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Top predators respond to post-fire logging: a trait-based approach

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ABSTRACT

Complete wood extraction is a widespread salvage logging practice after wildfire, implemented to obtain economical benefit and to reduce the risk of pest outbreaks. Such intense logging can strongly affect the ecosystem natural succession. In response, new sustainable approaches have been proposed to minimize impacts while still providing economical returns. In this study, we conducted a seven-year experiment to analyse the effects of different intensities of post-fire logging on vegetation structure and ground-level spider communities. We applied generalized linear mixed models (GLMMs) to test the effects of treatments and years since fire on vegetation structure, and spider functional traits. The most pronounced differences across logging treatments were observed in vegetation recovery, with sustainable practices promoting intermediate levels of regeneration between no intervention and conventional logging. Intense conventional logging tended to amplify the effects of fire on spider functional traits, whereas more sustainable logging practices facilitated a recovery trajectory more closely aligned with non-intervention. Measures such as the construction of woody piles proved particularly important during the early post-fire years, providing refuges that supported the initial recovery of spider communities. Overall, our findings highlight the effectiveness of sustainable techniques in balancing the economic benefits of logging with the need to minimize environmental impacts.

1. Introduction

Wildfires are a crucial component of the natural dynamics in many ecosystems worldwide (He et al., 2019). However, global change, land use, and biotic mixing are modifying fire historical frequency, intensity, severity, spatial pattern and seasonality across the globe (Liu et al., 2010). In this context, land managers and policymakers require robust information to make informed decisions on ecosystem management (Puig-Gironès et al., 2025). For these reasons, understanding how wildfires affect ecosystem structure, composition, and function has become a fundamental topic in ecological research, leading to a substantial body of literature on fire effects and post-fire dynamics (Griffiths and Brook, 2014; Certini et al., 2021; Franklin et al., 2023; Erdozain et al., 2024).

Forest ecosystems and associated economic interests are significantly affected by wildfires (Hessburg and Agee, 2003). In these ecosystems, salvage logging has traditionally been the most common management practice after wildfires worldwide (Hutto, 2006; Lindenmayer et al., 2004; Pons and Rost, 2017). The primary purpose of salvage logging is to obtain economic profit from burned trees. Additionally, it could be implemented to prevent the spread of xylophagous insect outbreaks and pathogenic fungi (Leverkus et al., 2012). Other stated reasons for performing salvage logging include facilitating safe and efficient access to burned areas, addressing aesthetic concerns, or enhancing future tree survival (Martínez-Sánchez et al., 1999; Lindenmayer and Noss, 2006).

Nevertheless, this practice represents a drastic alteration of post-fire habitat conditions, modifying both the abiotic and biotic components of the ecosystem (Beschta et al., 2004; DellaSala et al., 2006). Wildfires alone already cause major alterations by reshaping vegetation structure, increasing habitat openness, and removing plant cover (Pausas and Keeley, 2009). How vegetation subsequently regenerates after fire largely determines the responses of animal communities (Arnan et al., 2006; Barton et al., 2014). Building on this initial disturbance, salvage logging further promotes soil erosion and compaction, disrupt

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hydrological cycles, and reduce organic carbon storage (García-Orenes et al., 2017; Malvar et al., 2017; García-Carmona et al., 2021; Dulamsuren et al., 2024). These changes can hinder vegetation recovery, affecting plant cover and ecosystem functions (Castro et al., 2011; Griffin et al., 2013). Furthermore, studies examining its effects on animal communities often reveal differences between areas that have only burned and those that have undergone both burning and logging (Rost et al., 2012; Thorn et al., 2018; Kelly and Hodges, 2022; Volkmann and Hodges, 2024). These differences can be either beneficial or detrimental, depending on the habitat preferences of the species involved. In general, species associated with dead wood are negatively affected, while those adapted to open habitats typically experience positive effects (Thorn et al., 2018).

Nowadays, new management strategies have been proposed to mitigate the impact of logging while maintaining economic benefits from burned forests (Pons et al., 2020). Some studies suggest that creating wood debris piles can benefit small mammal communities by providing shelter (Torre et al., 2023; Puig-Gironès, 2023), while also supporting seed dispersal by both small mammals (Puig-Gironès et al., 2020) and birds (Rost et al., 2010). Additionally, the implementation of mulching treatments may enhance seedling species diversity (Lucas-Borja et al., 2020).

However, little is known about the effects of post-fire management alternatives on most animal communities. This is particularly the case for invertebrates, which play crucial roles in ecosystem functioning, and changes in their community assemblages can have cascading effects throughout the food web (Wurtsbaugh, 1992; Benndorf et al., 2000). Therefore, understanding how invertebrates respond to post-fire logging treatments is important at both the species and ecosystem levels. Adopting a functional approach that incorporates the biological traits of indicator organisms can greatly enhance our understanding of these effects.

Spiders are an extremely rich order of arthropods, with more than 53,000 described species (World Spider Catalog, 2025). In contrast to many other invertebrates, spiders are relatively well-studied regarding their response to fire (McLean et al., 2023). Their ubiquity and diversity and their role as top predators makes them good indicators of ecological disturbance (Churchill, 1997; Nyffeler and Birkhofer, 2017), while exhibiting diverse ecological, behavioral and life-history traits (Pekár et al., 2021). Variation in hunting strategies, dispersal ability and body size, specifically, make them ideal candidates for incorporating functional traits into ecological studies about the effects of post-fire logging treatments.

Fire effects on spider communities depend on the habitat characteristics. In burned grasslands, spider communities show no significant differences between burned and unburned zones after only one year since fire (Podgaiski et al., 2013). Contrastingly, spider abundance and species composition in forests are more affected (Vidal-Cordero et al., 2022; McLean et al., 2023). In forests, taxa associated with leaf-litter (York, 1999; Hanula and Wade, 2003; Driscoll et al., 2010) and related with web-building (Robinson, 1981) are the most affected by a wildfire. Contrastingly, active hunters and burrowing species usually are more favored by fire. Generally, changes in species assemblages seem mostly driven by fire-related vegetation changes (Langlands et al., 2012; McLean et al., 2023).

Clear cutting interventions have mixed effects on spider communities. Some studies report increases in spider abundance and diversity after logging (Plath et al., 2025), while others document declines (Ménival et al., 2025; Prieto-Benítez and Méndez, 2011). Despite these contrasting results, there is a broad agreement on the general patterns of community composition changes after such management practices: species associated with open and drier habitats tend to increase, while forest specialists decline or may even disappear (Larrivé et al., 2005; Plath et al., 2025).

