin plots show data density. Boxes indicate the interquartile range, horizontal bars indicate median values, and vertical bars indicate the first and third quartiles. Jittered points represent individual plots.

3.3. Post-Fire Community Dynamics

Because overall vegetation cover, mean height and $dNBR_{3yr}$ did not differ significantly among burned forest types, we further examined whether forest types differed in the composition and species-level structure of the recovering vegetation.

In contrast to overall structural variables, PERMANOVA confirmed that post-fire vegetation composition differed significantly among forest types, indicating that forest type explained approximately 75% of the variation in community composition among burned plots (Table 3).

Table 3. PERMANOVA testing differences in vegetation composition among burned forest types.

Source	df	R^2	F	*p*
Forest type	2	0.751	84.674	**0.001**
Residual	56	0.249		
Total	58	1.000		

df = degrees of freedom; R^2 = proportion of variance explained by the factor; F = pseudo-F value. Bold *p*-value indicate statistically significant differences ($p < 0.05$).

SIMPER analysis showed that the strongest dissimilarities between holm oak stands and conifer reforestations were associated with *Quercus ilex* resprouts, *Cytisus villosus* Pourr., and *Pinus* spp. seedlings. Differences between holm oak stands and broadleaf reforestations were mainly driven by *C. villosus* and *Arbutus unedo*, whereas differences between conifer and broadleaf reforestations were largely explained by *Q. ilex* resprouts, *Pteridium aquilinum* (L.) Kuhn, and *Pinus* spp. seedlings (Table 4).

Indicator Species Analysis further highlighted contrasting recovery pathways among forest types. Conifer reforestations were characterized by *P. aquilinum* and *Pinus* spp. seedlings, holm oak stands by *Arbutus unedo*, while *Q. ilex* resprouts were associated with both holm oak stands and broadleaf reforestations (Table 5).

The NMDS ordination showed a clear separation among burned holm oak forests, broadleaf reforestations and conifer reforestations. The two-dimensional NMDS provided a graphical representation of community dissimilarities (Figure 3).

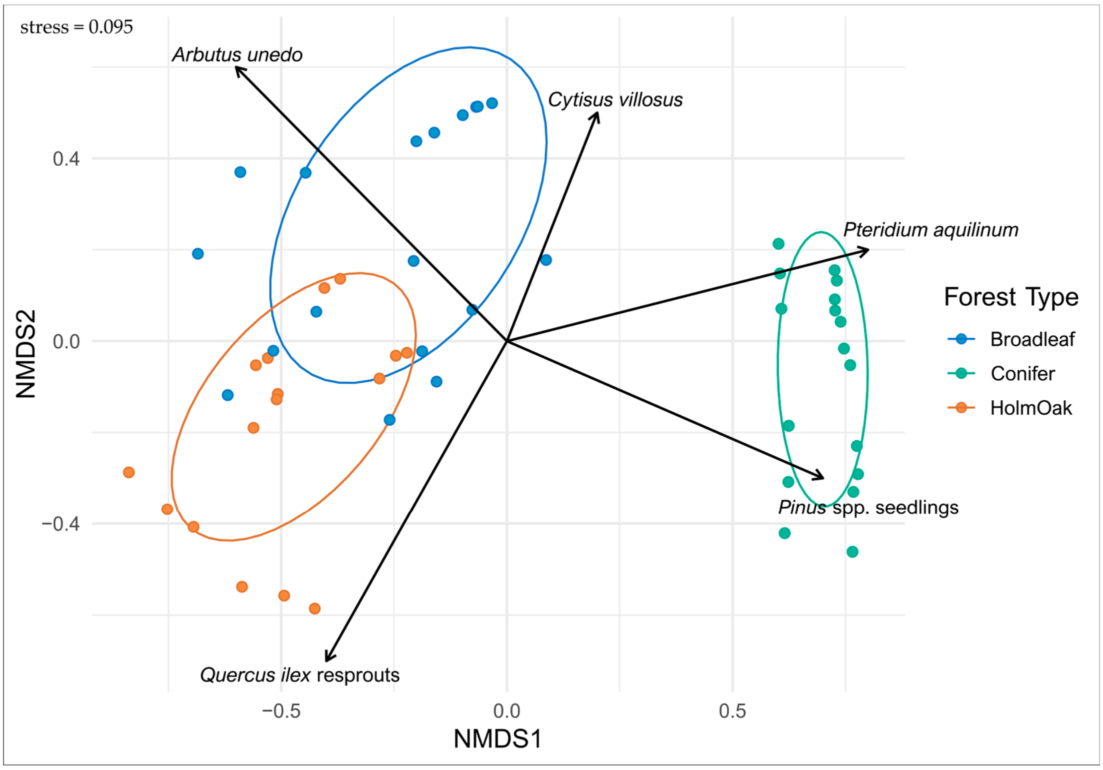

Figure 3. Non-metric multidimensional scaling (NMDS) ordination of burned plots based on species composition. Points represent individual sampling plots belonging to broadleaf reforestations (Broadleaf), conifer reforestations (Conifer), and natural holm oak stands (HolmOak). Arrows represent species significantly associated with the ordination, with arrow length proportional to the strength of their correlation with the NMDS ordination.

