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Effects of Post-Fire Management on a Mediterranean Small Mammal Community

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Abstract: Wildfires simplify ecosystems, modifying the ecological niches of the fauna living in the recently burned areas. Small mammals respond rapidly to changes in habitat structure and composition after fire, but the effects of fire can be ameliorated by some management strategies (e.g., salvage logging). Hence, it is necessary to explore whether alternative management strategies may be able to return the ecosystem to its initial state. We studied the small mammal community by live trapping on eight plots under different post-fire treatments in Sant Llorenç del Munt i l'Obac Natural Park (Barcelona province, NE Spain). At the community level, an increase in overall relative abundance and species density was observed in the burned areas. *Apodemus sylvaticus*, the most abundant mammal in study area, used woody debris piles as a shelter against predators. *Mus spretus* was more abundant in post-fire sites with large open areas interspersed with woody debris piles. *Crocidura russula* steadily increased its presence in later successional stages when ground cover became more complex. Our results suggest that combining different management strategies may be appropriate to improve the habitat suitability and biodiversity of small mammals and other key open-land species throughout the burned area.

Keywords: rodents; shrews; salvage logging; vegetation structure; forest recovery; habitat management

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1. Introduction

Wildfires are considered essential components of the dynamics of Mediterranean ecosystems [1,2], and can even be used to promote biodiversity [3]. However, the advancement of desertification and increasing drought conditions, along with the human-induced changes in fire regimes (fire recurrence [4]), are serious threats to the conservation of Mediterranean forests under the global climate change scenario [5]. Indeed, Mediterranean forests are prone to wildfires, changing the composition and structure of vegetation and soil properties, and decreasing soil water retention [6,7]. After fire, there is an evident simplification of the habitat, and many faunal species lose their niche because they depend on habitat structure for foraging, breeding, and shelter [8–10]. Forest faunal species may disappear from recently burned areas, but open-habitat species take the opportunity to thrive in those new structurally simple habitats where competitors and predators are lacking. In general, greater between-site and landscape faunal diversity are predicted to occur after fires. Shortly after fire, the species richness increases, as new species colonize sites that now meet their habitat requirements [11,12]. The effect of fire, however, varies between and within groups of species as a consequence of local factors conditioning diversity [13].

Mediterranean small mammal communities are relatively diverse, but the bulk of such communities is composed of a few common, generalist, dominant, and widespread species [14]. Indeed, two rodents (wood mouse, *Apodemus sylvaticus*, and Algerian mouse, *Mus spretus*) and one shrew (greater white-toothed shrew, *Crocidura russula*) represented 95% of the captures in a small mammal monitoring program implemented in the area [14]. These species also become dominant in post-fire habitats, when specialists associated with forest environments are lacking [15,16]. Small mammal communities can be affected by wildfires through fire-induced changes in vegetation structure and habitat suitability [17]. Despite small mammal populations responding to changes in habitat structure and composition after fire [18], the effects of forest fires on communities can be ameliorated with some management strategies aimed at favoring populations and diversity. This can be important owing to the valuable ecosystem services they provide, acting as both pest predators and seed dispersers [19,20], as well as playing a fundamental part of the diet of many predators [21–23]. Indeed, fires negatively affect populations of small mammal predators (e.g., common genets, tawny owls) and competitors (e.g., brown rats, red squirrels) which largely depend on trees, thus enhancing small mammal populations living in open habitats (e.g., scrubland) [24].

Salvage logging, a practice of logging trees in forest areas that have been affected by disturbances, is a common worldwide forest management practice aimed at providing rapid economic return after forest disturbances. However, salvage logging is often unplanned and executed quickly just after fire [25,26]. Consequently, in many cases, this practice implies a structural simplification of burned habitats that can increase soil compaction and erosion due to forestry operations [27,28], slow down vegetation regeneration [7], and reduce the diversity of plant and animal communities [26]. Conversely, some post-fire practices may be adequate to reduce erosion on severe slopes, or to generate open areas, where forest was previously homogeneous, thus benefitting open-habitat specialist species [29–31]. In any case, salvage logging after a disturbance requires prior ecological assessment and planning.

Less severe management options, including non-intervention, are recommended under the assumption that snags and decaying burned wood are biological legacies that promote ecosystem recovery and diversity [32–34]. In addition, it is important to maintain biological legacies, such as unburned trees or stone walls [34], for forest recovery [35]. For example, post-fire woody debris remains on the landscape as forests regenerate, providing nutrient pools for regenerating the ecosystem and facilitating microsite conditions for seedling survival; it is also an important structural habitat component [7,36–39].

Thus, it is necessary to explore whether alternative management strategies can return the ecosystem to its initial state (pre-fire condition). Therefore, knowing the post fire treatment conditions, including the small mammal presence and relative abundance, can be fundamental for plant regeneration and the rapid recovery of predator densities in burned areas [15,40]. In this sense, managing each burned area as a single unit, through different treatments scattered across the landscape, providing some spatial heterogeneity, may be an appropriate strategy to increase the presence of small mammals and the diversity in recently burned areas.

In order to understand the relative contribution of wildfire and salvage logging in a single burned area, to provide evidence for decision making in restoration, and to improve forestry practices, we compared how some post-fire scenarios affected the recovery of small mammal populations. For this purpose, we used the pine forest, burned in 2003, in the Sant Llorenç del Munt i l'Obac Natural Park (NE of the Iberian Peninsula). We hypothesized that shortly after fire: (1) burned habitats (irrespective of the management) will hold more small mammals (relative abundance and species density) because these habitats are more suitable for these mammals (e.g., more food, but fewer predators and competitors) than unburned forests [41], and (2) burned habitats showing higher structural complexity at the floor level and lower complexity at the canopy level will exhibit a higher relative abundance and species density of small mammals [16].