Here, we studied the effects of three real-case post-fire management alternatives that differ in the intensity of post-fire logging. Given the effects of management practices on post-fire vegetation and soil, we hypothesize that spiders will be affected by the intensity of post-fire logging. Within this context, our aims are to:

(1) Assess the effects of logging intensity in a burned forest on vegetation structure. (2) Evaluate how post-fire logging intensity influence spider communities using both taxonomic and functional approaches. (3) Examine the effects of logging intensity, years since fire, and vegetation structure on spider functional traits. (4) Determine the role of microhabitats, generated by fire and post-fire management, in the recovery of functional traits after disturbance.

2. Materials and methods

2.1. Study site and post-fire treatments

This research was conducted near the city of Blanes, located in the northeastern Iberian Peninsula (N 41º52', E 2º46', at an elevation of 60–118 m above sea level). The region has a Mediterranean climate, with an average annual temperature of 15,3ºC and annual rainfall of 770 mm. In July 2016, a crown wildfire affected 31 ha of forest dominated by (*Pinus pinea*) and cork oak (*Quercus suber*). The understory vegetation was primarily composed of typical Mediterranean shrub species such as sage-leaved rock-rose (*Cistus salviifolius*), tree heath (*Erica arborea*), madrone (*Arbutus unedo*), along with herbaceous species such as Mediterranean false brome (*Brachypodium retusum*).

After the fire, we designed an experimental setup consisting of three treatments that are used in real post-fire forest management. Treatments differed in logging intensity, machinery type and weight, restrictions on machinery movement, harvesting method, and the quantity and spatial distribution of retained wood (Pons et al., 2020). Thirteen experimental plots were established within the burned area, from which we selected ten (between 0.6 and 3.1 ha in size) for spider sampling (Fig. 1). Plots were assigned to one treatment: non-intervention (NI, three plots), sustainable logging (SL, four plots), or conventional salvage logging (CL, three plots). The spatial distribution of the experiment was designed to alternate treatments, in agreement with the landowners. In NI plots, no management actions were taken, allowing the ecosystem to follow its natural dynamics. Only a few standing burned trees near roads were felled and left on the ground for safety reasons in March 2019. SL plots were managed following recommendations found in (Mauri and Pons, 2019). Manual logging was conducted using chainsaws to remove most standing burned trees, while retaining cork oaks with active resprouting and stone pines with at least 50 % green crown. Logged trunks were used for economical purposes, and tree crowns were cut, and grouped into piles. For the log extraction, light forestry machinery (12.7 tonnes) was employed within pre-established 3-meter-wide extraction corridors, separated 15 m apart. In some of these corridors, branches were placed transversely to reduce the impact of machinery. A total of 63 % of the available wood was removed. These actions were carried out between March and April 2017, 8 months post-fire. CL plots were managed following the usual commercial approach to burned forests in the region. Manual logging using chainsaws removed most standing burned trees, retaining cork oaks with active resprouting and some stone pines with at least 50 % green crown. Whole trees were harvested. Heavy forestry machinery (24 tonnes) was used for log extraction, operating across the plot without spatial constraints. A total of 91 % of the available wood volume was removed. Manual logging was carried out in February 2018, 20 months post-fire, followed by log extraction in Abril 2018.

After implementing the treatments, several indicators were monitored to compare the results between the three experimental treatments. These included soil properties, wood biomass, plant regeneration, ant, beetle, spider and vertebrate communities, as well as acorn removal by rodents. For more details on methods and ecological indicators, see Pons et al. (2020).

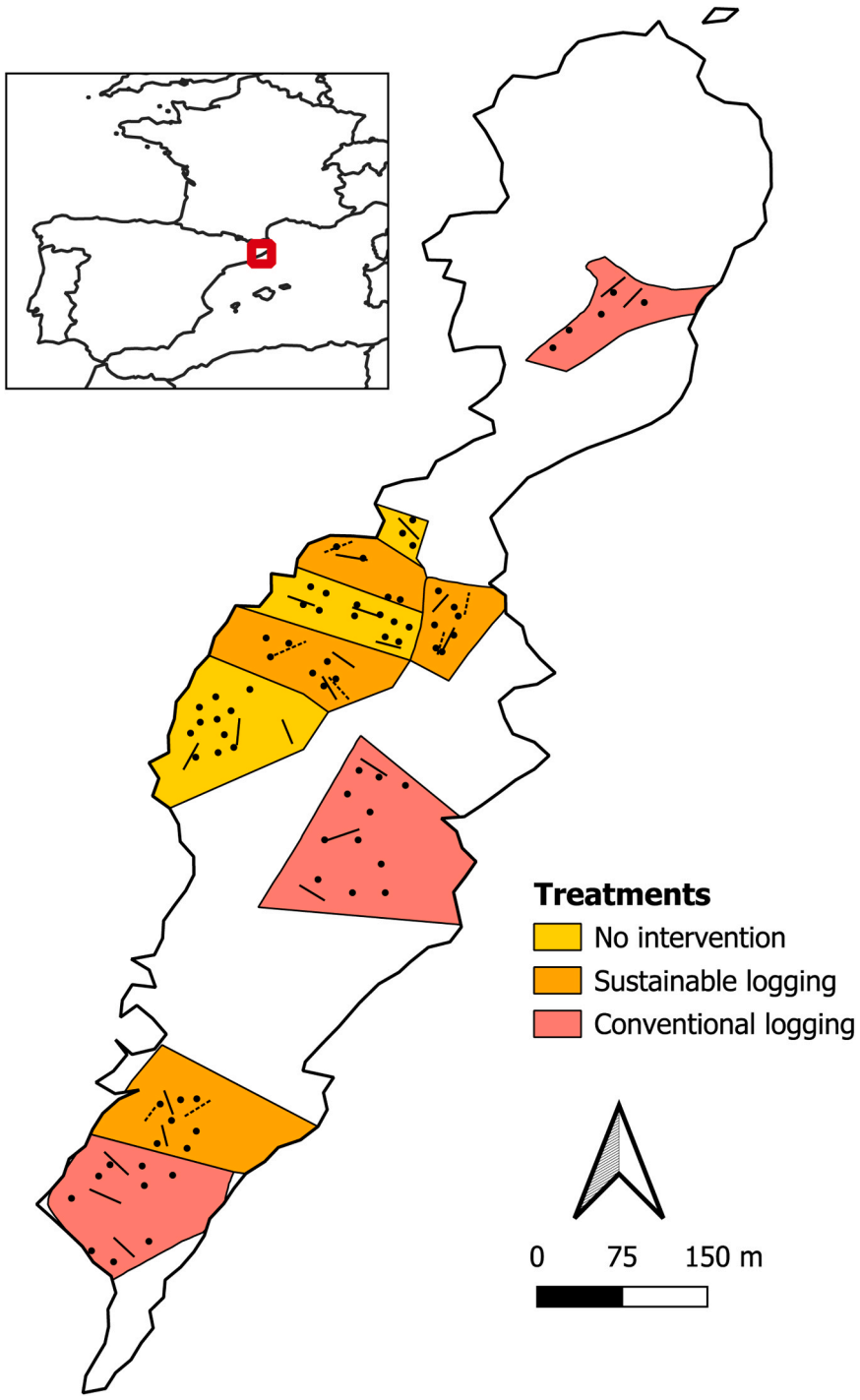

Fig. 1. Study area showing the location of the selected experimental plots, vegetation and soil cover transects (lines), and trap stations (dots). Dotted lines indicate transects sampled along machinery trails in sustainable logging plots.