Table 4. Species contributing to differences in community composition among burned forest types according to SIMPER analysis.

Comparison	Species	Avg.	sd	Avg.gr.1	Avg.gr.2	Cumsum	*p*
Holm oak—Conifer	*Quercus ilex* resprouts	0.249	0.038	0.808	0.000	0.405	**0.001**
	Cytisus villosus	0.136	0.083	0.299	0.730	0.626	**0.001**
	Pteridium aquilinum	0.085	0.048	0.337	0.613	0.764	0.488
	Pinus spp. seedlings	0.054	0.045	0.000	0.181	0.852	**0.001**
	Arbutus unedo resprouts	0.046	0.040	0.158	0.000	0.926	**0.001**
Holm oak—Broadleaf	*Cytisus villosus*	0.107	0.080	0.299	0.615	0.350	**0.001**
	Pteridium aquilinum	0.068	0.051	0.337	0.142	0.570	0.996
	Arbutus unedo resprouts	0.045	0.040	0.158	0.074	0.716	**0.001**
	Quercus ilex resprouts	0.042	0.031	0.808	0.700	1.000	1.000
	Pinus spp. seedlings	0.000	0.000	0.000	0.000	1.000	NA
Conifer—Broadleaf	*Quercus ilex* resprouts	0.226	0.042	0.000	0.700	0.417	**0.001**
	Pteridium aquilinum	0.155	0.076	0.613	0.142	0.703	**0.001**
	Cytisus villosus	0.062	0.046	0.730	0.615	0.818	1.000
	Pinus spp. seedlings	0.057	0.047	0.181	0.000	0.922	**0.001**
	Arbutus unedo resprouts	0.021	0.037	0.000	0.074	0.961	0.998

Avg. = average contribution to between-group dissimilarity; Avg.gr.1 = average Hellinger-transformed value of the variable in group 1; Avg.gr.2 = average Hellinger-transformed value of the variable in group 2; sd = standard deviation; cumsum = cumulative percentage of total between-group dissimilarity. Bold *p*-values indicate statistically significant differences ($p < 0.05$); NA = Not Available.

Table 5. Indicator Species Analyses for community composition among the three forest types.

Forest Type	Indicator Species	Indicator Value	*p*
Conifer	*Pteridium aquilinum*	0.753	**0.005**
Conifer	*Pinus* spp. seedlings	0.706	**0.005**
Holm oak	*Arbutus unedo*	0.452	**0.002**
Broadleaf + Holm oak	*Quercus ilex* resprouts	0.972	**0.005**
Broadleaf + Conifer	*Cytisus villosus*	0.694	**0.005**

Bold *p*-values indicate statistically significant differences ($p < 0.05$).

3.4. Post-Fire Structural Dynamics

PERMANOVA including species-specific cover and height variables revealed significant structural differences among the three burned forest types, indicating that forest type explained approximately 47% of the variation in community composition among burned plots (Table 6).

Table 6. PERMANOVA testing differences in vegetation structure among burned forest types.

Source	df	R^2	F	*p*
Forest type	2	0.472	24.994	**0.001**
Residual	56	0.528		
Total	58	1.000		

df = degrees of freedom; R^2 = proportion of variance explained by the factor; F = pseudo-F value. Bold *p*-value indicate statistically significant differences ($p < 0.05$).

SIMPER analysis showed that structural dissimilarity among forest types was mainly driven by *Quercus ilex* resprout cover, which alone accounted for approximately 50% of the dissimilarity between holm oak stands and conifer reforestations. Additional contributors included *Cytisus villosus* cover, *Pteridium aquilinum* cover and *Pinus* spp. seedling cover. Species height variables contributed less to overall dissimilarity, although *Q. ilex* and *Arbutus unedo* resprout height significantly differentiated holm oak stands from reforestation systems (Table 7).

Table 7. Species contributing to differences in community structure among burned forest types according to SIMPER analysis.

