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Divergent Dynamics of Aboveground and Soil Organic Carbon Stocks in Post-Fire Mediterranean Cork Oak Shrublands

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Abstract

Wildfires are a dominant ecological disturbance in Mediterranean ecosystems, yet how post-fire aboveground carbon dynamics and vegetation characteristics govern soil organic carbon stock (SOC) remains poorly understood. This study characterized the dynamics of the carbon pool and changes in the plant community in cork oak shrublands in southern Portugal 11 and 19 years after a fire. Unburned stands were used as a reference. Five plots of each scenario were selected, for a total of 45 independent transects (15/scenario). Aboveground carbon, litter carbon, SOC, and community structural and diversity traits were quantified. Random Forest regression was used to identify the structural and compositional predictors at each stage. The results showed that 11 and 19 years after the fire, the stands held approximately 3:1 and 2:1 more aboveground carbon than the unburned sites due to higher post-fire shrub growth. Total litter carbon amount reached the highest value at 19 years, accompanied by a transient increase in species richness. However, SOC did not differ significantly across any scenario, revealing a clear decoupling between above- and belowground pools, likely constrained by Mediterranean drought conditions. Random Forest analysis showed that the nature of the vegetation–SOC relationships shifted qualitatively across the chronosequence, from structurally dominated in unburned stands to increasingly species-identity-driven. These findings highlight the limitations of assuming monotonic post-fire carbon recovery and underscore the role of species functional identity in mediating long-term SOC dynamics in Mediterranean shrublands.

Keywords: post-fire chronosequence; soil organic carbon stock; carbon pool dynamics; Mediterranean; functional traits

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1. Introduction

The Mediterranean basin exhibits a confluence of climatic, environmental, and socio-economic conditions that are conducive to wildfire ignition and propagation, positioning fire as a fundamental ecological driver of natural landscape dynamics in this region, as well as across other fire-prone biomes globally [1,2]. Despite their ecological significance, wildfires exert substantial effects on ecosystem integrity, affecting organic and mineral soil horizons, vegetation structure, and hydrological processes, ultimately inducing profound landscape transformation [3,4]. Since the latter half of the 20th century, the magnitude of fire-related impacts has escalated markedly [5,6]. The increased frequency and intensity of fires raise critical concerns about greenhouse gas emissions from wildfires in the Mediterranean

region and worldwide [7–9]. Moreover, there is the issue of the impairment of carbon sequestration capacity, given that soil organic carbon constitutes the largest carbon reservoir in the terrestrial biosphere [10,11]. The most severe effects are observed in Mediterranean landscapes [12]. Perhaps more importantly, projections suggest that wildfires will become more intense and cover larger areas in a warmer climate [7].

Cork oak (*Quercus suber* L.) woodlands are among the most ecologically and economically significant ecosystems on the Iberian Peninsula. In Portugal, they cover approximately 2.2 million hectares and provide a wide range of ecosystem services, including carbon storage, biodiversity conservation, and cork production [13,14]. These woodlands are characterized by an open canopy structure with low-to-moderate tree density. Beneath this, the shrub stratum is the dominant structural and functional vegetation component in terms of ground cover, carbon turnover, and fire behavior [15,16]. The open canopy configuration means that the shrub understory is the primary driver of post-fire dynamics, as the low tree density does not provide sufficient canopy closure to suppress shrub recovery following a fire.

Fire is the principal disturbance restructuring cork oak shrubland understories, redistributing carbon among aboveground biomass, litter, and soil pools through combustion, mortality, and subsequent vegetation recovery [17]. Following a fire, many plant species show fire-adaptive traits in the post-fire environment by resprouting [18], which enable rapid community reassembly [15,19]. However, changes in these communities, traits, and diversity occur in the short, medium, and long term, depending on characteristics of the fire [20,21]. The carbon stored in the understory is often estimated as a cumulative function of net primary productivity [22], which has been positively linked with plant diversity (e.g., species, phylogenetic, and/or functional) in a range of forest types [23–25].

Beyond the quantity of organic matter inputs, several authors argue whether the mechanisms underpinning the carbon storage and are highly dependent on species biodiversity (the niche complementarity effect), whereby diverse communities are more likely than species-poor communities to contain highly functional species that contribute strongly to ecosystem productivity and carbon storage [26–28]. Others discuss that this depends solely on functional trait diversity (the mass-ratio hypothesis) [29–31] or on the interplay between the two. This is especially important for carbon recovery strategies for soil organic carbon storage. Differences in species-specific litter chemistry, root traits and mycorrhizal associations modify the pathways of organic matter stabilization, particularly the formation of mineral-associated organic matter [32], and the structural traits of this matter mediate species-specific outputs and their relationship with soil organic carbon stock.