2.2. Habitat variables

Vegetation and ground-type cover were recorded in each experimental plot using 30-meter line transects, with a total of 29 transects (Fig. 1). In the SL treatment, each transect was duplicated, with one placed within the established machinery trails and the other in the untrampled logged area, in order to capture the effect of machinery on vegetation. Transects were conducted annually in May-June from 2017 to 2020, with an additional survey in 2023.

At each of the 31 points per transect (distributed at 1-meter intervals), ground cover was classified into ten cover types (Table A.1). The percentage of each cover-type was calculated as the number of points of that type divided by the total number of points. To reduce the number of variables, similar cover-types were grouped (Table A.1).

Plant community was recorded at each point using a 1,5-meter calibrated rod to note all plant species that touched it. Species cover was calculated by counting the number of contacts with the rod for each species, divided by the total number of points per transect. Habitat structure was also characterized by grouping plant species into Raunkiaer life forms (macrophanerophyte, nanophanerophyte, phanerophyte, chamaephyte, therophyte and hemicryptophyte) (Raunkiaer, 1934). Two additional categories were included: dead vegetation and

points without vegetation.

For the subsequent spider analysis, seven transects per treatment were used (Table A.2). In SL plots, the proportion of land occupied by the machinery trails was measured using orthophotography. Consequently, the duplicated SL transects were then merged into a single one, weighting plant cover with a 1:8 ratio, where one corresponds to transects inside the corridors and eight for those outside.

Ground-cover types were summarized into two main components using a Principal Component Analysis (PCA). The first component (hereafter, litter cover) explained 46.7 % of the variance, representing a gradient from bare soil to high litter cover. The second component (hereafter, moss cover) showed a 20.8 % of the variance, corresponding to a gradient from moss absent to low moss cover.

The cover of plant life forms was also summarized using a PCA. The first component (hereafter, vegetation cover) explained 30.1 % of the variance, representing a gradient from transects with greater plant presence to those with more points lacking vegetation. The second component (hereafter, vegetation woodiness), representing 20.5 % of the variance, corresponds to the transition from sites dominated by short-lived or ground-level resprouting plants to those with persistent lignified aerial buds.

2.3. Spider sampling

We established 25 trap stations per treatment (Fig. 1), with a minimum spacing of 10 m between stations. At each station, two pitfall traps were set in distinct microhabitats: bare ground (BG) and under-shrub (US) (we selected *Arbutus unedo* when available; otherwise, *Viburnum tinus*). In the SL treatment, a third pitfall trap was added at each station to sample the microhabitat created by branch piles (UP). Pitfalls traps within the same station were placed at least 2 m apart.

We used pitfall traps to capture epigeic arthropods. This method was chosen because it is widely used to study terrestrial arthropod communities (Brantley, 2020; Vidal-Cordero et al., 2022; Šerić Jelaska et al., 2022) and provides representative samples of key indicator groups, including ants, beetles, and spiders (Feest and Cardoso, 2012; Micó et al., 2020). Traps (50 ml jars with a mouth of 25 mm, sufficient to capture ground-dwelling arthropods while minimizing the capture of small vertebrates) were half-filled with a 1:1 mixture of propanediol and water. To have a complete characterization of the spider community, multiple sampling methods are commonly employed (Cardoso, 2009; Podgaiski et al., 2013). Given that pitfall traps are biased toward capturing epigeic and highly active species, this study focused on ground-dwelling spiders.

Traps were placed for 12 days during the second week of May each year from 2017 to 2020, with an additional sampling in 2023, representing 1, 2, 3, 4 and 7 years after the fire. Individuals were identified to the lowest reliable taxonomic level (species, genus or family). Given that most spiders can only be identified at the species level by their sexual characters, only mature individuals were used in the present study. Although individuals were sexed, sex was not considered as a factor in the analyses. We acknowledge that pitfall trapping is biased toward capturing wandering males (Topping and Sunderland, 1992;); however, addressing sex-specific responses was beyond the scope of this study. Specimens were examined using a LEICA MZ16A stereoscopic microscope and identified using the available material from Nentwig et al. (2025). The abundance of each species was calculated as the number of individuals per trap.

Each trap station was associated with the nearest vegetation and ground-type cover transect (Fig. 1). Each transect provided habitat data for two to five trap stations. Spider data from these pitfall traps were merged for analyses (hereafter referred to as a sampling unit), greatly reducing the number of zeros in the spider dataset. This approach also allowed us to compare samples across years, even when some data were missing due to wild boar disturbance to traps. Species abundance per sampling unit was calculated as the mean across all pitfall traps within that unit in microhabitats BG and US. UP microhabitat was analysed separately because it is only found in the SL treatment. For the taxonomic analysis, species that accounted for less than 5 % of the total abundance in the entire dataset were excluded.

2.4. Functional traits classification

We characterized 14 functional traits for each spider species. However, for most traits, information was only available at the family level, meaning that all species within a given family were assigned the same trait category. Spiders were assigned to different groups based on their hunting strategies, habitat use, and colonization capability (Table 1). These traits are useful for understanding the ecosystem function of spider communities and how they respond to ecosystem disturbances such as fire (Langlands et al., 2011). Trait data were gathered from various sources in the literature (Cardoso et al., 2011; Langlands et al., 2011; Schirmel et al., 2012; Nentwig et al., 2025). For the analysis, we calculated the community-weighted mean (CWM) for each functional trait and sampling unit. For categorical traits, the CWM was calculated as the proportion of individuals in a sampling unit exhibiting a given trait category. Traits with an abundance of less than 5 % in the entire dataset were excluded. For continuous traits, the CWM was calculated as the abundance-weighted mean value per sampling unit.