Comparison	Variables	Avg.	sd	Avg.gr.1	Avg.gr.2	Cumsum	*p*
Holm oak—Conifer	*Quercus ilex* resprouts Cover	0.359	0.035	81.580	0.000	0.501	**0.001**
	Cytisus villosus Cover	0.182	0.112	19.470	57.000	0.754	**0.002**
	Pteridium aquilinum Cover	0.113	0.080	14.740	39.500	0.911	**0.001**
	Pinus spp. seedlings Cover	0.026	0.021	0.000	6.000	0.947	**0.001**
	Arbutus unedo Cover	0.025	0.022	5.790	0.000	0.982	**0.002**
	Quercus ilex resprouts Height	0.006	0.001	1.250	0.000	0.990	**0.001**
	Arbutus unedo resprouts Height	0.003	0.003	0.720	0.000	0.994	**0.001**
	Cytisus villosus Height	0.003	0.003	0.840	1.360	0.998	0.093
Holm oak—Broadleaf	*Cytisus villosus* Cover	0.151	0.106	19.470	48.500	0.443	0.206
	Quercus ilex resprouts Cover	0.114	0.062	81.580	55.000	0.778	1.000
	Pteridium aquilinum Cover	0.044	0.036	14.740	5.000	0.907	1.000
	Arbutus unedo Cover	0.023	0.021	5.790	2.500	0.974	**0.003**
	Cytisus villosus Height	0.003	0.003	0.840	1.450	0.984	**0.001**
	Arbutus unedo resprouts Height	0.003	0.003	0.720	0.250	0.992	**0.003**
	Quercus ilex resprouts Height	0.001	0.001	1.250	1.080	1.000	1.000
	Pinus spp. seedlings Cover	0.000	0.000	0.000	0.000	1.000	NA

Table 7. *Cont.*

Comparison	Variables	Avg.	sd	Avg.gr.1	Avg.gr.2	Cumsum	*p*
Conifer—Broadleaf	*Quercus ilex* resprouts Cover	0.256	0.069	0.000	55.000	0.422	**0.001**
	Pteridium aquilinum Cover	0.161	0.088	39.500	5.000	0.688	**0.001**
	Cytisus villosus Cover	0.140	0.100	57.000	48.500	0.920	0.779
	Pinus spp. seedlings Cover	0.027	0.022	6.000	0.000	0.964	**0.001**
	Arbutus unedo Cover	0.012	0.021	0.000	2.500	0.984	0.997
	Quercus ilex resprouts Height	0.005	0.001	0.000	1.080	0.992	**0.001**
	Cytisus villosus Height	0.002	0.001	1.360	1.450	0.996	0.974
	Arbutus unedo resprouts Height	0.001	0.002	0.000	0.250	1.000	0.999

Avg. = average contribution to between-group dissimilarity; Avg.gr.1 = average original value of the variable in group 1; Avg.gr.2 = average original value of the variable in group 2; sd = standard deviation; cumsum = cumulative percentage of total between-group dissimilarity. Bold *p*-values indicate statistically significant differences ($p < 0.05$); NA = Not Available.

Indicator Species Analysis identified distinct structural attributes associated with each forest type. Conifer reforestations were characterized by *Pinus* spp. seedling cover, whereas holm oak stands were associated with greater *A. unedo* resprout height. Resprouting of *Q. ilex* (cover and height) characterized both holm oak stands and broadleaf reforestations, while *P. aquilinum* cover was associated with holm oak and conifer reforestations (Table 8).

The NMDS ordination confirmed the structural separation among the three burned forest types. Fitted vectors indicated that the main gradients of structural differentiation were associated with *Q. ilex* and *A. unedo* resprouting, *Pinus* spp. seedling recruitment, *C. villosus* and *P. aquilinum* cover (Figure 4).