In cork oak ecosystems, fire has been shown to promote understory shrub encroachment, leading to sustained increases in vegetation density that persist over decadal timescales [33,34]. This shift is expected to enhance aboveground carbon stock and consequently soil organic carbon stock via litter accumulation and its decomposition. However, the extent to which aboveground recovery translates into soil carbon gains is uncertain. Fire-driven changes in soil organic matter stability can offset or compound combustion losses, depending on the ecosystem [12]. Losses of both particulate and mineral-associated organic carbon have been shown to persist after fire, driven by microbial carbon demand outpacing vegetation inputs [35], suggesting that aboveground recovery does not necessarily translate into soil carbon replenishment. Nevertheless, this decoupling has not been examined across decadal timescales in Mediterranean woodlands.

Recent evidence suggests that leaf litter and root inputs can lead distinct soil organic matter fractions [20,36] and that trait and species turnover follow decoupled trajectories after fire in Mediterranean shrublands [37]. This raises the question of whether structural or compositional attributes primarily drive soil carbon recovery and whether their relative

importance changes as communities mature. This is especially relevant in cork oak ecosystems, where the governing carbon dynamics in the above- and belowground environments and how they shift across successional stages remain largely unexplored.

This study aimed to address this gap through a chronosequence design to investigate the changes in C stock across the ecosystem compartments in plots burned 11 and 19 years previously compared with adjacent unburned reference stands. It was hypothesized that changes in aboveground carbon stock do not necessarily lead to an increase in soil organic carbon stock and that superficial soil organic carbon can show a weaker response to fire than aboveground and litter pools. This study also characterized the changes in community functional and diversity traits among the scenarios and further identified the structural and compositional drivers of soil organic carbon stocks within each scenario.

2. Materials and Methods

2.1. Study Area and Experimental Design

Serra do Caldeirão is located in the Algarve region, southern Portugal. The study area consisted mainly of *Quercus suber* forests of varying density and with extensive shrub cover, especially *Cistaceae* species (e.g., *C. ladanifer* L., *C. salvifolius* L.), *Ulex* sp., *Genista* sp. and *Ericaceae* species. Some areas present low altitudes, up to 500 m, with slopes that range between 3 and 35%, which make these stands prone to erosion. The soils are developed on schists and graywackes, included in the Mira Formation [38], being classified mainly as Leptosol or Umbrisol (cambic) [39]. Two very large wildfires occurred in the past decades. The fire of 2004 burned about 13,600 ha, and the fire of 2012 burned 24,300 ha. These areas correspond to 17% and 30% of the study area, respectively (Figure 1). Although the affected areas were extensive, the burned areas were mainly dominated by low (68.3%) and medium–low (21.6%) severity. The area affected by medium–high severity corresponded to less than 2% of the total area [40]. Since the occurrence of these fires, these areas were left to regenerate naturally, all under the same management associated to cork extraction.

