

Fire resilience in a Mediterranean cultural landscape

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Case Report

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Abstract

Background

Traditional agricultural terraces are widespread features of Mediterranean Basin landscapes, yet it remains unclear how these landscape legacies affect fire resilience. Eleven years after a mixed-severity wildfire in a Mediterranean cultural landscape, I surveyed overstory, recruitment, understory vegetation, and forest-floor attributes across 29 plots (15 terraced, 14 non-terraced) with varying fire histories to assess whether terraced hillslopes differed in fire resistance and recovery, and which landscape and stand characteristics were associated with contrasting *Pinus halepensis* post-fire establishment. For the 23 burned plots, resistance was quantified as the proportional retention of pre-fire overstory structure, recovery as multivariate convergence toward unburned reference conditions, and establishment as *P. halepensis* sapling density. These three dimensions were integrated within a resilience framework that identified plots into five pathways: resistant and recovering, resistant but recovery-limited, recovery-driven, hyperdense, and transition-risk.

Results

Overstory resistance did not differ significantly between hillslope systems, although terraced stands consistently retained a greater proportion of pre-fire tree density, basal area, and small-diameter trees than non-terraced stands. Instead, resistance was more strongly associated with elevation, aspect, and tree size. Burned non-terraced stands showed greater multivariate convergence toward their unburned reference conditions than burned terraced stands, driven primarily by overstory structure and recruitment. Post-fire establishment varied substantially among burned plots, ranging from low (< 700 saplings ha^{-1}) to hyperdense ($\geq 4,000$ saplings ha^{-1}). Patterns in establishment suggested a potential role for pre-fire stand structure and reproductive potential in post-fire recruitment, but none of the variables examined were statistically significantly associated with sapling density. Nearly half of burned plots showed evidence of a trajectory toward pre-fire conditions, but the transition-risk pathway was the most common (39.1%).

Conclusions

Historical agricultural terraces had limited influence on fire resilience. The prevalence of the transition-risk pathway suggests risk of vegetation-type conversion from *P. halepensis* forest to persistent shrubland. The framework provides a potential early-warning approach for identifying declining resilience and emerging shifts in forest trajectories, although its generality and predictive value require testing across additional disturbance events, landscapes, and longer post-fire periods. If validated, it could help identify stands requiring closer monitoring or targeted management before alternative post-fire vegetation states become established.

Background

Fire-prone forests and woodlands have experienced fires for millennia, shaping the ecosystem's composition, structure, and functioning (Naveh 1975; Bond et al. 2005; He et al. 2019; Pausas and Keeley 2019). In Mediterranean ecosystems, the interplay of winter precipitation and mild temperatures supports biomass growth, while alternating years of summer drought increase biomass drying and flammability, creating favorable fire conditions (Keeley and Pausas 2022). Plant communities in Mediterranean fire-prone ecosystems are generally considered resilient to recurrent wildfires *sensu* Holling (1973), reflecting adaptations that allow them to persist under historical fire regimes. Resilience encompasses three related dimensions: resistance to disturbance, recovery of structure and function following disturbance, and the capacity to avoid shifts into alternative ecosystem states (Chambers et al., 2019; Falk et al., 2019).

Fire regimes are being fundamentally altered by the interaction of climate change and shifting land use patterns. Recognized as a significant hotspot for climate change (Giorgi 2006; Diffenbaugh and Giorgi 2012; Lionello and Scarascia 2018), the Mediterranean Basin is projected to experience an increase in drought frequency and heatwaves (Spinoni et al. 2017), warming roughly 20% faster than the global annual mean surface temperature, with especially pronounced increases during summer (Lionello and Scarascia 2018). Concurrently, major alterations to historical fire regimes have largely resulted from changes in land use and fire management. While anthropogenic fire use has been practiced in fire-prone regions, serving as a multifaceted tool for agriculture, forestry, and livestock management (Pyne 2009; Hoffman et al. 2021; Maclean et al. 2023), economic restructuring and surge in tourism in the Mediterranean Basin during the latter half of the 20th century triggered a transformative period marked by rural land abandonment and urban sprawl (García-Ruiz and Lana-Renault 2011; Pausas and Fernández-Muñoz 2012; Pons and Rullan 2014). The cessation of traditional agricultural and silvicultural practices, combined with decades of strict fire suppression, has led to fuel accumulation, increased biomass continuity, and lost landscape heterogeneity (Radeloff et al. 2005; Fernandez-Anez et al. 2021; Chen et al. 2024). Together, warming trends and fuel accumulation can prolong the fire season and intensify biomass flammability, resulting in more frequent, larger, and longer-lasting wildfires (Moriendo et al. 2006; Ruffault et al. 2020; Pausas and Keeley 2021; Guion et al. 2022; Jones et al. 2022).

As wildfire activity escalates in intensity and scale, the ecosystems' capacity to resist fire and recover from its impacts has become increasingly uncertain. Ecosystem resistance is shaped by species-specific fire-adaptation traits, pre-fire stand maturity (Pausas and Vallejo 1999; Buhk et al. 2005), topography, fire intensity, and other environmental conditions (Tsitsoni 1997; Arnan et al. 2007; Moreno et al., 2011; Stevens-Rumann and Morgan 2019). Post-fire recovery, in turn, depends on species survival and post-fire regeneration strategies, as well as climatic conditions (Elvira et al. 2021), soil properties and nutrient availability (Certini 2005), and fire refugia (Coop et al. 2019). Mediterranean vegetation has evolved under recurrent fires and includes species with contrasting post-fire recruitment strategies, including seeders (e.g., *Pinus halepensis*) and resprouters (e.g., *Quercus ilex*) (Pausas and Keeley 2014). These functional traits are specifically adapted to maintain demographic stability, enabling the

ecosystem to persist under historical fire regimes (Arnan et al. 2007). For resprouting species, frequent burning can deplete belowground reserves, leading to “resprout exhaustion syndrome” (Karavani et al. 2018), while for obligate seeders, burning before seed bank replenishment can induce “immaturity risk” (Keeley et al. 1999; Batllori et al. 2019; Baudena et al. 2020). These risks are amplified under increasingly unfavorable climatic conditions (Stevens-Rumann et al. 2018; Nolan et al. 2021; Elvira et al. 2021), potentially driving transitions from forests to persistent shrublands or other alternative vegetation states, with substantial losses of ecosystem functions and services (Camarero et al. 2015; Coop et al. 2020; Torres et al. 2021; García-Llamas et al. 2024).

In western Mediterranean landscapes, these broader land-use changes also led to the abandonment and degradation of one of the region's most distinctive landscape legacies: traditional agricultural terraces. Consisting of leveled cultivation surfaces supported by dry-stone retaining walls and maintained through generations of local ecological knowledge (Vadell et al. 2022). These terraces transformed steep, resource-limited landscapes into productive and resilient socioecological systems (Price and Nixon 2005; Petanidou et al. 2008; Calsamiglia et al. 2017a) characterized by heterogeneous land-use mosaics that reduced fuel continuity, enhanced soil and water retention, controlled erosion, and supported biodiversity (Calsamiglia et al. 2017b; Socci et al. 2019; Cornu 2019). However, the widespread abandonment of these agroforestry systems has led to soil degradation (Calsamiglia et al. 2017a), the collapse of many dry-stone walls (Tarolli et al. 2014; Calsamiglia et al. 2017b), and broader alterations to ecosystem processes (Mantero et al. 2020), potentially weakening the mechanisms through which terraces may have influenced fire behavior and fire resilience. Nevertheless, the extent to which these landscape legacies affect fire resilience remains unclear.

Because the first decade following wildfire is considered a critical period for shaping long-term forest trajectories (Millar and Stephenson 2015; Larson et al. 2022), this study evaluated forest fire resilience eleven years after a mixed-severity wildfire across terraced and non-terraced hillslope systems within a Mediterranean catchment. Within a resilience framework, I quantified resistance as the proportional retention of pre-fire overstory structure and assessed recovery as the degree to which post-fire stand structure and composition converged toward unburned reference conditions. In addition, I evaluated *P. halepensis* sapling density as an indicator of post-fire establishment. I integrated all three dimensions to characterize contrasting resilience pathways, reflecting potential trajectories toward continued forest development or divergence from mature forest conditions.

Specifically, I asked: (1) Did overstory resistance to wildfire differ between terraced and non-terraced hillslope systems? (2) To what extent did burned stands recover toward unburned reference conditions within each hillslope system? (3) Which environmental and stand characteristics were associated with contrasting post-fire *Pinus halepensis* establishment outcomes? and (4) What were the predominant resilience pathways across the study site?

Methods

Study area

The Sa Font de la Vila River (Fig. 1a, b, c) is a ca. 4.80 km² catchment in the southwestern county of the Tramuntana mountain range in the municipality of Andratx on the island of Mallorca. The catchment is representative of many Mediterranean Basin landscapes characterized by a complex topography, with elevations ranging from 63 to 517 m a.s.l. and a mean slope gradient of 38%. The soil is primarily calcareous, shallow, and stony, often interspersed with rocky outcrops.