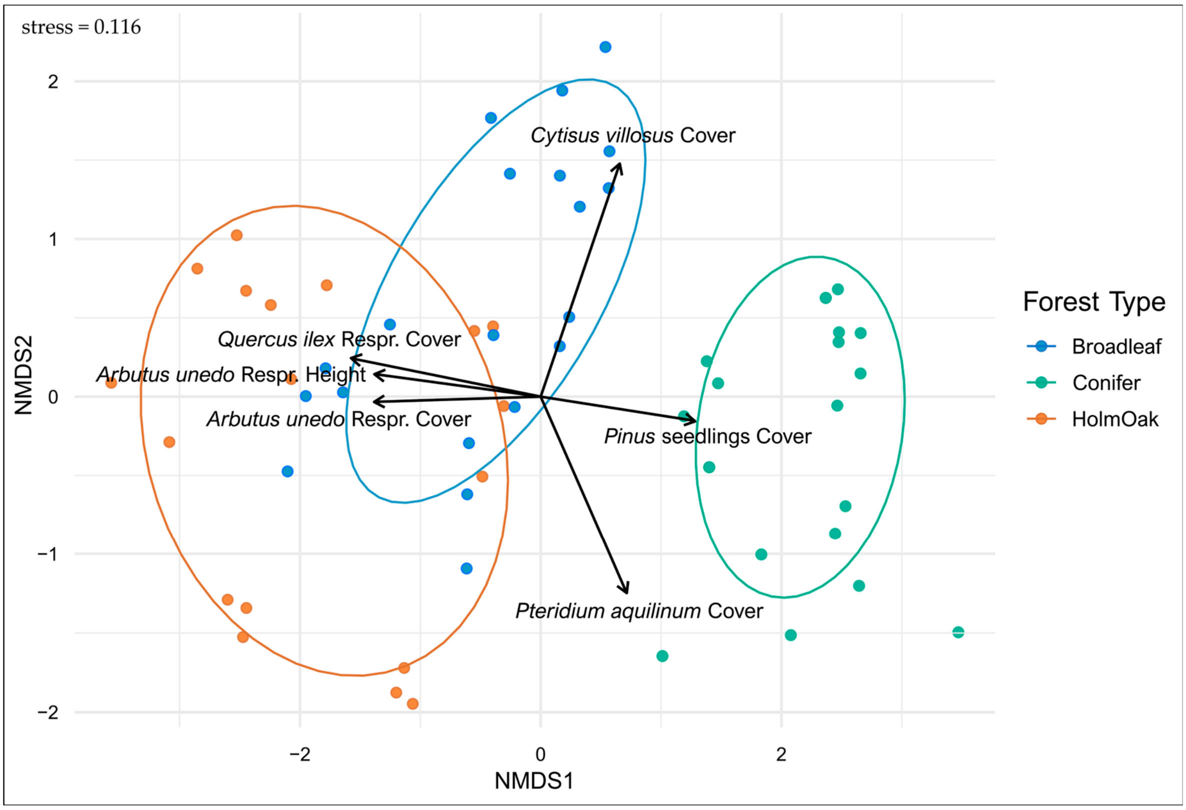

Figure 4. Non-metric multidimensional scaling (NMDS) ordination of burned plots based on standardized vegetation structural attributes (species cover and mean height). Points represent individual sampling plots belonging to broadleaf reforestations (Broadleaf), conifer reforestations (Conifer), and natural holm oak stands (HolmOak). Arrows represent species showing the strongest correlations with the NMDS ordination, based on their standardized cover and mean height values.

Table 8. Indicator Species Analyses for community structure among the three forest types.

Forest Type	Indicator Species	Indicator Value	*p*
Conifer	*Pinus* spp. seedlings Cover	0.775	**0.001**
Holm oak	*Arbutus unedo* resprouts Height	0.656	**0.001**
Broadleaf + Holm oak	*Quercus ilex* resprouts Cover	1.000	**0.001**
Broadleaf + Holm oak	*Quercus ilex* resprouts Height	1.000	**0.001**
Broadleaf + Holm oak	*Arbutus unedo* resprouts Cover	0.641	**0.003**
Conifer + Holm oak	*Pteridium aquilinum* Cover	0.957	**0.001**

Bold *p*-values indicate statistically significant differences ($p < 0.05$).

3.5. Post-Fire Vegetation Resilience

The detection of marked differences in species composition and species-level structure among burned forest types prompted a final comparison with the corresponding unburned reference communities, in order to quantify the degree of compositional resilience.

Kruskal–Wallis test on compositional resilience, quantified as the Euclidean distance between post-fire communities and their corresponding unburned reference centroids, differed significantly among forest types ($\chi^2 = 39.59$, df = 2, $p < 0.001$). Dunn's post hoc pairwise comparisons revealed that conifer reforestations exhibited significantly higher compositional deviation from their reference state compared to both holm oak forests and broadleaf reforestations. Broadleaf reforestations also showed higher deviation than holm oak stands, although differences between these two forest types were less pronounced and statistically not significant (Table 9 and Figure 5).

Table 9. Dunn's post hoc pairwise comparisons of compositional resilience among forest types.

Comparison	z	r_{rb}	p_{Bonf}
Broadleaf—Conifer	−5.055	0.856	**<0.001**
Broadleaf—Holm oak	0.765	0.184	1.000
Conifer—Holm oak	5.754	0.855	**<0.001**

z = z-score; r_{rb} = Rank-biserial correlation based on individual Mann–Whitney tests; p_{Bonf} = Bonferroni-adjusted *p*-value. Bold *p*-values indicate statistically significant differences ($p < 0.05$).