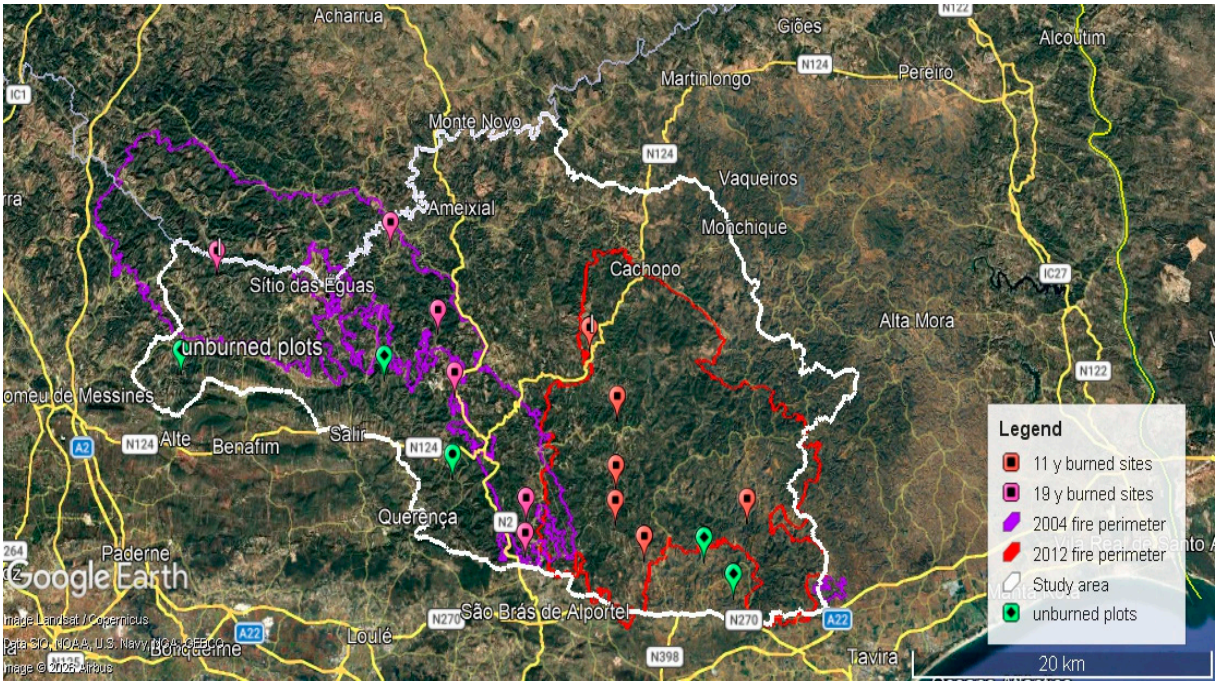


Figure 1. Delimitation of the studied scenarios and localization of the sampling points.

This study employed the space-for-time substitution method. In August 2022, field surveys were conducted in the forest, taking into consideration three specific scenarios: unburned areas, areas burned 11 years previously (11 yr post-fire), and areas burned 19 years previously (19 yr post-fire) (Figure 1). Plot selection was constrained to ensure comparable topography, aspect, substrate, and pre-fire vegetation type across scenarios. All plots were on similar parent material and shared analogous edaphic conditions, to minimize confounding soil variation. Five plots of 15 m in radius were randomly selected in each scenario. Within each plot, samples of vegetation, litter and soil were collected using three independent line transects and quadrat sampling. A total of 45 independent transects were sampled (n = 15/scenario) and were subject of further analysis. These sampling methods were implemented to accurately capture the plant community structure while maintaining statistical rigor in spatial data collection.

2.2. Sampling and Quantification of Vegetation Carbon Stock

Three transects (1 m × 10 m) were randomly established along the slope gradient, and vegetation was surveyed along each transect using the line-intercept method developed by [41]. The following variables were recorded for each shrub along the transect: species name, height (SH, in cm), and total cover (%), estimated as the proportion of the transect intercepted by aboveground vegetation. From these measurements, a fractional cover–stem length index (FCSL, $m^2\ m^{-2}$) was computed as the product of fractional cover and mean shoot height per species per transect, providing an integrated measure of phytovolume. Shrub bulk density (SBD, kg m^f) for each intercept was estimated using the allometric equations reported by [42].

Community coverage was estimated by assessing the proportional area covered by each species relative to the total sampled area in vertical projection. Aboveground carbon (AGC, kg m^{-2}) for each species was estimated by multiplying species-specific bulk density and by its respective phytovolume and carbon-to-biomass coefficient (0.5). Additionally, species-level plant diversity was characterized using three indices: species richness (S) [43], the Shannon–Wiener diversity index (H') [44], and Pielou's evenness index (E) [45].

2.3. Litter Sampling and Carbon Quantification

Litter was collected inside each quadrat (1 m × 1 m), and the cover was estimated. A total of 45 quadrats were collected. The fine (<2 cm) and coarse (2–7 cm) litter fractions were separated, oven-dried at 45 °C, until constant mass, and then weighed. The total litter carbon content (g m^{-2}) was determined by multiplying the biomass by the total carbon content obtained by the calcination method.