Historical agricultural terraces supported by dry-stone walls occupy approximately 37% of the catchment area and remain a defining landscape feature despite widespread land abandonment and natural afforestation. Vegetation on terraced slopes was dominated by fruit groves, which now account for only 8% of the catchment area. Natural afforestation consisted of pine-oak forests dominated by Aleppo pine (*P. halepensis*) and holm oak (*Quercus ilex* L.), as well as shrublands at various stages of succession.

The climate is Mediterranean according to the Köppen classification, characterized by hot, dry summers and mild winters. The island has an average annual temperature of 16.5°C and a mean annual rainfall of 531.7 mm (Estrany and Gago 2019). Mallorca experiences a highly variable rainfall regime, with dry years alternating with wet ones. Heavy rainstorms exceeding 100 mm in 24 hours often cause severe flooding of ephemeral rivers (Estrany and Grimalt 2014). The driest period extends from June to August.

The catchment has experienced two recent large wildfires. The first, La Trapa (LT) wildfire, burned approximately 25% of the catchment area in June 1994. The second, Sa Coma Calenta (SCC) wildfire burned approximately 71% of the catchment area in July 2013, with part of its perimeter overlapping the area burned in 1994.

An unpublished monitoring study reported a fast understory recovery and adequate pine recruitment following the SCC wildfire. Plant cover was dominated by the perennial tussock grass [*Ampelodesmos mauritanicus* (Poiret) T. Durand et Schinz] –14.7% cover–, the Mediterranean dwarf palm –2.7% cover–, the vigorous resprouter *Pistacia lentiscus* L. –2.1% cover–, and the perennial false brome grass [*Brachypodium retusum* (Pers.) Beauv.]. One year after the 2013 SCC wildfire, *P. halepensis* seedlings averaged 2000 individuals ha⁻¹; however, many failed to survive the summer drought. Between October 2014 and January 2016, new seedlings germinated, reaching average densities of 6000 individuals ha⁻¹. By the final inventory in November 2017, *P. halepensis* seedlings averaged 1900 individuals ha⁻¹, with a mean height of 35cm.

Plot selection

To capture the spatial heterogeneity of the catchment, I generated 1000 random plot centers in a GIS. Candidate plots were classified according to hillslope system (T, terraced; NT, non-terraced), SCC wildfire burn status and severity (U, unburned; M, moderate; H, high), and LT wildfire burn status using spatial layers representing the distribution of dry-stone walls (adapted from Calsamiglia et al. 2017b), and

dNBR-derived burn-severity classes, and the 1994 wildfire perimeter (both adapted from García-Comendador et al. 2017). Candidate plots located outside the catchment, intersecting more than one classification category, or overlapping houses or major roads were excluded. Following GIS-based screening and field verification, 29 plots (15 T and 14 NT) were retained for sampling (Figs. 1a & 2).

Field methods

Sampling was conducted during Spring and early Summer 2024, eleven years after the 2013 SCC wildfire. At each plot center, I recorded elevation, aspect, and slope. Canopy closure was estimated using a spherical densiometer positioned 2 m from the plot center and oriented towards each of the four cardinal directions.

Live and dead overstory trees were surveyed within a 25-m-radius circular plot centered on each sampling point, following the methodology of the Fourth Spanish National Forest Inventory (MITECO, 2012; Fig. 1d). Trees were included if they had a diameter at breast height (DBH; 1.3 m) ≥ 7.5 cm for pines or ≥ 2 cm for resprouting species. For each tree, I recorded species identity, spatial location, and status (live, snag, or stump). DBH was measured for live trees, whereas diameter at stump height was measured for dead individuals.

Trees below the overstory size thresholds were classified as recruits and tallied within a nested 5-m radius circular subplot centered on the sampling point (Fig. 1d). Recruits were identified to species and assigned as seedlings (< 0.5 m height) and saplings (≥ 0.5 m height).

Understory vegetation cover was quantified using the line intercept method along two 20 m radial transects. One transect extended from northeast to southwest, and the second from northwest to southeast, intersecting at the sampling point at right angles (Fig. 1d). The forest floor depth (litter and duff) was measured at ten points spaced 1.5 m apart, along the same transects.

Data analysis

To verify that burned and unburned plots had comparable topographic characteristics within each hillslope system, I compared aspect, slope, and elevation among plots. Aspect was transformed into an ecologically meaningful heat load index following the methods of Beers et al. (1966), ranging from 0 (warm southwest-facing slopes) to 2 (cold northeast-facing slopes), with intermediate values representing intermediate heat loads.

Plant species were classified as seeders, resprouters, or facultative species based on their post-fire regeneration strategy using the FLAMITS database (Ocampo-Zuleta et al. 2023). Understory plant seeder-to-resprouter ratio (S/R) was calculated following (Lloret et al. 2005).

Fire history was classified according to exposure to the 2013 SCC wildfire. Plots that experienced the 2013 SCC wildfire were classified as burned ($n = 23$), whereas all other plots were classified as unburned

($n = 6$). Among burned plots, the fire-free interval was 19 years for plots that experienced the 1994 wildfire and ≥ 30 years for plots with no evidence of a fire event between 1980 or earlier and 2013.

Resistance

Fire resistance was assessed by reconstructing pre-fire stand structure and quantifying post-fire structural retention and compositional change following the 2013 SCC wildfire. Because pre-fire inventories were unavailable, pre-fire stand structure was approximated by combining surviving trees with individuals killed in the 2013 SCC wildfire. For fire-killed trees, stump diameter was used as an estimate of pre-fire DBH. Tree density (Tph; trees ha^{-1}), and basal area (Baph; $\text{m}^2 \text{ha}^{-1}$) were then estimated for each burned plot. The relative dominance of seeders in the overstory was quantified using the ecological importance value of *P. halepensis* (EIVpine), calculated as the sum of its relative density and relative basal area. To evaluate size-dependent survival, trees were classified as small (Dclass S; < 20 cm DBH) or large (Dclass L; ≥ 20 cm DBH).

I assessed overstory resistance using structural and compositional metrics. Overstory structural resistance was calculated as the proportional retention (post-fire / pre-fire) of Tph, Baph, and species- and diameter-class-specific stem density, with values approaching one indicating greater retention of pre-fire structure. Overstory compositional resistance was quantified as the absolute change in EIVpine ($\Delta\text{EIVpine} = \text{post-fire} - \text{pre-fire}$), where more negative values indicate a greater decline in the dominance of *P. halepensis*.

Normality and homogeneity of variance were assessed using Shapiro–Wilk and Levene's tests, respectively. Because most variables deviated significantly from normality ($p < 0.05$), differences between hillslope systems were evaluated using nonparametric Wilcoxon rank-sum tests.

Recovery

Ecological recovery was defined as the multivariate convergence of burned plots toward unburned reference conditions within each hillslope system. To quantify recovery, I selected 11 variables representing four structural components: overstory structure (canopy openness, Tph, Baph, and EIVpine), recruitment (total seedling density, total sapling density, and *P. halepensis* sapling density), understory vegetation (total cover and S/R ratio), and forest floor characteristics (litter and duff depth). All variables were standardized as z-scores prior to analysis.

I constructed a multivariate Euclidean distance matrix from the standardized variables. For each burned plot ($n = 23$), recovery distance was calculated as the mean Euclidean distance to all unburned reference plots within the same hillslope system ($n = 3$ for each hillslope system). Smaller distances therefore indicated greater similarity to the corresponding unburned reference condition and, consequently, greater relative recovery. Differences in relative recovery between T and NT burned plots were evaluated using Wilcoxon rank-sum tests, and effect sizes were estimated using the rank-biserial correlation (r_{rb}).

To ensure that recovery comparisons were not biased by differences in natural variability of unburned reference conditions, I calculated the mean pairwise Euclidean distance among unburned reference plots separately for the T and NT hillslope systems. Similar mean pairwise distances were considered evidence of comparable reference heterogeneity, supporting direct comparisons of recovery between hillslope systems.

Pine establishment

I conducted an exploratory analysis to identify factors associated with contrasting pine establishment outcomes. Burned plots ($n = 23$) were classified into three *Pinus halepensis* sapling density classes: low (< 700 pine saplings ha^{-1}), intermediate ($700\text{--}3999$ pine saplings ha^{-1}), and hyperdense (≥ 4000 trees ha^{-1}). The lower threshold followed Pausas et al. (2004), who reported that regeneration densities below 700 pines ha^{-1} are likely to result in low-density woodlands eight years postfire, whereas the hyperdense threshold followed Rodríguez-García et al. (2022).