2.5. Statistical analysis

To evaluate the effects of the three post-fire treatments (SL, CL, NI) on habitat characteristics (vegetation cover, vegetation woodiness, litter cover, and moss cover), we used linear mixed models (LMM), with time since fire included as a random factor. To assess the effects of time since fire on habitat characteristics, quadratic mixed models were used, because we expected non-linear effects across the seven years. We included the experimental plots where transects were located as a random factor. If residual diagnostics showed poor model fit, a Yeo-Johnson transformation was applied, selecting lambda values that maximized normality (Weisberg, 2001). This transformation was specifically applied to vegetation woodiness and moss cover.

To assess whether the taxonomic and functional composition of spider communities varied across post-fire treatments or years since fire, permutational multivariate analyses of variance (PERMANOVA) were performed using 999 permutations on a Bray-Curtis distance matrix. Non-metric multidimensional scaling (NMDS) was also conducted based on a Bray-Curtis distance to visualize and interpret these effects.

Subsequently, Generalized Linear Mixed Models (GLMMs) were used to assess the effects of post-fire treatments, time since fire, and habitat characteristics, as explanatory variables, on spider abundance and functional traits (Table A.3). When analysing post-fire treatment effects, time since fire was included as a random factor. A quadratic mixed

Table 1
Names of the functional traits used in the study, their corresponding ecological group, and data typology. Traits marked with an asterisk (*) were excluded from the analysis because their abundance was less than 5 % in the entire dataset.

Trait group	Trait name	Data type
Colonization capability	Body length female	Continuous
	Ballooning	Binary
Hunting strategy	Active hunter	Binary
	Web user	Binary
	Ambush hunter	Binary
Diet specialization	Stenophagous	Binary
	Euryphagous	Binary
Habitat use	Strictly ground	Binary
	Strictly vegetation*	Binary
	Both ground and vegetation	Binary
	Strictly diurnal	Binary
	Strictly nocturnal	Binary
	Both diurnal and nocturnal	Binary

model was used for time since fire effects, with experimental plots as a random factor. To analyse the effect of habitat variables, a single model incorporating all of them was applied, with time since fire included as a random factor. Initially, a Gaussian error distribution was assumed, but if residual evaluation indicated poor model fit, a log-normal error distribution with a log link function was applied. In most functional trait models, a zero-inflated or one-inflated approach was needed to achieve optimal model fit, with the zero-inflated component modelled as a constant. One-inflation was handled by inverting the data, ensuring appropriate model convergence and interpretation.

GLMMs were also used to test the effects of microhabitat on spider abundance and functional traits, with time since fire and sampling unit included as random factors. This analysis was restricted to SL plots, as they were the only ones where three distinct microhabitats were sampled, with one of them (branch piles) directly arising from the treatment interventions. We applied the same approach to error structure as in the previous analysis, but with microhabitat added as a predictor in the zero-inflated component of the model. All LMMs and GLMMs were submitted to residual analysis to evaluate error distribution adequacy (Hartig, 2022)

Analyses were conducted in R (v. 4.4.2; R Core Team, 2025) with the package *vegan* for the PERMANOVA and NMDS, the package *lme4* for the LMM and the package *glmmTMB* for the GLMM.

3. Results

A total of 1698 individual spiders were captured, of which 890 were adults, representing 88 species across 20 families (summary in Table 2, full list in Table B.1). Of the 825 pitfall traps installed, 85 were disturbed by wild boars, particularly in 2023.

Table 2
Acronyms of the spider species analysed by NMDS, along with their total raw abundance (sum of spiders collected) in each treatment (NI: non-intervention, SL: sustainable logging, CL: conventional logging) in bare ground (BG) and under shrub (US) microhabitats. The total number of samples per treatment is also shown.

		Treatments		
Species	**Acronym**	**NI**	**SL**	**CL**
Aelurillus vinsignitus	Ae.vi	32	26	18
Agyneta pseudorurestrislike	Ag.ps	7	3	3
Alopecosa albofasciata	Al.al	7	14	16
Asagena phalerata	As.ph	1	2	3
Callilepis concolor	Ca.co	5	5	2
Cepheia longiseta	Ce.lo	4	5	2
Civizelotes dentatidens	Ci.de	8	23	10
Civizelotes medianus	Ci.me	6	1	0
Eratigena fuesslini	Er.fu	33	21	14
Euophrys herbigrada	Eu.he	6	3	4
Fam. Linyphiidae	Fa.Li	1	0	4
Haplodrassus dalmatensis	Ha.da	2	4	2
Haplodrassus macellinus	Ha.ma	4	7	5
Haplodrassus typhon	Ha.ty	0	3	3
Heser nilicola	He.ni	0	3	1
Iberina candida	Ib.ca	5	1	6
Liophrurillus flavitarsis	Li.fl	4	5	1
Marilynia bicolor	Ma.bi	3	2	4
Nomisia exornata	No.ex	2	0	4
Ozyptila pauxilla	Oz.pa	14	3	4
Pardosa hortensisgroup	Pa.ho	20	9	27
Setaphis parvula	Se.pa	15	11	11
Silhouettella loricatula	Si.lo	1	2	0
Tenuiphantes herbicola	Te.he	4	3	3
Thanatus arenarius	Th.ar	1	1	3
Thanatus vulgaris	Th.vu	16	16	37
Theonina cornix	Th.co	3	2	4
Zelotes fulvopilosus	Ze.fu	19	21	17
Zelotes gallicus	Ze.ga	7	0	1
Zelotes thorelli	Ze.th	4	1	2
Zodarion pseudoelegans	Zo.ps	21	15	14
Number of samples		224	226	171

Time since fire and post-fire treatments influenced most habitat variables (Fig. 2, Table C.1). Vegetation cover, vegetation woodiness, and litter cover were higher in the NI and SL treatments. In addition, time since fire had a positive effect on vegetation and litter covers. Moss cover showed no significant relationships with any of the predictors and was therefore excluded from subsequent analyses.

The NMDS ordination (Fig. 3) and PERMANOVA analysis (Table C.2) indicated that both post-fire treatment and years since fire influenced the spider community in terms of both taxonomic and functional composition.

Spider abundance was influenced by time since fire and vegetation woodiness, whereas no significant differences were detected between post-fire treatments (Fig. 4, Table C.3). Of the 12 functional traits examined, 9 showed significant relationships with at least one predictor. Time since fire affected traits related to hunting strategy and daily activity. Post-fire treatment influenced traits associated with stratum use and daily activity. Finally, vegetation cover was negatively associated with body length and positively associated with the ambush hunting strategy.