2.4. Soil Sampling and Soil Organic Carbon Stock Quantification

A total of 45 soil samples were collected from same quadrat after litter collection at a depth of 0–5 cm, which corresponds to the layer most directly influenced by surface litter inputs and changes in organic matter caused by fire. In each quadrat, one undisturbed soil sample was collected using a rigid metal cylinder of 2 cm in height and 5 cm in diameter. Then, disturbed soil samples were collected. The undisturbed soil samples were dried at 45 °C to determine their bulk density. The disturbed soil samples were homogenized, air-dried and then used to determine fine (<2 mm) and coarse fractions and total C by dry combustion [46]. Subsequently, the soil organic carbon stock (SOC) was calculated following [47] as follows:

$$SOC\ (MgC{\cdot}ha^{-1}) = OC \times BDfine \times (1 - vG) \times t \times 0.1$$

where SOC is the soil organic carbon stock (MgC·ha^{-1}); OC is the organic carbon content (g·kg^{-1}) in the soil fraction (<2 mm); BDfine is the bulk density of fine soil; vG is the volumetric content of coarse fraction (>2 mm); t is the thickness of the soil; and 0.1 is the conversion factor.

2.5. Statistical Analysis

Differences in SOC, AGC, and total litter C among the three scenarios were assessed using one-way analysis of variance (ANOVA). Homogeneity of variances was tested using Levene's test and normality was evaluated graphically. Pairwise scenario comparisons were conducted using Tukey's (HSD) test. The same statistical test was conducted to evaluate the differences in plant community characteristic and diversity profile across scenarios.

To identify the structural and compositional vegetation predictors of soil carbon stock, two-layer Random Forest (RF) regression models were fitted separately for each scenario using the rfPermute package in R studio [48]. Structural models used six transect-level predictors: total AGC (kg m^{-2}), mean canopy height (m), total phytovolume (FCSL, m^2 m^{-2}), fine litter C (g m^{-2}), coarse litter C (g m^{-2}), and community-weighed mean species bulk density (CWM SBD, kg m^{-3}). Compositional models used the per-transect FCSL values of the eight most abundant species across the full dataset as predictors: *Cistus ladanifer* L., Herbaceous, *Lavandula stoechas* L., *Genista tridentata* L., *Ulex argenteus* Welw. Ex Webb, *Arbutus unedo* L., *Cistus salviifolius* L., and *Quercus suber* L. All models were run with 500 trees (ntree = 500). Variable importance was quantified using the permutation-based percentage increase in mean squared error (%IncMSE), estimated with 999 permutations.

3. Results

3.1. Carbon Pools Across the Post-Fire Chronosequence

Soil carbon stock was similar among the scenarios (kg m^{-2}—11-years: 1.61 ± 0.13; 19-years 1.64 ± 0.14 kg m^{-2}; Unburned: 1.39 ± 0.20) but the carbon pools associated with vegetation and litter exhibited contrasting responses to fire history compared with the unburned reference site (Figure 2). The burned plots showed higher values in aboveground carbon pool (AGC) than the unburned plots, which had total AGC of 0.36 ± 0.07 kg m^{-2}. Among the burned areas, the plots 11 years post-fire recorded the highest AGC values, with an average of 1.11 ± 0.14 kg m^{-2} (19 years post-fire: 0.73 ± 0.15 kg m^{-2}; Figure 2).

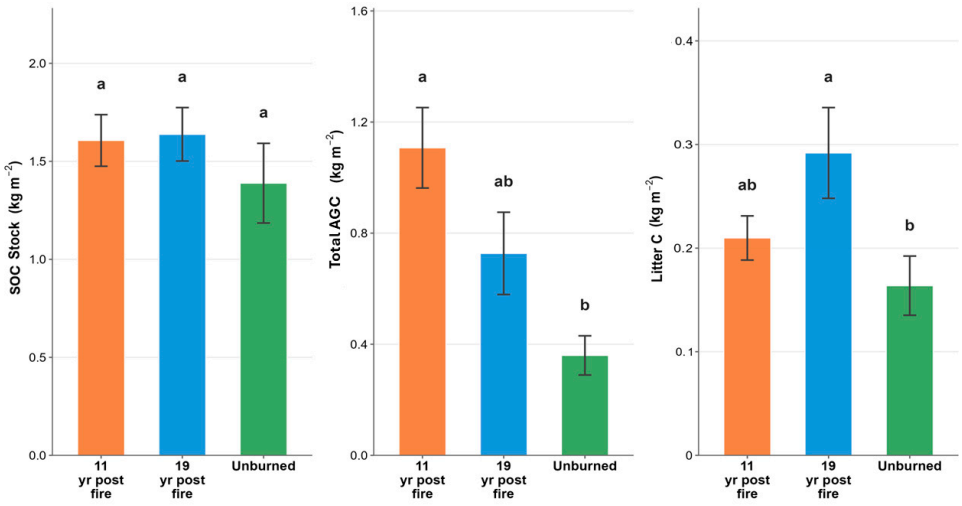


Figure 2. Carbon pools in the different components of the forest system (soil, aboveground and litter) across the post-fire chronosequence (Mean ± SE). Unburned stands serve as the no-disturbance reference. Different letters for the same component indicate significant differences.