I then evaluated associations between establishment class and a suite of landscape and stand predictors. These included pre-fire large pine density (Dclass L[pine] pre-fire), environmental conditions (elevation, slope, Beers index, canopy openness), hillslope system and time since previous fire, and post-fire site characteristics (retention of large pines, canopy openness, understory cover, and litter and duff depth). Associations with categorical predictors were evaluated using Fisher's exact tests, whereas continuous predictors were analyzed using Kruskal–Wallis tests. I assessed statistical significance at $p < 0.05$.

Resilience

Resilience was assessed as the current trajectory of post-fire stand development rather than as a long-term outcome. The assessment was conducted at an intermediate stage of post-fire succession, 11 years after the 2013 SCC wildfire, when post-fire stand development was sufficiently advanced for contrasting trajectories to emerge but insufficient to determine long-term ecosystem outcomes. This approach is consistent with recent applications of mid-term post-fire resilience assessment, which emphasize evaluating the direction and degree of post-fire change (e.g., Sánchez-Pinillos et al., 2023, 2024; Codina et al., 2026). I therefore developed a hierarchical framework that integrated resistance, recovery, and establishment to characterize alternative resilience pathways at the time of assessment (Fig. 3). This approach recognizes that resilience can arise through different combinations of overstory persistence, ecological recovery, and establishment and that these combinations may change as stands develop.

The resilience classification integrated the three previously calculated dimensions. Resistance was quantified as the proportion of pre-fire basal area retained by the surviving overstory. Burned plots retaining at least 50% of their basal area were classified as having “high resistance”, whereas those

retaining less than 50% were classified as having “low resistance”. This threshold is consistent with fire-severity classifications in which > 50% basal-area mortality represents substantial overstory loss (Welch et al., 2016). To classify relative recovery among burned plots, the combined recovery-distance distribution was divided into tertiles. Plots in the lowest third of the distance distribution were classified as “aligned”, those in the middle third as “intermediate”, and those in the highest third as “limited”. These categories represent relative degrees of convergence among the burned plots rather than absolute percentages of ecological recovery. Establishment was classified using the pine sapling density thresholds described above as low, intermediate, and hyperdense.

The three dimensions were then integrated to identify five resilience pathways (Fig. 3), which differed in the strength and certainty of evidence for stands to “bounce back” to the pre-disturbance state. Plots with high resistance and aligned recovery were classified as “Resistant and recovering”, representing the strongest evidence of high resilience, as substantial overstory structure was retained and stand conditions showed relatively high convergence with unburned reference conditions. Plots with high resistance and limited or intermediate recovery were classified as “Resistant but recovery limited”, representing a resilient trajectory based primarily on persistence of the surviving overstory, but with weaker evidence of recovery toward reference conditions at the time of assessment. Plots with low resistance, aligned or intermediate recovery, and intermediate establishment were classified as “Recovery-driven,” representing a resilient pathway in which recovery is occurring despite substantial overstory loss. In this pathway, future development of the pine cohort may play a greater role in determining how much the stand returns toward the pre-fire condition.

Among plots with low resistance, those with hyperdense establishment were classified as following a “Hyperdense pathway”. This pathway represents strong pine establishment but high uncertainty in the long-term trajectory. Future self-thinning and subsequent stand development may determine whether these dense cohorts develop toward a structurally similar *P. halepensis* forest or follow a different trajectory. Finally, plots with low resistance and either limited recovery or low establishment were classified as following a “Transition-risk pathway”. This pathway represents the weakest evidence of return toward pre-fire conditions, because limited overstory persistence, establishment, and/or recovery provided little indication that the stand was returning toward mature *P. halepensis* forest conditions at the time of assessment.

All statistical analyses were conducted in R version 4.4.1 (R Core Team, 2024).

Results

Before assessing fire resilience, I compared the topographic characteristics of terraced (T) and non-terraced (NT) hillslope systems (Table 1). Elevation, slope, and aspect were broadly comparable between hillslope systems (all $p > 0.05$), although NT plots occurred at slightly higher elevations (310.7 ± 14.9 vs. 265.8 ± 20.0 m) and on steeper slopes (29.3 ± 4.7 vs. $19.1 \pm 1.5\%$) than T plots.

Table 1
Topographic characteristics of terraced (T) and non-terraced (NT) burned plots. Values are presented as mean $\pm$ standard deviation. Differences between terrace categories were assessed using Wilcoxon rank-sum tests.

Variable	NT (n = 11)	T(n = 12)	p-value
Elevation	310.7 $\pm$ 14.9	265.8 $\pm$ 20.0	0.093
Slope	29.3 $\pm$ 4.7	19.1 $\pm$ 1.5	0.229
Aspect (Beers index)	1.01 $\pm$ 0.18	0.96 $\pm$ 0.15	0.827

Resistance

Reconstructed pre-fire overstory structure was broadly comparable between hillslope systems, although terraced plots exhibited greater tree density and basal area than non-terraced plots (Table 2). Following the 2013 SCC wildfire, both hillslope systems experienced substantial reductions in overstory density, basal area, and pine dominance. On average, tree density declined by approximately 82% in NT plots and 66% in T plots, whereas basal area declined by approximately 50% in NT plots and 66% in T plots. QMD declined by approximately 40% in both systems. The dominance of *P. halepensis* also declined markedly following wildfire, by approximately 61% in NT plots and 43% in T plots.

Table 2
Mean ($\pm$ SE) reconstructed pre-fire and post-fire overstory characteristics used to quantify fire resistance in terraced (T) and non-terraced (NT) hillslope systems across burned plots sampled in 2024. Tree density (Tph), basal area (Baph), and quadratic mean diameter (QMD) were reconstructed from surviving trees, snags, and stumps attributed to the 2013 SCC wildfire. EIVpine represents the ecological importance value of *P. halepensis*.

Tph (trees ha ⁻¹)	NTpre	NTpost	Tpre	Tpost
	204.6 $\pm$ 48.6	36.6 $\pm$ 16.9	251.7 $\pm$ 44.0	85.7 $\pm$ 42.5
Baph (m ² ha ⁻¹)	9.94 $\pm$ 2.70	4.98 $\pm$ 2.27	13.98 $\pm$ 2.38	4.72 $\pm$ 2.01
QMD (cm)	25.9 $\pm$ 4.1	15.3 $\pm$ 6.5	26.4 $\pm$ 1.8	15.8 $\pm$ 4.6
EIVpine	165.7 $\pm$ 17.8	65.1 $\pm$ 28.0	162.2 $\pm$ 9.3	93.2 $\pm$ 25.2

Structural resistance was consistently greater in terraced than in non-terraced hillslopes, although differences were not statistically significant (Table 3). Terraced plots retained a greater proportion of pre-fire tree density and basal area, with the largest contrasts observed for small-diameter *P. halepensis*, whose retention was more than three times higher in T than in NT plots (0.28 $\pm$ 0.09 vs. 0.09 $\pm$ 0.06). In contrast, retention of large *P. halepensis* was similar between hillslope systems. Small-diameter resprouters also exhibited higher retention in T plots, whereas large-diameter resprouters showed similar retention between hillslope systems. Compositional resistance followed a similar pattern, with T plots exhibiting a smaller decline in *P. halepensis* dominance than NT plots (Table 3).

Table 3

Overstory structural and compositional resistance in terraced (T) and non-terraced (NT) hillslope systems. Structural resistance is structured as proportional retention (post-fire/pre-fire), where a value of 1 indicates complete retention of pre-fire conditions and 0 indicates complete loss.

Dclass S and Dclass L represent small and large tree density, respectively. Δ EIVpine represents the change in *P. halepensis* ecological importance value between reconstructed pre-fire and post-fire conditions. Values are means $\pm$ SE. Differences between hillslope systems were evaluated using Wilcoxon rank-sum tests.

Resistance metric	NT	T	p-value
Tph	0.18 $\pm$ 0.08	0.24 $\pm$ 0.08	0.425
Baph	0.28 $\pm$ 0.12	0.34 $\pm$ 0.11	0.425
Dclass S[pine]	0.09 $\pm$ 0.06	0.28 $\pm$ 0.09	0.17
Dclass L[pine]	0.29 $\pm$ 0.12	0.31 $\pm$ 0.11	0.878
Dclass S[resprouters]	0.10 $\pm$ 0.07	0.21 $\pm$ 0.10	0.351
Dclass L[resprouters]	0.36 $\pm$ 0.36	0.21 $\pm$ 0.14	0.849
Δ EIVpine	-100.64 $\pm$ 31.33	-69.08 $\pm$ 29.85	0.370

Although resistance did not differ significantly between hillslope systems, several resistance metrics were associated with topographic position. Tree-density retention decreased with elevation (Spearman's $\rho = -0.53$, $p = 0.009$), as did Baph retention ($\rho = -0.52$, $p = 0.012$). Likewise, higher-elevation plots experienced greater declines in *P. halepensis* dominance (Δ EIVpine; $\rho = -0.59$, $p = 0.003$). Resistance also varied with aspect: cooler northeast-facing slopes (higher Beers index values) exhibited lower Baph retention ($\rho = -0.42$, $p = 0.046$), with a similar trend for greater declines in *P. halepensis* dominance ($\rho = -0.41$, $p = 0.054$). In contrast, slope was not significantly associated with any resistance metric (all $p > 0.12$).