Microhabitat influenced 5 of the 12 functional traits studied, as well as spider abundance (Fig. 5, Table C.4). Overall, the US and UP microhabitats showed similar effects on spiders, whereas BG differed. BG was positively associated with spider abundance, active hunting strategy and

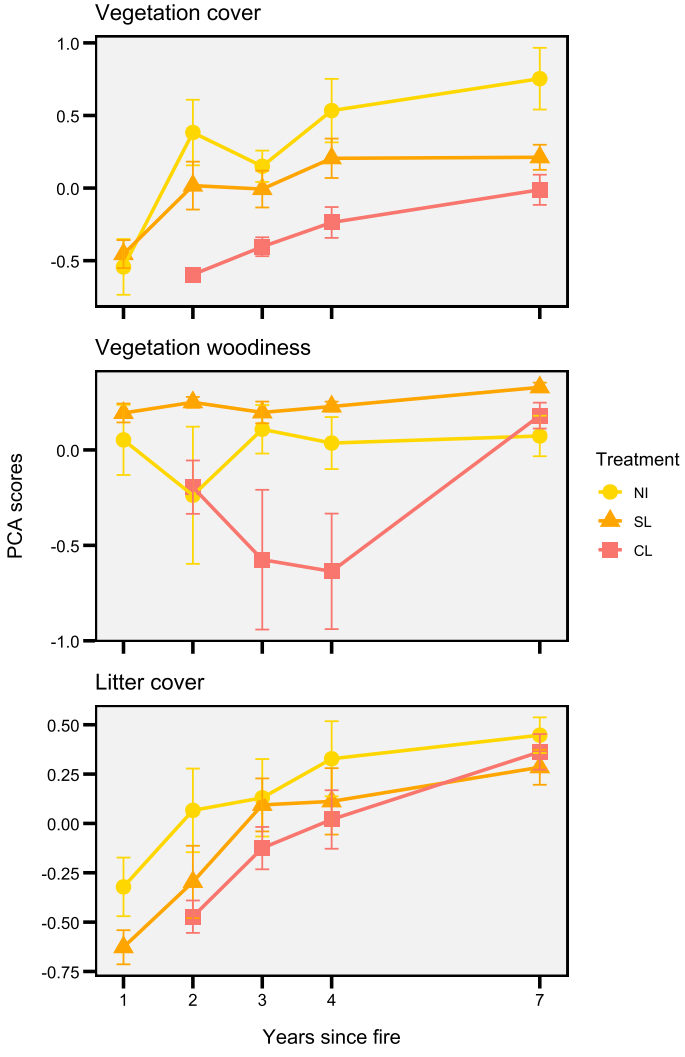

Fig. 2. Variation in habitat characteristics explained by years since fire and post-fire treatments (NI – No intervention, SL – Sustainable logging, CL – Conventional logging).

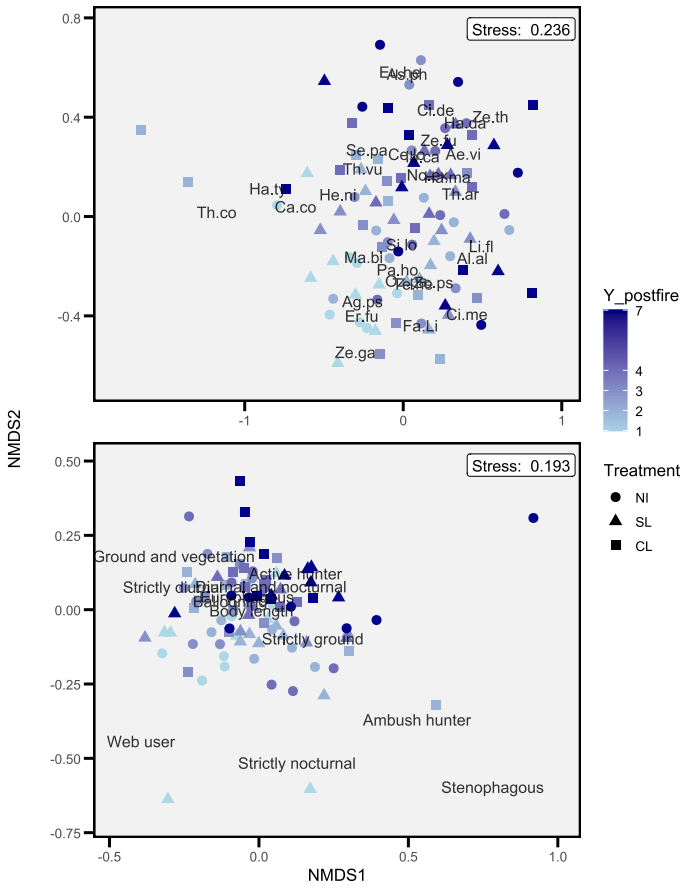

Fig. 3. Output of the NMDS models. The top biplot represents the taxonomic approach, while the bottom one corresponds to the functional approach. See acronyms on Table 2.

both diurnal and nocturnal activity patterns. In contrast, the US and UP microhabitats were positively associated with strictly ground stratum use, web-building strategy and strictly nocturnal activity.

4. Discussion

In this paper, we assessed how the intensity of post-fire logging affects vegetation structure and ground-level spider species. As demonstrated in previous studies, both fire and clear-cutting can alter spider assemblages (Campbell et al., 2022; McLean et al., 2023). Disturbances may modify spider communities directly, by increasing mortality, or indirectly, by modifying habitat structure and microclimatic conditions (Engstrom, 2010; Underwood and Quinn, 2010). Here, we aimed to evaluate whether it is possible to extract economic value from burned forest without causing the severe impacts typically associated with conventional salvage logging. To do so, we first examined the effects of logging intensity on vegetation, and subsequently on ground-level spider communities.

4.1. Effects of post-fire treatments on vegetation

Post-fire treatments had an effect on vegetation structure and composition. In general, the CL (conventional logging) treatment showed significantly poorer recovery variables compared to NI (no intervention), while SL (sustainable logging) had an intermediate response between the former two. It should be noted that SL was implemented 8 months after the fire, whereas CL was implemented 20 months after the fire due to logistical constraints. Although this difference in timing may influence the recovery stage at which each treatment was evaluated, the observed patterns still provide useful information on vegetation responses under contrasting post-fire management practices.

Regarding vegetation composition, we found that CL treatment was characterized by a higher prevalence of non-lignified plants, primarily annual germinative species. Instead, SL treatment exhibited a plant composition more similar to that of the NI plots, including a higher proportion of lignified plants. These patterns indicate that the SL treatment promoted vegetation recovery more effectively than CL. However, this difference was not observed in the last year of sampling, suggesting a slower but eventual convergence in vegetation composition (Peterson and Dodson, 2016). It is important to note, though, that this final sampling took place during a severe three-year drought, during which most annual species were unable to germinate, potentially influencing the observed patterns.