In contrast to AGC, the highest litter carbon amounts were found in plots 19 years post-fire (g m^{-2}—291.85 ± 43.79; 11-years post-fire: 209.78 ± 21.34; Unburned: 163.77 ± 28.56; Figure 2).

3.2. Plant Community Characteristics and Diversity Profile Across the Post-Fire Chronosequence

Total canopy cover and community-weighed mean species bulk density were similar among the scenarios (Table 1). However, mean heights and total phytovolumes (FCSL) followed contrasting temporal patterns. Shrubs growing in plots 11 years post-fire were almost twice the height of those in unburned stands, while heights in plots 19 years post-fire increased slightly. FCSL values at both post-fire stages were significantly higher than in the unburned scenario. Although species richness has increased from the unburned scenario until 19 years after the fire, which reach the highest value, this trend was not observed for the other diversity indices (Table 1).

Table 1. Structure and diversity of plant community and amounts of C in fine and coarse fractions of litter across the post-fire chronosequence (Mean ± SE; n = 15 transects per scenario). Different letters within each parameter indicate statistically significant pairwise differences.

Variable	Unburned	11 yr Post-Fire	19 yr Post-Fire	F	Df(2)	P
			Aboveground			
Total Cover (%)	43.00 ± 7.94 a	56.67 ± 7.71 a	65.33 ± 7.66 a	2.099	2	0.135
Mean Height (m)	0.57 ± 0.09 b	1.01 ± 0.11 a	0.73 ± 0.12 ab	4.380	2	0.018
Total Phytovolume (FCSL, m^2 m^{-2})	0.56 ± 0.09 b	0.87 ± 0.03 a	0.78 ± 0.06 a	6.366	2	0.004
CWM Species Bulk Density (g m^{-3})	3.22 ± 1.25 a	2.24 ± 0.10 a	2.56 ± 0.28 a	0.046	2	0.955
Species Richness (S)	4.60 ± 0.51 b	5.27 ± 0.36 ab	6.07 ± 0.36 a	3.161	2	0.042
Shannon–Wiener Index (H')	1.04 ± 0.14 a	1.13 ± 0.09 a	1.33 ± 0.07 a	2.176	2	0.126
Pielou's Evenness (E)	0.74 ± 0.04 a	0.69 ± 0.05 a	0.75 ± 0.03 a	0.626	2	0.540
			Litter			
Fine Litter C (kg m^{-2})	0.08 ± 0.03 b	0.10 ± 0.02 ab	0.2 ± 0.04 a	3.746	2	0.032
Coarse Litter C (kg m^{-2})	0.08 ± 0.01 b	0.11 ± 0.02 ab	0.19 ± 0.03 a	5.799	2	0.026

Both fine and coarse litter fractions accumulated substantially after the fire, reaching peak amounts in plots burned 19 years before this study. These amounts differed significantly from those in unburned areas (Table 1).

3.3. Structural and Compositional Drivers of Soil Carbon Stock

Permutation-based variable importance identified consistent and ecologically interpretable patterns across both compositional and structural levels of soil carbon predictors across the scenarios chosen (Figure 3).

In the unburned plots, RF achieved good accuracy, with R^2 ranging between 0.61 and 0.59 respectively for structural and compositional variables. At the structural level, soil carbon stock was mainly influenced by CWM species bulk density and total AGC (32% and 27% respectively), followed by total FCSL (18%) and mean canopy height (14%). The compositional aspect was dominated by *Genista tridentata* (L.) Samp. (80%) followed by *Cistus ladanifer* L. (11%) and *Ulex argenteus* Welw. Ex Webb (8%) as minor contributors.