Reconstructed pre-fire diameter-class distributions further illustrated contrasting fire effects between hillslope systems (Fig. 4). Prior to the 2013 SCC wildfire, both hillslope systems were dominated by small-diameter stems, particularly *P. halepensis* individuals between approximately 10 and 30 cm DBH. Following the SCC wildfire, stem density declined across all diameter classes, but losses were especially pronounced among small-diameter trees in NT hillslopes. Consequently, T plots retained a broader distribution of small-diameter *P. halepensis* and resprouter stems, whereas several small-diameter classes were nearly absent from NT plots.

Recovery

Across all recovery components combined, burned non-terraced plots were closer to their unburned reference conditions than burned terraced plots 11 years after the 2013 SCC wildfire. The mean

Euclidean distance = 5.16 vs. 5.89; $W = 27$, $p = 0.016$, indicated greater overall convergence in NT plots. This difference represented a large effect ($r_{rb} = 0.50$; Table 4).

Among the four components, however, recovery differed between hillslope systems for overstory structure and recruitment, but not for understory vegetation or forest-floor characteristics (Fig. 5).

Overstory structure remained substantially different from unburned reference conditions. Burned plots exhibited substantially lower tree density and basal area and greater canopy openness than unburned reference stands. Median tree density was 0 and 31 stems ha^{-1} in burned NT and T stands, respectively, compared with 224 and 469 stems ha^{-1} in their corresponding unburned reference stands. Similarly, median basal area was 0.0 and 1.7 $\text{m}^2 \text{ha}^{-1}$ in burned NT and T stands, respectively, compared with 15.3 and 17.5 $\text{m}^2 \text{ha}^{-1}$ in unburned stands, while canopy openness ranged from 82–100% in burned plots compared with 42–56% in unburned stands. Despite these structural differences, the relative dominance of *P. halepensis* remained similar between burned and unburned stands (median EIVpine = 117 vs. 122). Multivariate overstory distance was significantly lower in burned NT than in burned T plots, indicating greater convergence toward unburned reference conditions in NT plots (Table 4; $W = 22$, $p = 0.007$, $r_{rb} = 0.57$).

Recruitment patterns differed between burned and unburned reference stands. In NT hillslopes, burned stands had greater total recruitment than unburned reference stands (median = 2674 vs. 509 stems ha^{-1}), associated with higher sapling density (382 vs. 0 stems ha^{-1}). In contrast, total recruitment in T hillslopes remained lower in burned than unburned reference stands (1592 vs. 2292 stems ha^{-1}), largely because seedling density was lower (509 vs. 1528 stems ha^{-1}). Pine saplings were absent from unburned NT reference stands but occurred at a median density of 382 stems ha^{-1} in burned NT stands, whereas median pine sapling density was similar between burned and unburned T stands (446 and 382 stems ha^{-1} , respectively). Consistent with these differences, the multivariate recruitment distance was significantly lower in burned NT than in burned T plots, indicating greater convergence toward unburned recruitment conditions in NT plots (mean distance = 1.05 vs. 2.57; $W = 20$, $p = 0.005$, $r_{rb} = 0.59$).

Understory vegetation also remained distinct from unburned reference conditions. Total vegetation cover was broadly similar between burned and unburned stands, with median cover ranging from 30–33% in burned stands compared with 28–38% in unburned reference stands. However, community composition differed from reference conditions. Burned stands had higher proportions of obligate seeders (median = 23.7% in NT and 10.4% in T) than their respective unburned reference stands (0% in both), and lower proportions of resprouters (71.6–72.9%) than reference stands (91.8–100%). Despite these differences in understory composition, multivariate understory distance did not differ between burned NT and T plots (mean distance = 1.69 vs. 1.34; $W = 74$, $p = 0.651$, $r_{rb} = 0.10$), indicating similar convergence toward unburned reference conditions in the two hillslope systems.

Forest-floor attributes showed contrasting patterns between burned and unburned stands.. Duff depth was consistently lower in burned than in unburned reference stands (median = 1.1 vs. 2.2 cm in NT and

1.0 vs. 1.3 cm in T). Litter depth differed little between burned and unburned NT stands (1.1 vs. 1.2 cm) but remained substantially lower in burned T stands (0.9 vs. 1.8 cm). Despite these differences from reference conditions, multivariate forest-floor distance did not differ between burned NT and T plots (mean distance = 1.89 vs. 1.82; $W = 66$, $p = 1.00$, $r_{rb} = 0.00$; Table 4), indicating comparable convergence toward unburned reference conditions in the two hillslope systems.

Table 4
Recovery of burned terraced (T) and non-terraced (NT) hillslope systems eleven years after the 2013 SCC wildfire. Recovery was quantified as the mean Euclidean distance to unburned reference stands within the same hillslope system. Lower distances indicate greater recovery. Differences between hillslope systems were assessed using Wilcoxon rank-sum tests, and effect sizes are reported as rank-biserial correlations (r_{rb}) and interpreted as negligible (< 0.10), small (0.10 – 0.29), medium (0.30 – 0.49), and large (≥ 0.50).

Combined	W	p-value	r_{rb}	Magnitude
	27	0.016	0.50	large
Overstory	22	0.007	0.57	large
Recruitment	20	0.005	0.59	large
Understory	74	0.651	0.1	small
Floor	66	1	0	small

Pine establishment

Post-fire *P. halepensis* establishment varied widely among burned plots, ranging from low to hyperdense. Median *P. halepensis* sapling density was 382 stems ha^{-1} (IQR 0–2610) in NT stands and 446 stems ha^{-1} (IQR 0–2546) in T stands. Low *P. halepensis* establishment (< 700 saplings ha^{-1}) occurred in six burned plots in each hillslope system, whereas hyperdensity (≥ 4000 saplings ha^{-1}) occurred in one NT plot and two T plots.

Establishment class was not significantly associated with hillslope system ($p = 1.00$) or time since previous fire ($p = 0.179$). Among continuous variables, canopy openness showed the strongest pattern, with median openness decreasing from 97.9% in low-establishment plots to 22.3% in hyperdense plots, although the overall association was not statistically significant (Kruskal–Wallis $\chi^2 = 5.91$, $p = 0.052$). Pre-fire density of large *P. halepensis* showed an increasing trend across establishment classes, with median densities of 40.7, 76.4, and 193.5 stems ha^{-1} in low, intermediate, and hyperdense plots, respectively ($p = 0.068$). Understory cover was highest in intermediate plots (34.7%), followed by low (32.4%) and hyperdense plots (15.2%), although this difference was also not statistically significant ($p =$

0.073). No evidence of differences among establishment classes was detected for large-pine retention, elevation, slope, aspect, litter depth, or duff depth (all $p \geq 0.121$; Table 5)

Table 5
Associations between post-fire pine establishment classes and environmental and stand characteristics. Time since previous fire and hillslope system were evaluated using Fisher's exact tests, whereas continuous variables were evaluated using Kruskal–Wallis tests.

Variable	Statistic	p-value
Hillslope system	—	1
Time since previous fire	—	0.179
Dclass L[pine] pre-fire	$\chi^2 = 5.37$	0.068
Dclass L[pine] retention	$\chi^2 = 2.29$	0.319
Elevation	$\chi^2 = 0.34$	0.845
Slope	$\chi^2 = 0.80$	0.669
Aspect (Beers index)	$\chi^2 = 2.88$	0.237
Canopy openness	$\chi^2 = 5.91$	0.052
Understory cover	$\chi^2 = 5.23$	0.073
Litter depth	$\chi^2 = 4.22$	0.121
Duff depth	$\chi^2 = 0.31$	0.856

Resilience

The distribution of resilience pathways was broadly similar between terraced and non-terraced hillslope systems. The transition-risk pathway was the most common resilience pathway overall, occurring in 9 of 23 burned plots (39.1%; Fig. 6). It was also the most frequent pathway within both hillslope systems, accounting for 36.4% of NT plots (4 of 11) and 41.7% of T plots (5 of 12). The resistant pathway was the second most common overall, occurring in 6 plots (26.1%), including 4 NT plots (36.4%) and 2 T plots (16.6%). Regeneration-driven recovery occurred in 3 plots (13.0%), two in NT and one in T plots. The hyperdense pathway also occurred in 3 plots, including 2 T plots and 1 NT plot. The recovery-limited pathway was observed only in two T plots.