However, the most pronounced effect was observed in vegetation cover. NI treatment exhibited substantially higher vegetation cover than CL treatment, as shown in other regions ((Purdon et al., 2004; Li and Xu, 2023). Although the SL treatment improved vegetation recovery compared to CL, it did not reach the levels observed under NI. The reduced soil disturbance and the retention of standing trees in SL likely enhanced the vegetation's regenerative capacity. In contrast, CL treatment caused severe impacts on vegetation, as soil compaction from heavy machinery hindered regeneration and reduced resprouting potential. This resulted in a structurally simpler habitat, with fewer shelter opportunities and greater soil exposure (Francos et al., 2019; Peña-Molina et al., 2024). Litter cover was also higher in SL treatments than in CL treatments, although it did not reach the values observed in NI plots.

Our analysis of the vegetation, therefore, revealed that the use of sustainable practices had an effect on post-fire vegetation recovery. The ecological objectives underlying these practices appear to be met in terms of vegetation response. However, their implementation also entails certain impacts, which must be acknowledged and considered in future management planning.

Beyond its intrinsic value, vegetation recovery also has cascading effects on other trophic levels (Xue et al., 2022; Jorge et al., 2023; Lang et al., 2023). In particular, vegetation structure strongly affects ground-level spider richness and abundance (Campbell et al., 2022). Litter cover, for example, contributes to shelter availability for invertebrates and increases the structural complexity of the forest floor, factors often associated with higher spider diversity (Uetz, 1979; Wagner et al., 2003), and other ground-level taxa (Fox et al., 2010; Roeder et al., 2022). Taxa associated with litter are also known to be among the most affected by a fire (York, 1999; Hanula and Wade, 2003; Driscoll et al., 2010). Accordingly, these structural differences may support more diverse spider assemblages in NI plots, with SL treatments potentially offering intermediate conditions.

4.2. Effects of post-fire treatments on spider assembly

When assessing how post-fire treatments and time since fire influenced spider assemblages, we found effects in both functional and taxonomic approaches. However, the treatment effect was relatively weak, while the effect of time since fire was more pronounced. Despite the detected effects, differences were not easily visualized or interpreted using the NMDS technique. Previous studies comparing burned and unburned areas (which represent a more pronounced contrast than the one examined here) have also reported difficulties in detecting clear differences in spider communities (Milne et al., 2021; Martínez et al., 2022). Therefore, it is reasonable to expect similar challenges when evaluating vegetation regeneration or the effects of post-fire treatments alone. For this reason, more specific models were applied to better understand these patterns. Moreover, because sampling was conducted during a single month each year, the dataset represents only a subset of the spider community, biased toward species that are more active during that period. This temporal constraint, inherent to the sampling design,

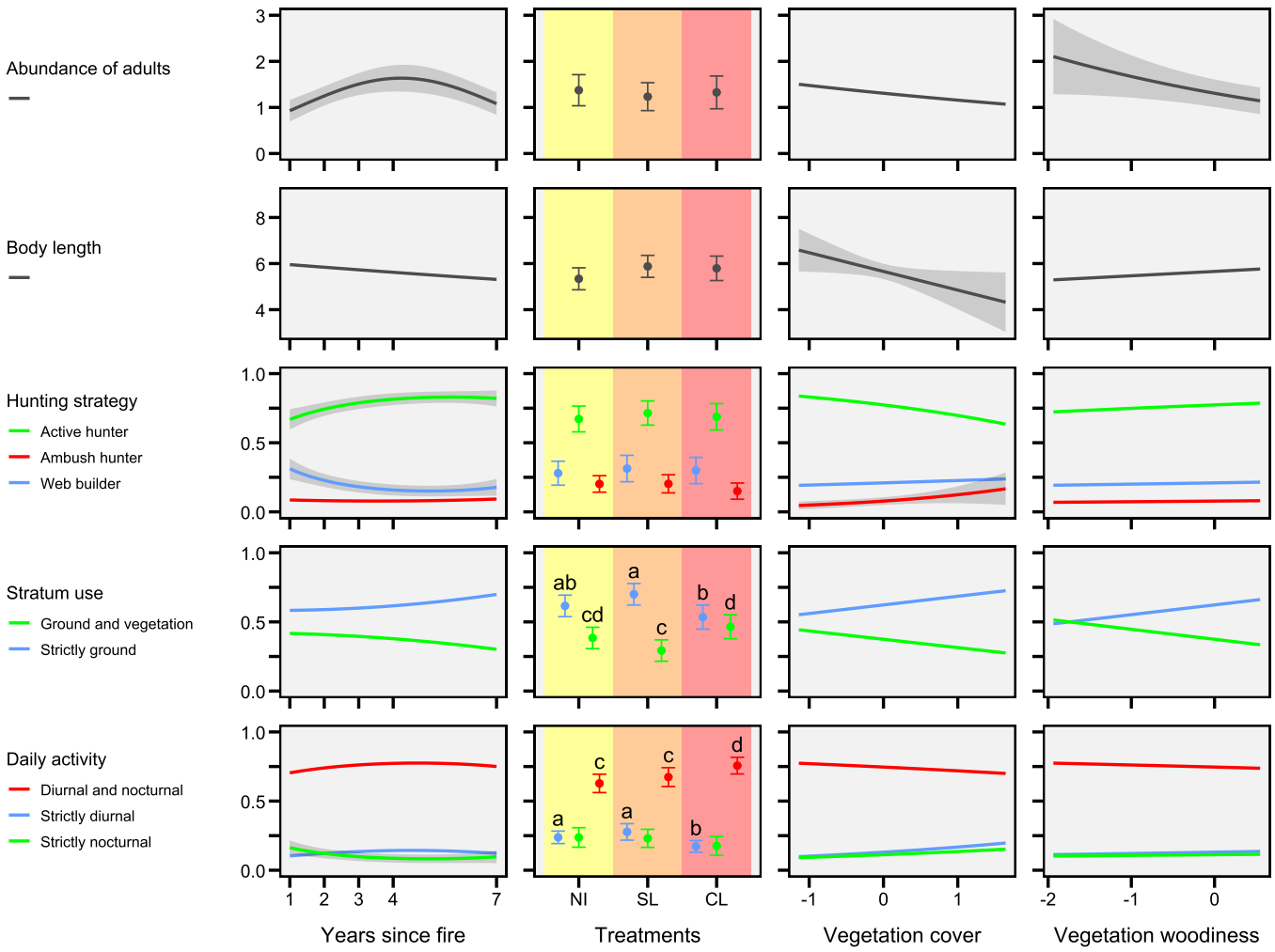

Fig. 4. Model predictions showing the influence of years since fire, post-fire treatments, and habitat characteristics on spider abundance and functional traits. Trend lines and shaded standard error areas (95 % confidence intervals) were obtained from GLMM model estimates. Lines without shaded areas and points lacking letters indicate non-significant relationships.

limits the detection of species with different phenologies. Nevertheless, adopting a functional trait–based approach helps capture broader ecological responses and reduces the influence of species-specific and seasonal biases on the interpretation of community-level patterns.