With respect to 11 years post-fire, RF R^2 ranged between 0.57 and 0.59 for both structural and compositional metrics. The soil carbon stock in the plots 11 years post-fire was influenced by five structural metrics, majorly by mean canopy height (26%), total FCSL (24%), fine litter biomass (16%), total AGB (8%), and coarse litter biomass (7%). In terms of composition, two plant species were identified as having a high level of influence: *Genista tridentata* (L.) Samp. (75%) and *Arbutus unedo* L. (25%).

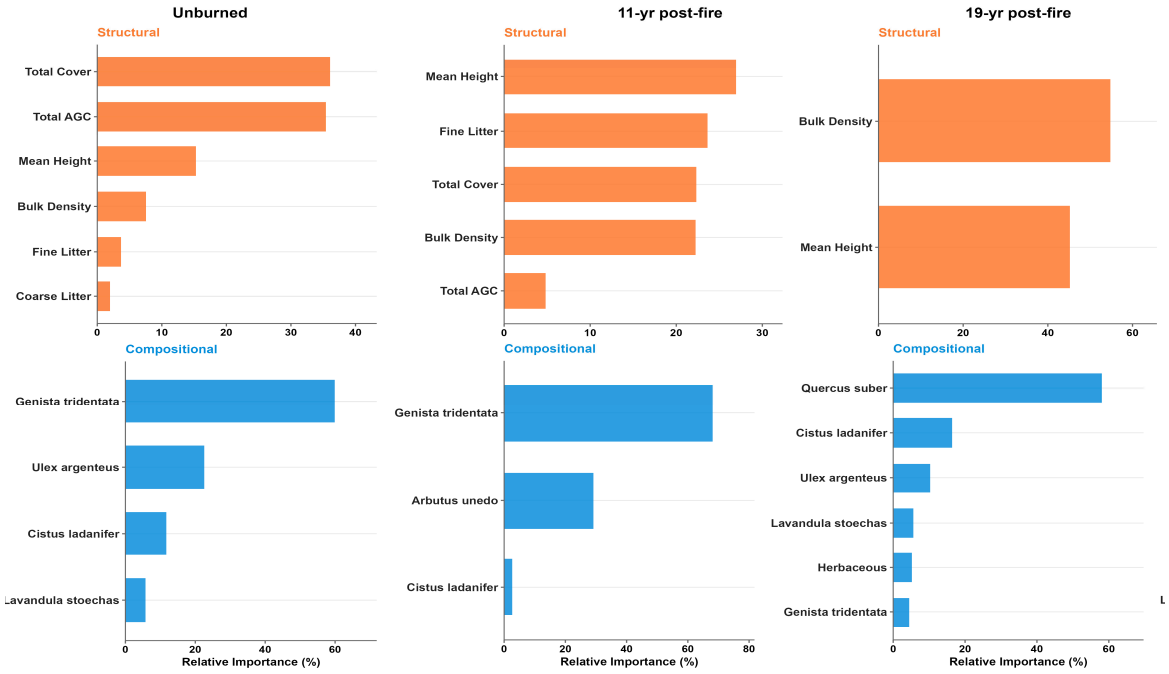


Figure 3. Random Forest variable importance for predictors of soil carbon stock across the chronosequence. Top row: Layer 1 structural predictors (total AGC, mean canopy height, total phytovolume FCSL, fine litter, coarse litter, bulk density, and CWM species bulk density). Bottom row: Layer 2 compositional predictors (per-species FCSL for the eight most abundant species).

In the scenario 19 years post-fire, RF explained 55% and 59% of the variance for the structural and compositional variables respectively. A major change was observed at the structural and compositional level in comparison with the previous scenarios. The structural model collapsed to just two predictors: mean canopy height (87%) and total AGB (13%). Also, the compositional level expanded considerably, having six plant species influencing soil carbon stock: herbaceous cover (32%), *Quercus suber* L. (32%), *Genista tridentata* (L.) Samp. (14%), *Cistus ladanifer* L. (6%), *Arbutus unedo* L. (5%), and *Lavandula stoechas* L. (4%) (Figure 3).