Discussion

The results provided little evidence that historical terracing altered overall fire resilience in this Mediterranean cultural landscape. Although terraced stands retained a greater proportion of their pre-fire overstory structure across several attributes, this advantage was not statistically significant and did not

translate into greater convergence toward unburned reference conditions. Instead, resistance appeared to be more strongly associated with topography and tree size, whereas patterns in *P. halepensis* establishment suggested that pre-fire stand structure and reproductive potential may have contributed to the differences in post-fire recruitment

Eleven years after the 2013 SCC wildfire, burned stands remained distinct from unburned reference conditions across the catchment. The integrated resilience framework also revealed substantial heterogeneity in post-fire trajectories, with transition-risk representing the most common pathway and indicating the weakest current evidence of a trajectory toward the pre-fire conditions.

Did overstory resistance to wildfire differ between terraced and non-terraced hillslope systems?

I found little evidence that historical terracing significantly affected overstory resistance to wildfire. Terraced stands consistently retained a greater proportion of pre-fire tree density, basal area, and small-diameter trees than non-terraced stands, but these differences were not statistically significant. Nevertheless, the consistent direction of the responses across multiple structural attributes suggests that terraces may provide a modest buffering effect against fire-induced overstory mortality.

Irrespective of hillslope system, *P. halepensis* survival was strongly size-dependent, with larger trees showing greater retention following wildfire. This pattern is consistent with observations from Mediterranean forests, where larger *P. halepensis* generally have greater resistance to fire because increasing diameter is associated with greater bark thickness and greater protection of the vascular cambium from lethal heat (e.g., Ducrey et al. 1996; Rigolot, 2004). The greater retention of larger trees therefore appears to reflect an intrinsic component of fire resistance that may have been more important than the presence of terraces themselves.

Topography showed a stronger association with overstory resistance than the hillslope system. Higher-elevation stands showed lower retention of tree density and basal area and experienced larger declines in *P. halepensis* dominance. Similarly, structural retention varied along the Beers aspect index, with stands on northeast-facing slopes showing lower retention than stands on warmer, more exposed aspects. One possible explanation is that these topographic differences reflect variation in pre-fire productivity and fuel accumulation. More productive sites may have supported greater biomass and fuel continuity, potentially increasing fire intensity during the 2013 SCC wildfire and, consequently, fire-induced overstory mortality (Agee and Skinner, 2005; Stephens et al. 2009; Lecina-Díaz et al. 2014). However, this interpretation should be considered cautiously because this study did not directly measure pre-fire fuel loads or spatial variation in fire intensity.

The relatively weak effect of terraces may reflect the long-term transformation of these cultural landscapes following agricultural abandonment. Historically, agricultural terraces and associated dry-stone walls created heterogeneous landscape mosaics that interrupted fuel continuity and modified

local soil and hydrological conditions. However, more than five decades of land abandonment have promoted forest expansion and the progressive deterioration of dry-stone walls, potentially reducing terraces' capacity to influence fire spread. In addition, the 2013 SCC wildfire occurred under extreme fire-weather conditions, which may have overwhelmed relatively fine-scale effects of these landscape features. This interpretation is consistent with Azpeleta et al. (under review), who used fire-spread hazard simulations under severe weather conditions across a range of wind speeds and found that dry-stone walls could reduce burned area by 15–40%,

To what extent did burned stands recover toward unburned reference conditions within each hillslope system?

Recovery toward unburned reference conditions differed between hillslope systems eleven years after the 2013 SCC wildfire. Across all recovery components combined, burned non-terraced stands were significantly closer to their corresponding unburned reference conditions than burned terraced stands, although the difference was driven primarily by overstory structure and recruitment rather than by understory or forest-floor characteristics. This suggests that non-terraced stands showed greater combined convergence toward their reference conditions. However, this result must be interpreted in relation to the reference state used to calculate recovery. Unburned terraced stands supported substantially greater overstory and recruitment than unburned non-terraced stands, creating a higher benchmark for terraced burned plots to attain. Therefore, the lower overstory and recruitment recovery scores in terraced plots do not necessarily indicate poorer recovery. Rather, they indicate greater divergence from the relatively higher overstory and recruitment characteristic of unburned terraced stands. The lower combined recovery of terraced plots may nevertheless be related to the legacy of agricultural abandonment. Previous research in the same catchment showed that abandoned terraces had reduced organic matter and microbiological activity, together with greater hydrological connectivity and erosion associated with dry-stone-wall collapse (Calsamiglia et al. 2017a). These altered soil and hydrological conditions, amplified by wildfire, could have slowed down post-fire regeneration and structural development. Thus, the lower recovery observed in terraced plots may reflect not a direct effect of terracing itself, but the diminished ecological functioning of abandoned and degraded terraces.

Overstory structure showed the clearest evidence of persistent structural divergence from unburned reference conditions. Burned stands had substantially lower tree density and basal area and greater canopy openness than unburned stands, reflecting the long-lasting effects of fire-induced mortality. Stand development in Mediterranean *P. halepensis* forests occurs over several decades (Retana et al., 2002; Rodríguez-García et al., 2022), and 11-year-old post-fire cohorts remain too young to compensate for the loss of basal area and canopy structure caused by wildfire. Consequently, the recovery of overstory structural attributes is expected to lag behind initial sapling establishment by decades.

Burned stands were characterized by higher proportions of obligate seeders and lower relative abundance of resprouting species in the understory compared to their reference stands. This pattern is consistent with Mediterranean post-fire succession models; heat-stimulated obligate seeders rapidly

occupy newly opened, high-light environments in early succession, establishing high initial densities that persist into juvenile stages, whereas resprouting species recover through surviving belowground structures and typically increase in relative abundance as stand development progresses (Bond and Midgley, 2001; Lloret et al. 2005).

Forest-floor recovery showed a similar pattern between hillslope systems. Burned plots retained shallower duff layers than unburned references. These differences are consistent with the combined long-term effects of combustion and post-fire erosion (Robichaud et al., 2010). Recovery of forest-floor horizons is consequently likely to depend on the gradual return of litter inputs and the stabilization of soil surfaces, a slow process that can take several decades and can be interrupted or reset by subsequent fires (Varner et al. 2005). Reduced canopy biomass may reinforce this process by limiting litter production, potentially slowing the re-accumulation of surface organic matter (Certini, 2005).

Which environmental and stand characteristics determine contrasting post-fire *Pinus halepensis* establishment outcomes?

Post-fire establishment exhibited substantial spatial heterogeneity, ranging from low to hyperdense sapling density among burned plots. However, none of the environmental, stand, or fire-history variables examined was significantly associated with establishment class. Although hyperdense establishment (≥ 4000 *P. halepensis* saplings ha^{-1} *sensu* Rodríguez-García et al. 2022) occurred more frequently in plots with the longer fire-free interval (≥ 30 years), and low sapling density (< 700 *P. halepensis* saplings ha^{-1}) was more common in plots with the shorter 19-year interval, this pattern was not statistically significant ($p = 0.179$). Thus, although fire history is widely recognized as an important influence on recruitment in Mediterranean pine forests (e.g., Pausas et al. 2004; Eugenio et al. 2006; Elvira et al. 2021), the results provide limited evidence that fire-free interval alone determined post-fire pine establishment. In addition, *P. halepensis* can reach reproductive maturity relatively early (Batllori et al. 2019; Baudena et al. 2020; Guiote and Pausas 2022), so even the 19-year fire-free interval may have allowed surviving trees to reach reproductive age and replenish at least part of the seedbank. Consequently, differences in fire-free interval may have been insufficient to generate strong contrasts in post-fire seed availability among the stands examined in this study.

Several patterns suggest potential ecological controls on *P. halepensis* establishment. Pre-fire density of large *P. halepensis* increased across establishment classes, from a median of 40.7 stems ha^{-1} in low-establishment plots to 193.5 stems ha^{-1} in hyperdense plots, although this relationship was not statistically significant ($p = 0.068$). This pattern is consistent with a potential role for pre-fire stand structure and reproductive potential in determining post-fire recruitment (Pausas et al. 2004; Guiote and Pausas 2022). Stands with greater densities of large trees may have supported larger reproductive populations and, consequently, greater seed availability following fire. Because *P. halepensis* is an obligate seeder whose post-fire regeneration depends strongly on seed availability from canopy seedbanks (Thanos and Daskalakou 2000), pre-fire stand structure may influence the potential for dense

regeneration. However, because these relationships were not statistically significant, they should be interpreted as suggestive rather than demonstrated determinants. Other local factors that were not evaluated in this study, including burn severity, competition, and topographic position (Baeza et al., 2007; Pausas and Keeley, 2014; González-de Vega et al., 2016; Muscolo et al., 2017; Taboada et al., 2017), may have had a clearer influence on pine establishment.