Time since fire was one of the stronger drivers in adult spider abundance. This increased over the first four years but declined noticeably by the seventh year. The initial increase in abundance aligns with expectations, as it has been reported in several studies (Moretti et al., 2002; Vasconcelos et al., 2009; Brantley, 2020). However, the subsequent decline is an unexpected result, as no similar patterns were found in the literature. One possible explanation is that the severe drought preceding the final sampling year affected the overall arthropod community (Gely et al., 2020), thereby reducing spider abundance. Spider abundance was also influenced by vegetation woodiness, with lower abundances recorded in areas dominated by lignified plants compared to those with a higher presence of annual species. Flowering annual plants can increase insect prey, thus favoring higher spider abundance (Campbell et al., 2022). In addition, during drought periods, annual plants may fail to germinate or flower (Chen et al., 2023), which could help explain the decline observed in the seventh year after fire. Although time since fire and vegetation composition influenced abundance, neither vegetation structure nor post-fire treatments showed significant effects.

Body length was expected to decrease with time since fire, as early post-fire communities are typically dominated by species with higher mobility and greater desiccation resistance (Langlands et al., 2011; McLean et al., 2023). However, no significant effect was detected in our analyses. Two factors may explain this result: first, spiders are highly efficient colonizers and are often among the first taxa to recolonize after disturbance (Bishop and Riechert, 1990; Foelix, 2010; Morley and Robert, 2018), with the relatively small size of the study area likely facilitating colonization from adjacent unburned habitats (Langlands et al., 2011); second, most species in our study are capable of ballooning dispersal, and the proportion of ballooning species did not vary across treatments or years. Together, these factors are likely to reduce the importance of body length as a constraint on dispersal. Nevertheless, we observed a negative relationship between vegetation cover and body length. This may reflect that areas with lower vegetation cover favor more mobile, ground-active species, which typically have larger body sizes, such as those from the family Lycosidae.

Hunting strategy was clearly dominated by active hunters, likely due to the simplified habitat structure generated by fire, which usually favors this group (Niwa and Peck, 2002; Heikkinen and MacMahon, 2004). In addition, pitfall traps are more efficient at capturing ground-active species (Churchill and Arthur, 1999; Wagner et al., 2003), which may contribute to their dominance in the samples. Nevertheless, the proportion of web-building spiders was surprisingly high in the first year after fire compared to subsequent years. This is unexpected as orb and sheet weavers are more likely to be absent after fire than other hunters (McLean et al., 2023), mostly because burned habitats reduce

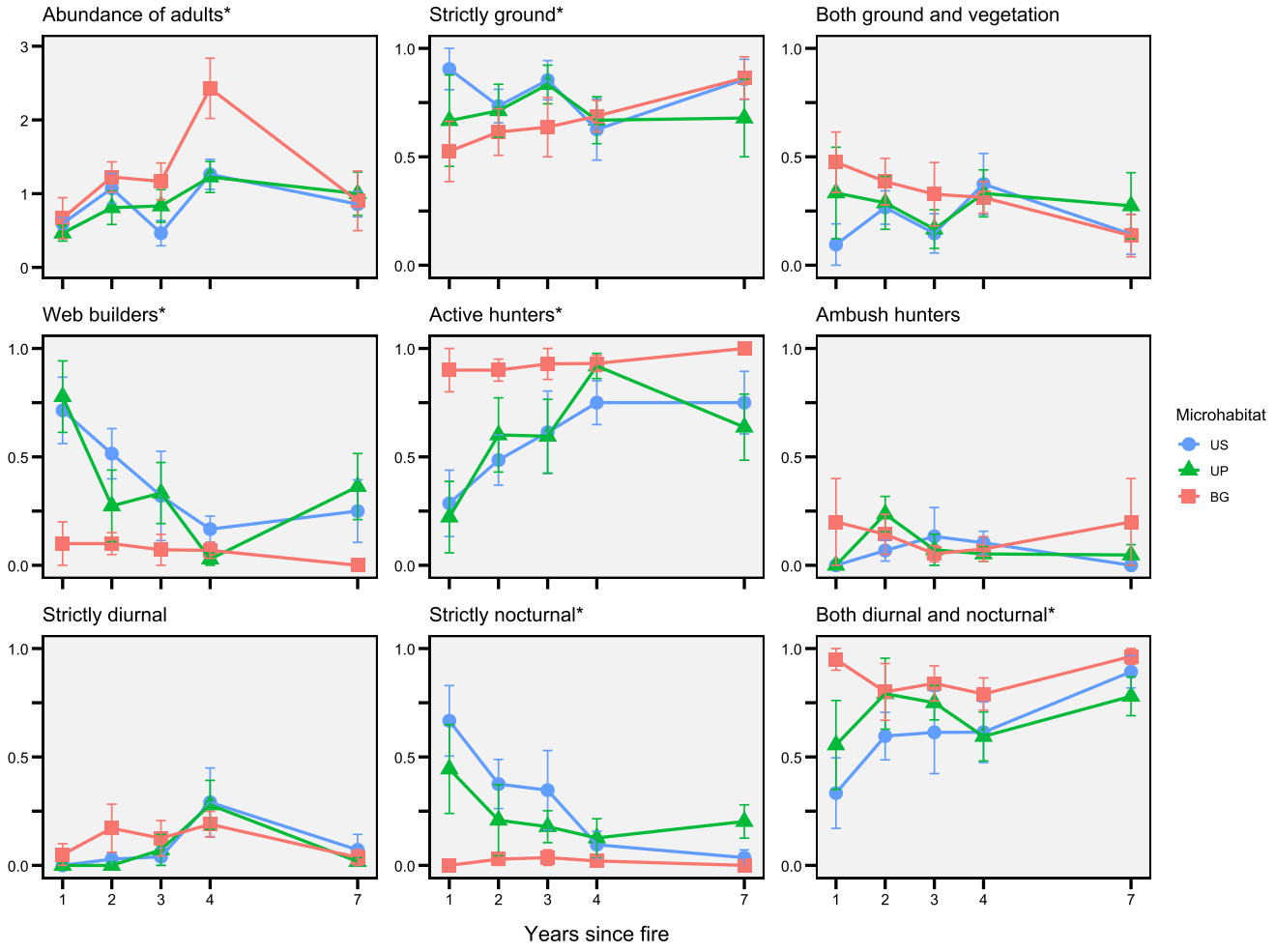

Fig. 5. Variation in spider abundance and functional traits explained by years since fire and microhabitat in sustainable logging plots (US – Under shrub, UP – Under pile, BG – Bare ground). Titles marked with an asterisk (*) indicate significant differences between BG and the other microhabitats (US and UP).