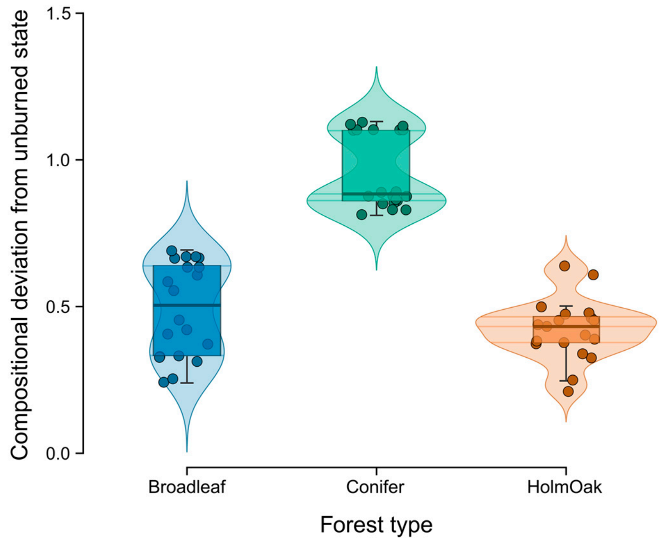

Figure 5. Distribution of compositional deviations from the unburned state for broadleaf reforestations (Broadleaf), conifer reforestations (Conifer), and natural holm oak stands (HolmOak). Violin plots show data density; boxes indicate the interquartile range, horizontal bars show median values, and vertical bars indicate the first and third quartiles. Jittered points represent individual plots.

SIMPER analyses comparing burned and unburned conditions within each forest type revealed significant shifts in community composition, although the dominant contributing species varied among forest types. In holm oak stands, compositional changes were primarily driven by increases in *Cytisus villosus* and *Pteridium aquilinum*, coupled with a reduction in *Ilex aquifolium*, while *Quercus ilex* remained relatively stable between pre- and post-fire conditions. In broadleaf reforestations, similar patterns were observed, with *C. villosus* and *P. aquilinum* increasing markedly after fire and *I. aquifolium* disappearing from burned plots, while *Q. ilex* showed a moderate decline. Conifer reforestations exhibited the strongest compositional shift, driven largely by a sharp reduction in the dominant *Pinus* spp. component and a concurrent increase in pioneer species such as *C. villosus* and *P. aquilinum* (Table 10).

Table 10. Species contributing to differences in community composition between burned and unburned plots according to SIMPER analysis.

Comparison	Species	Avg.	sd	Avg.gr.1	Avg.gr.2	Cumsum	*p*
Burned—Unburned Holm oak	*Cytisus villosus*	0.089	0.066	0.069	0.305	0.342	**0.001**
	Ilex aquifolium	0.050	0.052	0.163	0.000	0.534	**0.004**
	Arbutus unedo	0.050	0.045	0.056	0.164	0.726	**0.010**
	Pteridium aquilinum	0.033	0.041	0.262	0.345	0.855	**0.001**
	Quercus ilex	0.029	0.021	0.907	0.826	0.966	**0.001**
	Taxus baccata	0.009	0.027	0.029	0.000	1.000	0.904
	Pinus spp.	0.000	0.000	0.000	0.000	1.000	NA
Burned—Unburned Broadleaf	*Cytisus villosus*	0.117	0.072	0.262	0.621	0.378	**0.001**
	Quercus ilex	0.056	0.037	0.873	0.709	0.557	**0.001**
	Pteridium aquilinum	0.055	0.046	0.231	0.144	0.734	0.037
	Arbutus unedo	0.043	0.047	0.112	0.078	0.871	0.360
	Ilex aquifolium	0.040	0.054	0.126	0.000	1.000	**0.001**
	Taxus baccata	0.000	0.000	0.000	0.000	1.000	NA
	Pinus spp.	0.000	0.000	0.000	0.000	1.000	NA
Burned—Unburned Conifer	*Pinus* spp.	0.237	0.067	0.887	0.181	0.424	**0.001**
	Cytisus villosus	0.171	0.082	0.225	0.730	0.730	**0.001**
	Pteridium aquilinum	0.114	0.065	0.273	0.613	0.932	**0.001**
	Ilex aquifolium	0.020	0.039	0.064	0.000	0.968	0.038
	Taxus baccata	0.018	0.035	0.057	0.000	1.000	0.044
	Quercus ilex	0.000	0.000	0.000	0.000	1.000	NA
	Arbutus unedo	0.000	0.000	0.000	0.000	1.000	NA

Avg. = average contribution to between-group dissimilarity; Avg.gr.1 = average Hellinger-transformed value of the variable in group 1; Avg.gr.2 = average Hellinger-transformed value of the variable in group 2; sd = standard deviation; cumsum = cumulative percentage of total between-group dissimilarity. Bold *p*-values indicate statistically significant differences ($p < 0.05$); NA = Not Available.

The conservation-relevant species *I. aquifolium* and *T. baccata* showed limited and uneven occurrence across forest types. *I. aquifolium* was not detected in burned plots, although it occurred in the corresponding unburned plots, whereas *T. baccata* was detected only sporadically and was not detected in burned plots. However, an important clarification must be made regarding the presence of *I. aquifolium* and *T. baccata*. Occurrences of these two species were sporadic in the burned areas, and their distribution was therefore too limited to allow consistent inference on their post-fire occurrence, abundance, or regeneration across forest types. Although significant differences involving these species emerged in some statistical comparisons, these results should be interpreted with caution given their low and uneven occurrence. Their post-fire dynamics therefore warrant further investigation.