4. Discussion

4.1. Carbon Pool Dynamics Across the Post-Fire Chronosequence

Prominent differences in carbon pools were obtained when evaluating unburned and burned areas in an oak forest under Mediterranean conditions, 11 and 19 years after a fire (Figure 2). Contrary to the common assumption that fires lead to prolonged deficits in carbon, the post-fire community in the studied area had significantly higher AGC with ratios of approximately 3:1 and 2:1 for 11 and 19 years, respectively. This result is consistent with the ecology of dominant Mediterranean shrubland species, which possess strong recovery capacity through resprouting or fire-stimulated germination following fire disturbance [16,21]. Pyrophyte shrubs such as *Cistus ladanifer* L. show strong post-fire germination. On the other hand, *Calluna vulgaris* (L.) Hull, *Lavandula stoechas* L., and *Genista tridentata* (L.) Samp. resprout prolifically in structurally open environments where there is no established competition, forming dense, even-aged cohorts. This leads to an increase in carbon stock compared with unburned stands [43–45]. The observed decline in AGC in plots 19 years after the fire likely reflects the onset of density-dependent self-thinning. Stands at the 11-year stage likely reflect species competition for light and space, which is also visible, as these stands had the greatest height (Table 1). As stands mature, competition for water and nutrients increases, leading to the mortality of suppressed

individuals and the structural reorganization of the canopy. Such successional transitions are typical of Mediterranean shrublands and have been documented in numerous post-fire chronosequence studies [49–52]. From a carbon accounting perspective, this phenomenon highlights the limitations of assuming monotonic carbon recovery after fire.

As result of plant development, the total amount of litter was higher in burned plots than in unburned ones, with the highest value registered 19 years post-fire. This response is associated with accumulation over time and further suggest the self-thinning phase of vegetation development. However, the elevated litter inputs observed in the burned stands did not result in higher soil organic carbon stocks. Compared with the unburned scenario, SOC in both burned scenarios showed slight variation, with the 11- and 19-years scenarios having similar values. This stability indicates a clear decoupling between aboveground carbon accumulation dynamics and soil organic carbon storage. However, these parameters were not directly evaluated in this study.

Several non-exclusive factors may contribute to the absence of SOC differences. One possible explanation is related to the Mediterranean climate characteristics. Summer droughts and moderately cold winters limit decomposition processes and transformation of fresh litter into organic matter [53,54]. Therefore, the conversion of surface litter into soil carbon pools can be influenced by other environmental and biogeochemical factors, rather than just differences in litter quantity. However, soil microbial biomass and enzymatic activity can decline substantially under drought conditions [55–57]. Moreover, the development of microbial communities can increase considerably following ecological stress factors such as fire, contributing an important C source to soil [40].

The response of soil carbon to fire can often vary with depth. As the present study focused on the 0–5 cm mineral soil horizon, potential changes in deeper soil layers may have been overlooked [58]. Previous research has shown that the effects of fire on SOC can extend to deeper mineral horizons, where turnover rates are slower and carbon is more strongly stabilized by mineral associations [59]. Thus, fire may have reset the long-term soil organic carbon equilibrium by directly combusting surface organic matter and altering the soil's microbial biomass and community [60,61].

4.2. Plant Community Characteristics and Diversity Profile Across the Post-Fire Chronosequence

Beyond carbon pools, the community-level variables revealed several distinct ecological responses (Table 1). The structural variables, maximum height and total phytovolume (FCSL) exhibited distinct patterns. Maximum height showed a clear peak at the 11-year stage followed by a decline at 19 years, suggesting that shrub communities initially maximize vertical growth in response to reduced competition and high resource availability after fire [16,62]. Nevertheless, phytovolumes remained significantly elevated in both post-fire stages relative to the unburned reference. As phytovolume integrates both canopy height and horizontal vegetation cover, this metric captures the overall three-dimensional occupancy of vegetation within the canopy space. Therefore, the persistent elevation of phytovolume indicates that shrub stands remain structurally dense even after two decades of recovery. Further analysis of total cover and canopy bulk density suggest that where their values did not differ among scenarios, fire primarily alters vegetation structure and species composition rather than total cover and canopy density [59].

Species richness exhibited a significant peak in plots 19 years post-fire, whereas Shannon diversity (H′) and Pielou's evenness (E) remained unchanged across the different scenarios. These results align with the findings of [63,64] in semi-arid oak forests, where it was noted that the time elapsed since the last fire can significantly affect diversity indices, resulting in the lowest values of richness, evenness and diversity.

The pattern observed in the present study suggests that fire influences the number of species in a community without significantly altering the relative dominance of different species. The transient peak in species richness observed in the second decade after the fire is consistent with the intermediate disturbance hypothesis, which predicts maximum species richness at intermediate stages of disturbance and succession [33]. During this transitional phase, early successional pioneer species persist, while later-successional shrubs and woody species begin to establish, temporarily increasing total species richness.