Canopy openness showed the strongest pattern among the measured variables, declining from a median of 97.9% in low-establishment plots to 22.3% in hyperdense plots, although the overall association was also not statistically significant ($p = 0.052$). Hyperdense plots had little or no surviving overstory but were characterized by densely packed juvenile cohorts that had reached approximately 2 m or more in height and were already contributing to canopy closure eleven years after the 2013 SCC wildfire. Dense post-fire *P. halepensis* cohorts can develop rapidly following fire, but increasing density also intensifies competition for limiting resources and can influence subsequent stand growth and development (González-Ochoa et al., 2004). The accompanying decline in understory cover, from a median of 32.4% in low-establishment plots to 15.2% in hyperdense plots ($p = 0.073$), is consistent with increasing shading and competition as dense pine cohorts develop. Similar interactions between pine regeneration and competing vegetation have been documented in Mediterranean *P. halepensis* forests (Fernández-García et al., 2019). However, because these variables were measured eleven years after fire, the direction of the relationship cannot be established: lower understory cover may have facilitated pine establishment during earlier stages but may also result from the dense pine cohort that subsequently developed.

What were the predominant resilience pathways across the study site?

Eleven years after the 2013 SCC wildfire, stands were at an intermediate stage of post-fire development, when differences in overstory persistence, establishment, and stand recovery can begin to reveal contrasting resilience trajectories, while long-term outcomes remain uncertain. Early post-fire recruitment in the same catchment was highly dynamic. One year after the fire, *P. halepensis* seedlings averaged approximately 2000 individuals ha^{-1} , but many failed to survive the subsequent summer drought. A subsequent recruitment pulse increased mean seedling density to approximately 6000 individuals ha^{-1} , before densities declined to approximately 1900 individuals ha^{-1} four years post-fire (unpublished data). This temporal variability illustrates why early recruitment alone may provide an incomplete indication of longer-term succession and highlights the value of intermediate-term assessments that consider establishment alongside overstory persistence and recovery.

Substantial heterogeneity in mid-term post-fire resilience has been reported for *P. halepensis* across Mediterranean climatic gradients. Codina et al. (2026), for example, found that more than half of burned Mediterranean pine stands exhibited large net changes from their ecological dynamic regimes in the mid-term. Their results further showed strong regional variation in resilience, with poorer outcomes under drier climatic conditions. In this study, nearly half of burned plots (47.8%) followed pathways characterized by relatively strong evidence of a trajectory toward the pre-fire condition, although the

mechanisms underlying this trajectory differed among pathways. Resistant and recovering plots retained substantial overstory structure while also showing relatively strong convergence toward reference conditions, providing the clearest evidence of a trajectory toward the pre-fire condition. Resistant but recovery-limited plots similarly retained overstory structure, but their weaker convergence indicates that structural persistence alone did not necessarily coincide with strong convergence toward the reference conditions. Recovery-driven plots illustrate a different mode of resilience, in which post-fire establishment and convergence toward reference conditions occurred despite substantial overstory loss. In these stands, future development of the regenerating cohort will be particularly important in determining whether the trajectory continues toward the pre-fire condition. Because stand development in Mediterranean *P. halepensis* forests occurs over several decades (Retana et al., 2002; Rodríguez-García et al., 2022), the structural component of resilience in these stands is likely to develop over a longer period.

Transition-risk was the predominant resilience pathway across the catchment, accounting for 39.1% of burned plots. This pathway showed the weakest current evidence of a trajectory toward pre-fire forest condition, combining low overstory resistance with either limited recovery or low establishment. This uncertainty may be particularly important under increasingly unfavorable hydroclimatic conditions. Codina et al. (2026) found stronger resilience of *P. halepensis* near the climatic niche core and poorer resilience toward the dry edge, highlighting the role of climatic context in modulating post-fire responses. Similarly, drought and increasing fire frequency may constrain both post-fire establishment and subsequent stand development, potentially increasing the risk of vegetation type conversion (VTC) toward persistent shrub-dominated vegetation (Pausas et al., 2004; Suding et al., 2004; Coop et al., 2020).

The hyperdense pathway was less common (13% of burned plots) but presents a distinct structural challenge. These plots are characterized by densely packed juvenile cohorts that can accumulate high fuel loads as they develop. Such "dog-hair" stands can experience growth stagnation and heightened flammability, increasing their vulnerability to subsequent wildfire (Palmero-Iniesta et al., 2017). If density-dependent self-thinning is insufficient to reduce stand density, these hyperdense stands may represent a future vulnerability, particularly under increasing fire frequency (Coppoletta et al., 2016). Where hyperdense stands persist, management interventions aimed at reducing competition and fuel continuity may therefore help facilitate progression toward more structurally developed stands.

Study limitations

Several limitations should be considered when interpreting these results. First, resilience was assessed at a single point eleven years after wildfire, whereas recovery of forest structure and forest-floor horizons is a multi-decadal process. The resilience pathways identified here should therefore be interpreted as current resilience and developmental trajectories rather than long-term outcomes. Second, this study was conducted within a single catchment and following a single wildfire event, limiting the extent to which the observed relationships can be generalized across broader Mediterranean landscapes. Third, while the findings highlight the dominant influences of fire history, topography and tree size, the

observational study design cannot disentangle these variables from local variation in pre-fire fuel loads and burn severity. Finally, recovery was evaluated relative to unburned reference stands within each hillslope system. Pre- and post-fire measurements would provide a more direct assessment of recovery magnitude. However, because pre-fire measurements were not available, using unburned reference stands allowed recovery to be assessed consistently across the catchment while accounting for differences in baseline conditions between terraced and non-terraced systems.

Conclusion

Historical terracing showed a weak tendency toward greater overstory resistance but was not associated with combined multivariate recovery. Instead, overstory resistance was more strongly associated with topography and tree size. Across the catchment, nearly half of the burned plots followed pathways characterized by evidence of return to pre-fire conditions. However, transition risk was the predominant individual pathway, with 39.1% of burned plots showing the weakest current evidence of a trajectory toward pre-fire conditions, suggesting these plots may be at risk of vegetation-type conversion from *P. halepensis* forest to persistent shrubland.

Existing resilience approaches quantify the magnitude or degree of post-fire recovery, whereas this framework complements them by identifying alternative pathways through which resilience may manifest at an intermediate stage of post-fire development. By integrating overstory resistance, post-disturbance ecological recovery, and establishment, the framework can distinguish stands that are resilient through overstory persistence from those relying on regeneration, and identify trajectories characterized by high establishment potential but uncertain development or limited evidence of returning to pre-disturbance state. Its generality and predictive value will require testing across additional disturbance events, landscapes, and longer post-fire periods. If validated, this approach could provide an early-warning framework for identifying stands with declining or uncertain resilience and for prioritizing targeted management before alternative post-fire trajectories become more difficult to reverse.

Declarations

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Conflict of interest statement

The author declares there are no competing interests.