The complementary NMDS ordination including both burned and unburned plots provided a graphical representation of the compositional displacement of burned communities from their corresponding unburned reference conditions (Figure 6). The ordination showed distinct positions of the unburned communities according to forest type, while burned communities were displaced from their respective unburned centroids. The direction and magnitude of this displacement varied among forest types, consistent with the differences in compositional resilience observed in the distance-based analysis.

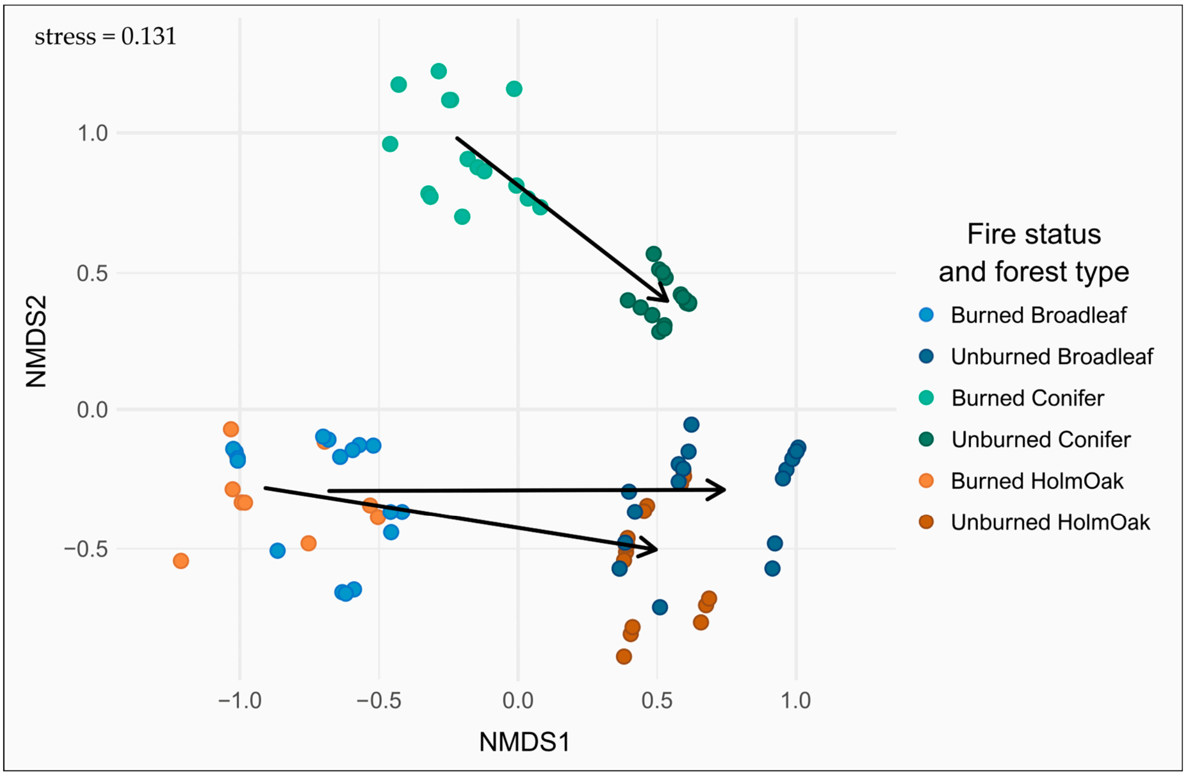

Figure 6. Non-metric multidimensional scaling (NMDS) ordination of burned and unburned plots based on Hellinger-transformed species composition and Bray–Curtis dissimilarities. Points represent individual sampling plots classified according to forest type and fire status. Vectors connect the corresponding unburned and burned centroids and illustrate the direction of compositional displacement from the burned reference condition to the unburned condition. Vectors represent differences between group centroids and do not imply temporal trajectories at the plot level.

4. Discussion

The aim of this study was to evaluate post-fire vegetation recovery three years after the large wildfire of Montiferru and assess whether natural forests and two reforestation types differed in terms of spectral recovery, vegetation structure, community composition and compositional resilience, including the response of key structural and conservation-relevant species. To the best of our knowledge, this is the first study that addresses this comparison by investigating three forest types affected by the same wildfire event under comparable fire severity conditions and integrating field-based vegetation surveys with remote sensing data, providing new insights into post-fire recovery dynamics in Mediterranean forests. Structural metrics alone suggested broadly similar recovery, whereas species-level analyses revealed divergent post-fire trajectories.