the availability of web anchor sites (Robinson, 1981; Uetz, 1991). A possible explanation is that these taxa are dominant in forest habitats and, as previously mentioned, the small size of the study area may have facilitated early colonization. However, they may be unable to maintain population growth, whereas active hunters may arrive later but encounter more suitable habitat conditions (Vidal-Cordero et al., 2022). It was expected that CL treatments, characterized by the simplest vegetation structure, would host a higher proportion of active hunters, but no significant differences were found. The only hunting group that responded to post-fire treatments or vegetation structure was ambush hunters, which were more frequent in plots with higher vegetation cover, most probably because of the increased availability of hiding places.

The results regarding the stratum use were unexpected and difficult to interpret. Treatments with a more complex vegetation structure (NI and SL) showed a higher prevalence of strictly ground-dwelling species compared to those using both ground and vegetation strata. One possible explanation is that strictly ground-dwelling species may depend on specific structural refuges such as leaf litter, which is more abundant in NI and SL plots. In contrast, species that use both ground and vegetation can use small plants, which are present across all treatments.

When analysing daily activity, strictly diurnal activity emerged as the dominant trait. This pattern is commonly observed in burned areas, probably because thermophilic species with more desiccation resistance tend to be diurnal (Vidal-Cordero et al., 2022). This may explain why CL plots showed a greater dominance of strictly diurnal species compared to NI and SL plots. The latter have more developed vegetation structure, which may support less thermophilic species, which are more prone to nocturnal activity.

Taxa associated with litter cover are known to be among the most affected after fire (York, 1999; Hanula and Wade, 2003; Driscoll et al., 2020). However, no relationship was found here between litter recovery and spider functional traits. This suggests that, although litter cover plays a key role in shaping species assemblages in unburned habitats (Campbell et al., 2022; Wagner et al., 2003), it may not be a major driver of post-fire functional recovery in spider communities.

Taking a broader perspective on the influence of post-fire treatments on spider functional traits, we observed that CL generally amplified the effects of fire, reinforcing the dominance of traits typically favored in burned environments. In contrast, functional trait patterns in SL plots more closely resembled those observed in NI plots. The habitat characteristics in SL and NI appeared to promote a higher representation of less dominant traits, thus facilitating the recovery of functional diversity after fire.

4.3. *Effects of microhabitat on spider assembly*

Microhabitat appeared to shape spider communities more than post-fire treatments, particularly spider abundance, which was significantly influenced by microhabitat type but not by treatments. Pitfall traps

placed on bare ground (BG) captured more individuals than those in the other microhabitats. While this may partially reflect a sampling bias toward ground-dwelling species inherent to pitfall traps, BG may also be more closely associated with flowering annual plants, which could support higher prey availability and thus greater spider abundance. This effect may help explain the peak in abundance observed in the fourth year post-fire, which coincided with an unusually rainy season that promoted widespread germination of flowering plants and increased invertebrate activity (Fischer et al., 2022).

The distribution of hunting strategies across microhabitats provides valuable insight. Web-building spiders were found exclusively under shrubs (US) and under pile (UP) microhabitats, with no significant differences between them. In contrast, BG was almost entirely dominated by active hunters, likely due to its low structural complexity and the unavailability of web anchor sites (Heikkinen and MacMahon, 2004). These findings highlight the importance of vegetation structure, including artificial elements such as wood piles, for the functional recovery of spider communities after fire.

The influence of microhabitat on daily activity exhibited a similar pattern to that observed across post-fire treatments. BG microhabitats showed a higher dominance of strictly diurnal species, whereas US and UP likely served as refuges for species with lower desiccation tolerance, typically associated with more nocturnal activity. A similar correspondence was found for stratum use, where strictly ground species were slightly more frequent in US and UP microhabitats, matching the trend observed under different treatment conditions. This supports the idea that these microhabitats provide critical structural refuges after fire (Puig-Gironès et al., 2017), not only through vegetation structure but also by promoting the accumulation of leaf litter on the soil.

Considering the overall role of microhabitat in shaping functional traits' assembly, wood piles appear to offer comparable ecological benefits to those of shrubs. This parallels findings in other animal groups, such as rodents (Sullivan et al., 2012; Puig-Gironès, 2023). This is particularly relevant during the early post-fire years, when vegetation cover is still limited and including the construction of wood piles on the post-fire management actions may play a key role in facilitating the recovery of faunal communities (Rost et al., 2010; Watchorn et al., 2024). Moreover, the strong influence of microhabitat on spider communities highlights the importance of accounting for it in future studies. Not considering the abundance of different microhabitat types in models may confound the interpretation of other ecological variables.

5. Conclusions

Overall, our findings suggest that sustainable post-fire logging practices, while not free of impact, cause less detrimental effects on ecosystem recovery compared to conventional practices. We emphasize and recommend the adoption of these practices, such as the use of extraction corridors and the implementation of wood-debris piles. These measures reduce unnecessary impacts and facilitate both vegetation and animal recovery by preserving soil integrity and providing refuges for numerous species. Importantly, microhabitat conditions played a significant role in shaping spider assemblages, highlighting the importance of accounting for microhabitat variability in future studies. Finally, we advocate for further research into the effects of sustainable practices on other groups, as this knowledge is essential to refine post-fire management strategies aimed at conserving biodiversity in fire-prone ecosystems.

CRediT authorship contribution statement

Adrià Bellvert: Writing – review & editing, Investigation. **Roger Puig-Gironès:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Quel Vilalta-Clapés:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Pere Pons:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Carles Tobella:** Writing – review & editing, Methodology, Investigation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary Material A. Summary of the variables and statistical models used in the study.

Supplementary Material B. Checklist of species ordered by family, including the number of individuals and their functional traits classification.

Supplementary Material C. Summary of all statistical outputs.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2026.123549.

Data availability

The data used in this study are deposited in the following repository: https://doi.org/10.5281/zenodo.18291347

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