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Figures

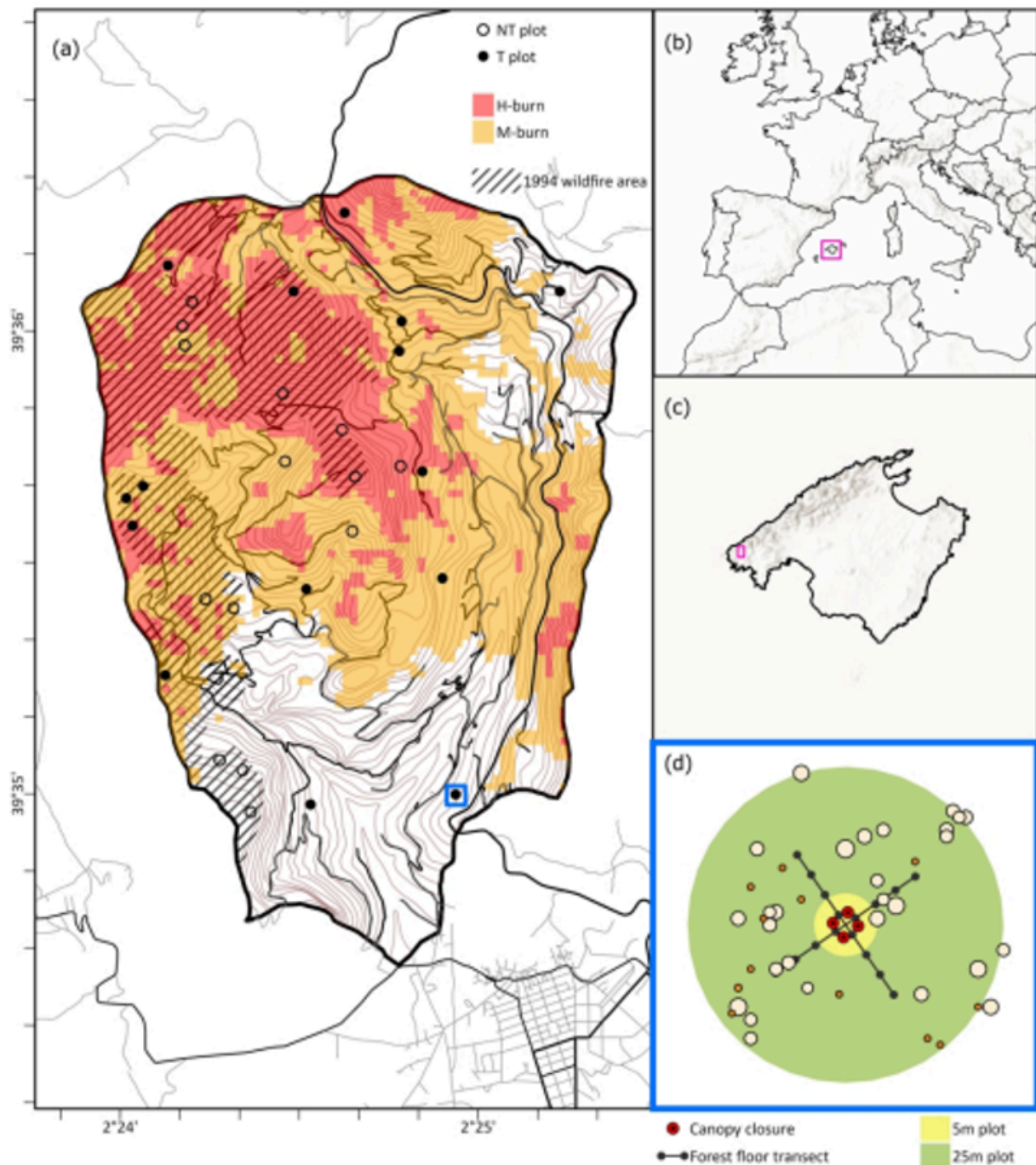


Figure 1

Location and study area. (a) Catchment area showing plot distribution, 2013 SCC wildfire burn severity, and 1994 LT wildfire extent. (b) Location of the catchment in Europe. (c) Zoomed-in view of the island of Mallorca, indicating the catchment location. (d) Example of a sampled plot.



Figure 2

Example of burned sampling plots from non-terraced and terraced stands. Photographs by AA.

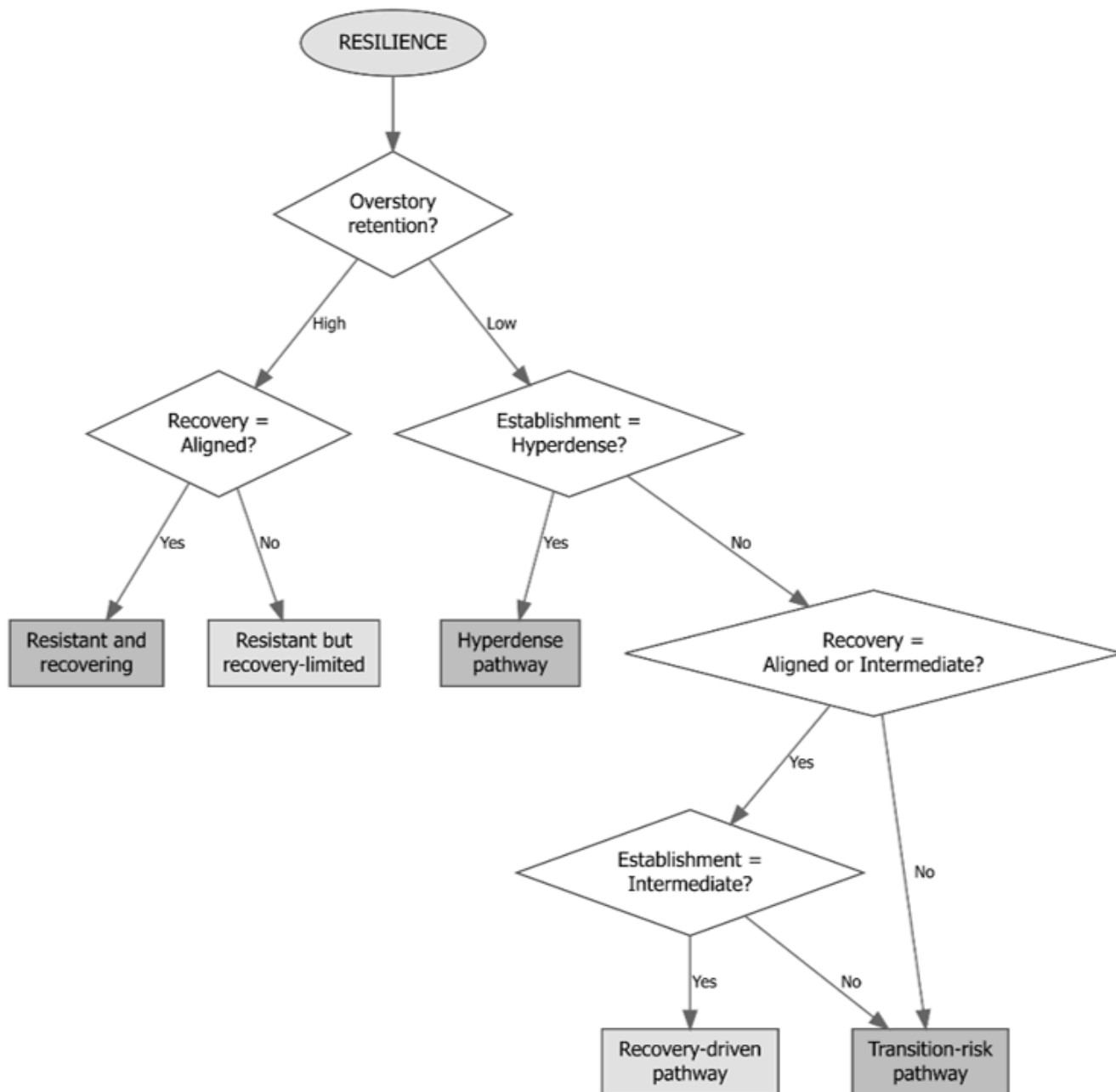


Figure 3

Decision framework for classifying fire resilience pathways based on overstory resistance, post-fire multivariate recovery, and establishment. Overstory resistance was classified based on the retention of $\geq 50\%$ of pre-fire basal area. Recovery was classified as aligned, intermediate, or limited according to the degree of convergence toward unburned reference conditions. Establishment was used to distinguish between hyperdense pathway, or among plots with low overstory retention, recovery-driven, and transition-risk pathways.