4.3. Structural and Compositional Drivers of Soil Carbon Stock

Random Forest analysis revealed that the nature of the association between vegetation and SOC can change qualitatively across the chronosequence, even though the mean SOC remains the same.

In the plant community growing in unburned plots, species bulk density, total AGC and total cover were the main factors explaining soil carbon stock in the structural model. This structural dominance is consistent with findings from other oak forests under temperate conditions [27], where species bulk density was one of the strongest predictors of carbon storage, along with height. Furthermore, the compositional model was dominated almost entirely by *Genista tridentata* (L.) Samp. (~80%). This nitrogen-fixing legume produces nitrogen-rich litter with low C:N ratios that decomposes differently from the recalcitrant litter of co-occurring heathland species. Its root nodules actively fix atmospheric nitrogen, thereby modifying soil N cycling and the stoichiometric controls on organic matter decomposition and microbial processing [6,63].

In the scenario 11 years post-fire, when the community diverges most strongly from the unburned reference in terms of aboveground properties, the structural Random Forest signal was distributed across five predictors, with mean height, total cover and fine litter providing the main explanation. In terms of plant composition, *Genista tridentata* (L.) Samp. continued to dominate (75%), with *Arbutus unedo* L. being present in smaller amounts. This indicates that the fire-driven overshoot in total AGC and mean height did not result in a corresponding increase in SOC and that the aboveground excess was not reflected belowground.

In plots 19 years post-fire, the structural model collapsed almost entirely into mean canopy height. This suggests that at this stage, this single metric integrates all available structural information for SOC. Simultaneously, the compositional model expanded to six species, including *Quercus suber* L. as a major predictor. Cork oak is a slow-growing, deep-rooted species with recalcitrant litter and strong mycorrhizal associations; its emergence as an SOC predictor 19 years after the fire indicates the start of a phase driven by species identity, consistent with evidence that late-successional species with distinct litter quality begin producing detectable belowground effects during the mid-successional stage rather than building structural aggregates [17,65–69].

5. Conclusions

The present study showed that Mediterranean shrubland undergoes substantial aboveground carbon accumulation within two decades after a fire. However, this accumulation does not result in significant increases in soil organic carbon stocks. The persistence of this aboveground–belowground decoupling throughout the entire two-decade period challenges the assumption that vegetation recovery is the primary factor in restoring SOC in fire-prone ecosystems. Instead, the findings suggest that edaphic and climatic constraints might be a possible cause, particularly the long drought periods characteristic of Mediterranean summers, as the dominant regulator of SOC stabilization, likely due to impaired microbial activity affecting organic matter incorporation rates. Aboveground biomass

trajectories, often used as proxies for ecosystem carbon recovery, may systematically overestimate belowground carbon gains in seasonally dry systems.

The chronosequence studied suggests that rather than being a dominance disruptor, fire acts as a compositional filter, reorganizing communities without fundamentally altering the structure of relative dominance. This results in a transient richness peak at 19 years and leaves diversity evenness largely intact, which is consistent with the intermediate disturbance hypothesis.

The drivers of SOC variation shifted qualitatively across fire history stages: from community-level structural metrics in unburned stands to multidimensional structural proxies after 11 years to canopy height as the dominant predictor after 19 years. This progressive simplification of the SOC–vegetation relationship indicates that chronosequence studies capturing only one post-fire stage may misidentify the mechanisms governing carbon dynamics. Additionally, the persistence of Genista tridentata dominance across all burned stages reinforces its role as a keystone structural species in early-to-mid succession. The emergence of *Quercus suber* as a significant SOC predictor at 19 years suggests a qualitative transition in ecosystem functioning, shifting from structurally driven SOC dynamics to species-identity-driven ones. Late-successional species begin generating detectable belowground effects independently of structural properties.

However, it is worth noting that even though the implemented methodology tried to account for several influencing factors, the results can be limited to draw robust conclusions. Together, these results suggest that post-fire vegetation recovery cannot be considered equivalent to carbon ecosystem recovery. They also suggest that Mediterranean ecosystems likely operate through mechanisms such as shifts in microbial communities, root turnover, and associations between mineral and organic matter. Further work should include a larger sample size and consider litter chemical quality and microbial processes to obtain a comprehensive understanding.

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