4.1. Overall Structural Recovery Converged Across Forest Types

One of the main findings of this study is that three years after the wildfire, vegetation cover, mean vegetation height and spectral recovery (dNBR3yr) did not differ significantly among holm oak forests, broadleaf and conifer reforestations. This suggests that, despite different stand origin and species composition, early post-fire overall structural recovery converged toward similar levels across forest types.

Mediterranean vegetation is widely recognized for its high resilience to recurrent fire disturbance, as many plant species possess effective regeneration strategies such as basal resprouting or persistent and fire-resistant seed banks [10,14,22,41,42]. Accordingly, previous studies showed that vegetation structure can recover relatively rapidly during the first years after fire, even under different forest conditions [1,18,28,43]. In this case-study, three years after the fire, burned plots showed substantial vegetation cover and structural development, although they still differed significantly from unburned reference plots.

The absence of significant differences in vegetation cover, mean vegetation height and spectral recovery among burned forest types should not be interpreted as ecological equivalence among them. Overall structural metrics describe the amount of recovering vegetation but provide limited information about the ecological processes driving ecosystem recovery, as described in the following sections.

4.2. Community and Structural Recovery Reveal Different Trajectories Among Forest Types

Although overall structural variables showed similar recovery among forest types, multivariate analyses revealed marked differences in community composition and structural recovery patterns. PERMANOVA, SIMPER, Indicator Species Analysis and NMDS consistently showed that post-fire communities differ according to forest type.

This apparent discrepancy highlights that structural recovery and compositional recovery are not necessarily synchronized. Focusing on woody vascular plant species, Mediterranean ecosystems may rapidly regain vegetation cover while following distinct successional pathways depending on climatic characteristics, pre-fire vegetation, regeneration strategies and competitive interactions [2,20]. Similar results have been reported in Mediterranean forests, where vegetation structure recovers relatively quickly whereas species composition remains strongly influenced by pre-fire community identity and regeneration mechanisms [2,18,44].

Consequently, vegetation cover and spectral indices alone may overestimate ecosystem recovery if changes in floristic composition are not simultaneously considered. Although remote sensing provides an efficient tool for assessing post-fire vegetation dynamics over large spatial extents, it cannot fully capture the compositional and structural changes occurring at the community and species levels. Field surveys therefore remain essential to accurately quantify vegetation recovery, identify species-specific responses, and validate remotely sensed observations [28,29,31,45].

The observed compositional patterns reflect contrasting regeneration strategies among forest types. Holm oak stands were characterized by resprouting woody species such as *Quercus ilex* and *Arbutus unedo*, indicating the strong resilience typically associated with evergreen Mediterranean forests. Resprouting allows rapid recovery after disturbance through the activation of dormant buds and the use of belowground carbohydrate reserves, representing one of the dominant adaptive strategies of Mediterranean sclerophyllous vegetation [3,5,41,46,47].

Conversely, conifer reforestations were associated with disturbance-adapted and early successional species, particularly *Pteridium aquilinum* and *Cytisus villosus*. This pattern likely reflects the greater canopy opening and altered microenvironment typically occurring after fire in planted conifer stands, conditions that favour colonization by pioneer species [2,48,49].

Broadleaf reforestations occupied a position similar to natural holm oak stands and were mainly associated with *Q. ilex* resprouting. The current composition of broadleaf reforestations may reflect their long-term successional development following establishment in the 1970s–1980s. Over approximately 40–50 years, these stands may have undergone a successional trajectory towards more natural-like vegetation. Nevertheless, the lack of a complete historical record of the original planting composition and subsequent management prevents us from determining the extent to which their current composition reflects the original reforestation versus subsequent natural succession. However, their stronger association with pioneer shrubs such as *C. villosus* suggests that, despite an overall convergence towards the recovery pathway of holm oak forests, these communities still follow a partially distinct successional trajectory characterized by a greater contribution of pioneer species.

4.3. Compositional Resilience Differs Among Forest Types

This comparison among forest types was designed to characterize differences in post-fire recovery states three years after disturbance, rather than to estimate differential effects of fire per se. The unburned stands therefore served as reference conditions against which the compositional deviation of burned communities was quantified.

The results showed a clear gradient in post-fire ecosystem recovery among forest types, with holm oak stands exhibiting the highest compositional resilience, followed by broadleaf forests, and conifer reforestations showing the greatest deviation from their pre-fire reference state. This pattern is consistent with the idea that vegetation recovery after disturbance is strongly constrained by both species' recovery strategy and pre-fire community composition [11,14,26,44].