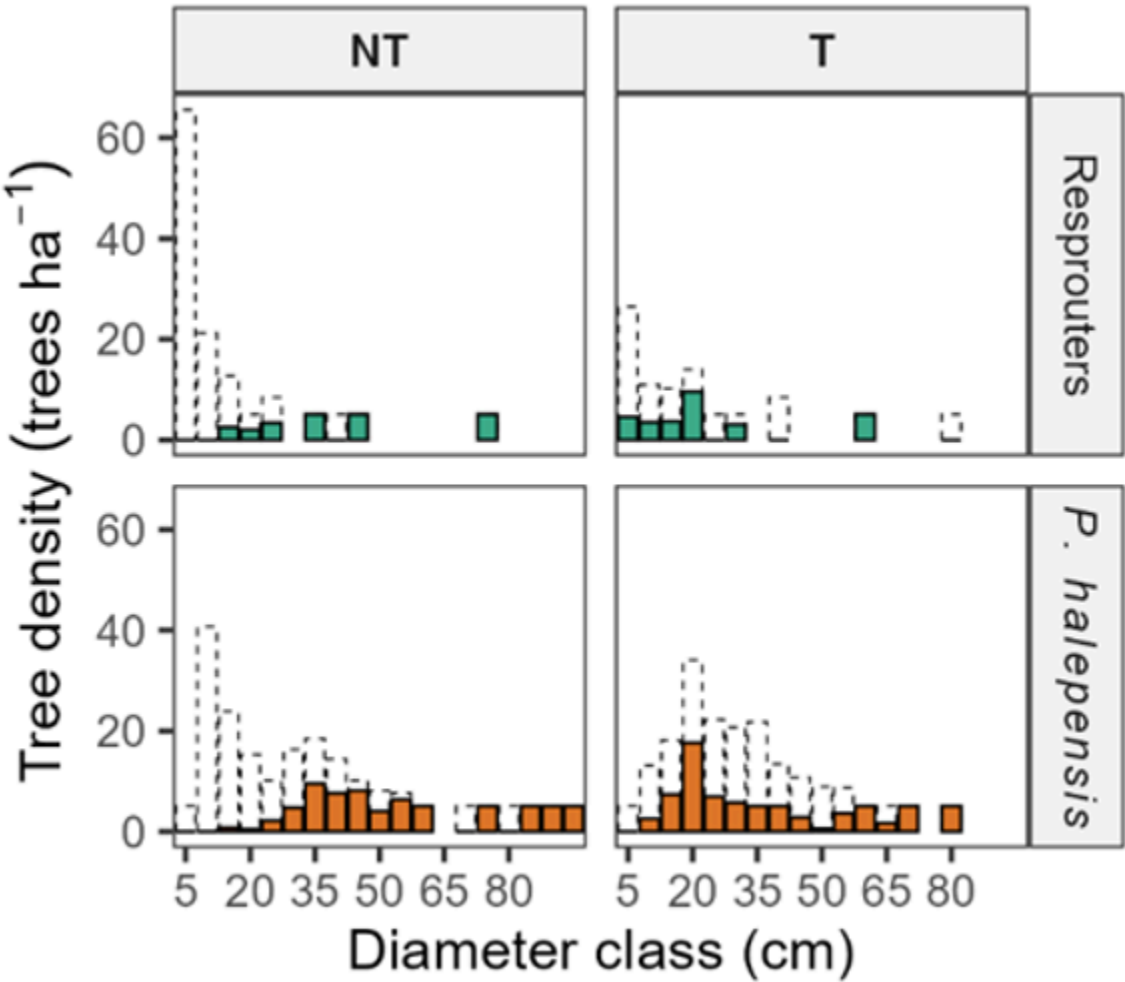


Figure 4

Live and dead overstory trees by diameter class distribution of *P. halepensis* and resprouter species within burned plots in terraced (T) and non-terraced (NT) hillslopes systems. The shaded portion of the bars represents live trees, while the white portion represents the dead trees inventoried during the 2024 sampling. Pre-wildfire density in burned stands was estimated as the sum of live and dead trees.

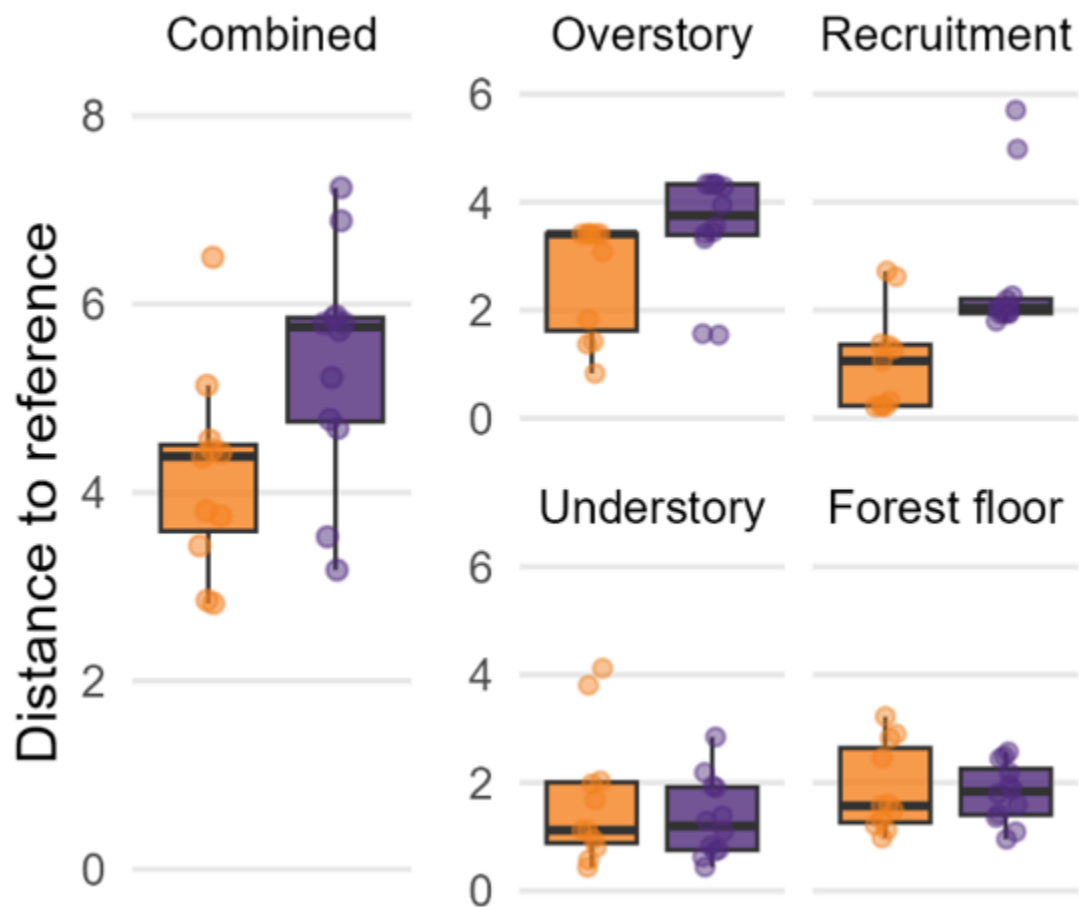


Figure 5

Multivariate recovery distance of burned terraced (purple) and non-terraced (orange) plots from unburned reference conditions. Distance to reference represents Euclidean dissimilarity, where greater distance indicates greater divergence from unburned reference conditions.

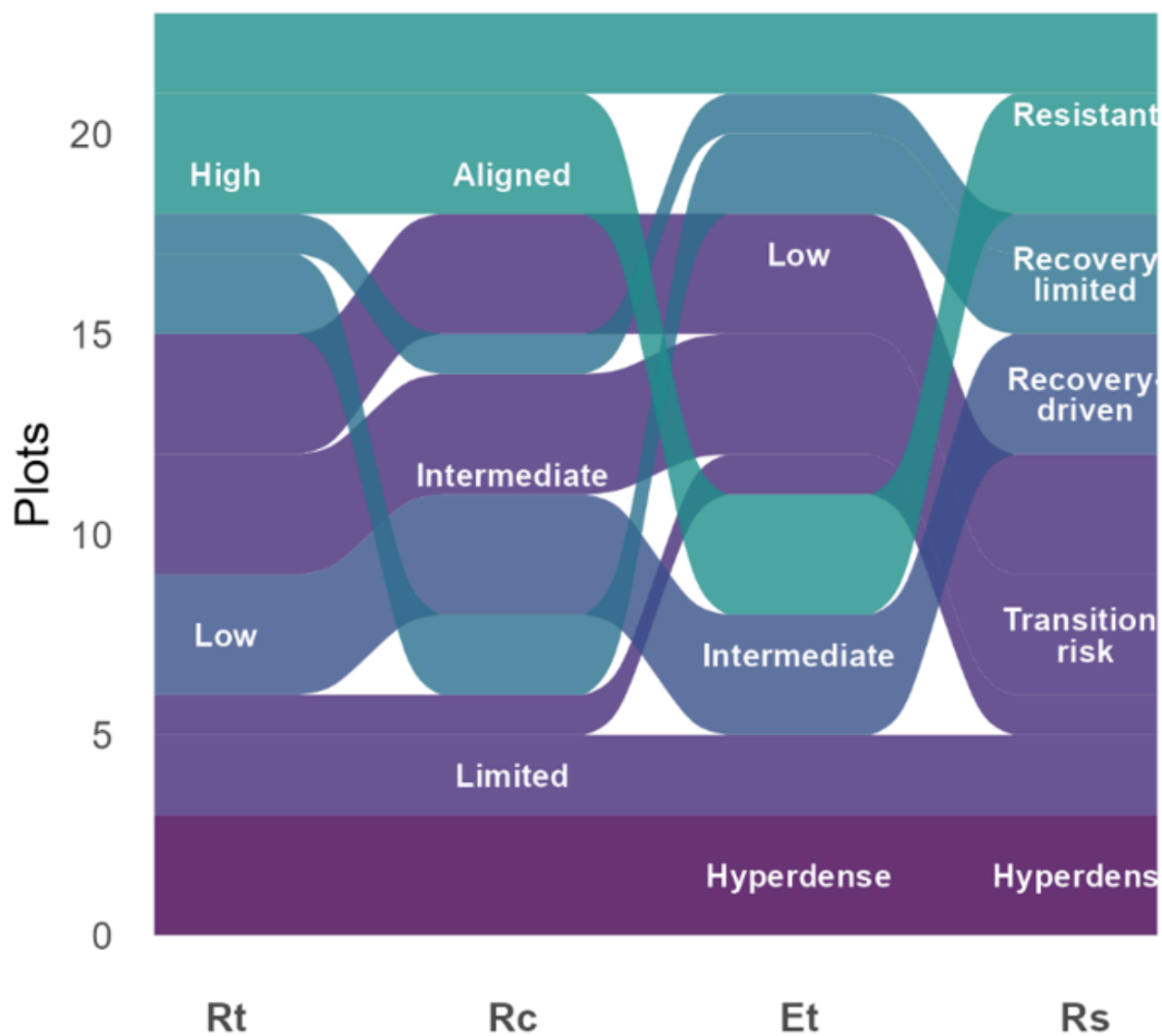


Figure 6

Resilience (R_s) pathways following the 2013 SCC wildfire, showing plot classification by overstory resistance (R_t), multivariate recovery (R_c), and *P. halepensis* establishment (E_t).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [TableS1.docx](#)