The lower compositional deviation observed in holm oak forests highlights the key role of resprouting species in promoting ecosystem resilience. *Quercus ilex* and associated sclerophyllous species are known for their strong resprouting capacity after fire, which allows rapid recovery of community composition [5,41,50]. Although some rare or relict species, such as *Taxus baccata* and *Ilex aquifolium*, were not detected in the burned plots, the persistence of dominant resprouting trees likely buffered overall compositional change. These findings are consistent with previous studies showing that post-fire dynamics in Mediterranean forests dominated by resprouting species often follow an auto-successional [51] trajectory, in agreement with the "initial floristic composition" model, whereby pre-fire species persist and drive community reassembly after disturbance [52–55].

In contrast, conifer reforestations exhibited the highest divergence from their reference unburned communities. This result may indicate low post-fire compositional resilience and may reflect the different regeneration strategy of the dominant pine species. In particular, obligate seeder strategies and high fire-induced mortality can result in strong compositional turnover during the first years after the fire [15,20–22,26]. The strong increase in pioneer species such as *Cytisus villosus* and *Pteridium aquilinum* further suggests a shift towards early successional communities dominated by fast-colonizing species, a common pattern following stand-replacing fires in conifer reforestations [1,49,56,57]. This pattern suggests that, unlike fire-prone Mediterranean communities dominated by resprouting species, conifer reforestations may not follow an auto-successional pathway after severe fires, particularly when dominant planted species show limited regeneration capacity. However, the relatively short post-fire observation period should be considered when interpreting this pattern, as some pine species may require longer periods to regenerate and contribute substantially to community recovery.

Broadleaf forests showed intermediate levels of compositional change, suggesting a mixed strategy of recovery. The simultaneous persistence of resprouting woody species and the increase in pioneer *taxa* may indicate that compositional recovery remains transitional, with pioneer species still contributing substantially to community succession.

SIMPER analyses further clarified the mechanisms underlying these patterns by identifying the species contributing most to compositional divergence. Across all forest types, increases in pioneer species such as *C. villosus* and *P. aquilinum* consistently drove post-fire dissimilarity, while reductions in rare mesophilous *taxa* such as *Taxus baccata* and *Ilex aquifolium*, although conditioned in this study by the low number of occurrences, may have contributed to the loss of pre-fire community diversity [47,58–60]. These species, especially in the Mediterranean mountains, are known to be particularly sensitive to high-severity fires [61] and our results may reflect such sensitivity in the short-time after a megafire. However, these short-term responses do not preclude their gradual recovery during later successional stages, given that suitable environmental conditions and local propagule sources are maintained.

5. Conclusions

The present study has shown that, in the first three years following the large wildfire of Montiferru, the recovery of vegetation follows different trajectories depending on the indicator considered and the type of forest. Although vegetation cover, average vegetation height and spectral recovery have shown substantial convergence between different forest types, the composition of plant communities has followed distinct successional paths, reflecting different levels of compositional resilience.

As expected, natural holm oak forests have shown the greatest ability to preserve their floristic identity thanks to the predominance of species with a high regrowth capacity, confirming the high resilience typical of Mediterranean sclerophyll ecosystems. Broadleaf reforestations showed an intermediate response, showing a partial convergence towards holm oak forests but maintaining a greater component of pioneer species. On the contrary, coniferous reforestation has shown the greatest divergence with respect to the reference communities, with a marked replacement of dominant species by pioneer plants and limited evidence of self-succession. Although holm oak forests showed the highest compositional resilience, the observed decline of rare mesophilous taxa may suggest that ecosystem resilience does not necessarily imply the complete recovery of all biodiversity components, at least in the short-term.

Furthermore, the results show that structural and spectral recovery do not necessarily coincide with compositional recovery and that the use of remote sensing indicators alone can lead to overestimating the resilience of ecosystems after fire. The integration between floristic-structural surveys and remote sensing data is therefore an indispensable approach to correctly evaluate post-fire recovery processes and understand the ecological mechanisms that determine them.

From a management point of view, the results suggest that post-fire interventions should be differentiated according to the forest type. In natural holm oak forests, the high capacity for spontaneous regeneration suggests favoring natural recovery processes, limiting interventions that may interfere with succession. In coniferous reforestation, on the other hand, the lower compositional resilience highlights the need for more prolonged monitoring and to evaluate renaturalization strategies aimed at encouraging the development of communities more resilient to future fires.

Finally, this study shows how the assessment of post-fire resilience cannot be limited to the quantification of vegetation regrowth, but must necessarily also consider the reconstitution of the composition of plant communities. Only an integrated approach makes it possible to reliably assess the real capacity of Mediterranean ecosystems to recover structure, composition and functionality after highly severe fire events.

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Abbreviations

The following abbreviations are used in this manuscript:

NBR	Normalized Burn Ratio
$dNBR_{3yr}$	Differenced Normalized Burn Ratio three years after the fire

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