2. Materials and Methods

2.1. Study Context

This study was performed in a burned area in the Sant Llorenç del Munt i l'Obac Natural Park (PNSLL) in Barcelona province (Catalonia, NE Spain, Figure 1). The PNSLL (total area = 13,694 ha) is characterized by a rugged landscape of sheer crags and unusual rock formations formed from a substrate of polymictic conglomerate rock. Its climate is subhumid Mediterranean, with an annual rainfall of around 600 mm, which is greater in spring and autumn than in summer; its highest peaks are windier, wetter, and cooler than the surrounding lowland areas [42]. The original forest cover of the area, prone to fast-spreading fires during hot, dry summers, is dominated by evergreen holm oak (*Quercus ilex* L.), Aleppo pine (*Pinus halepensis* Mill.), and Spanish black pine (*Pinus nigra* subsp. *salzmannii* (Dunal) Franco), generally with an evergreen holm oak understory [43].

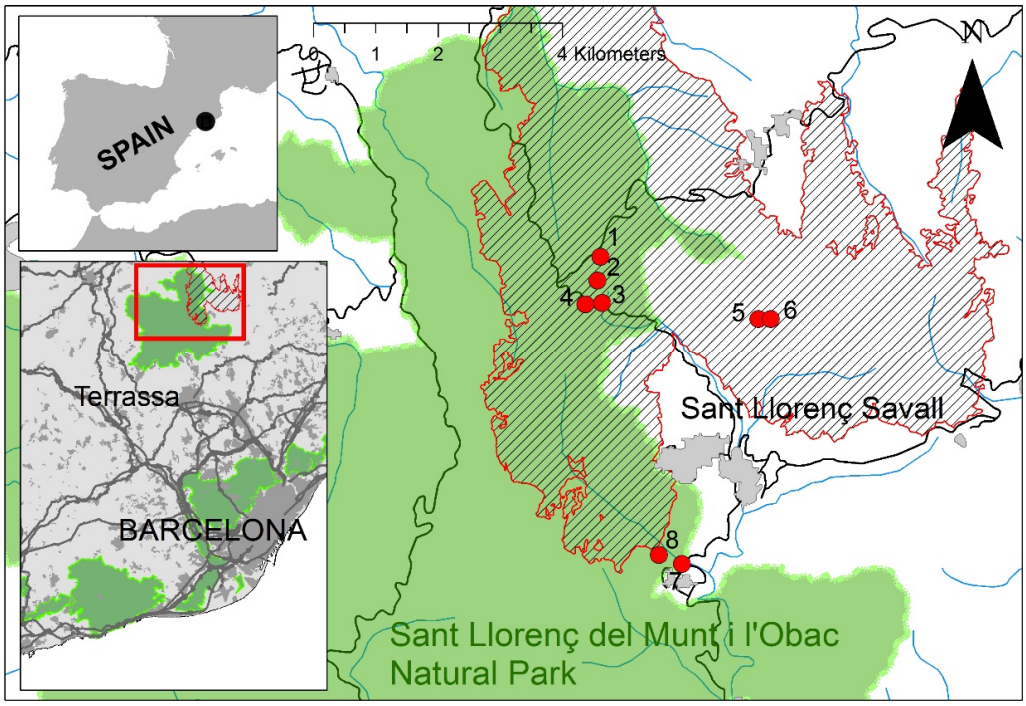

Figure 1. Map of the investigation plots with different treatments in Sant Llorenç del Munt i l'Obac Natural Park (Barcelona province, Catalonia, NE Spain). Plot numbers: 1, 2: burnt; 3, 4: burnt, trunk removal and branches in piles; 5, 6: burnt, trunk removal and branches sparse; 7, 8: unburned. Green color shows natural parks, and the hatched areas show fire extension; gray color shows urban areas.

In August 2003, 4543 ha of the eastern part of this park (10% of its total surface area, Figure 1) and neighboring areas were burned by a wildfire, which affected an area dominated by pine forest, with a holm oak understory (Figure 2). Soon after the fire and within two years, most of the burned area had been completely logged using different treatments [31,37]. Here, we selected three different post-fire treatments (PFT) and a control (unburned): (a) unburned; area outside of the 2003-burned area; (b) non-managed; burned with no post-fire treatment or removal; (c) managed 1: trunk removal with branches spread over the ground (PFT1); (d) managed 2: trunk removal with branches in piles (PFT2); unburned sampled treatment was on pine forest that covers peripheral areas of the park to avoid the effect of forest type on small mammal assemblages. Post-fire plots were placed far away from the forest edges (>1 km), but unburned plots (especially plot n°8) were near the forest edge (>150 m).

Figure 2. Photographs of the control unburned (**a**), burned (**b**), and post-fire treatments (**c**) PFT1, and (**d**) PTF2; see Section 2 for details.

2.2. Small Mammal Sampling

Sampling was conducted in June and September 2005 and June and November 2006, starting almost two years after the fire (August 2003). We established eight live trapping plots in the four treatments, with two replicates each. Each plot consisted of a regular grid of 16 (4 × 4) Sherman traps (Sherman folding small animal trap; 23 × 7.5 × 9 cm; Sherman Co., Ltd. Tallahassee, FL, USA) placed on the ground and spaced 15 m apart. The traps were baited with a piece of apple and a mixture of tuna, flour, and oil. The traps were operated during three consecutive days and checked during the early morning and early evening (six trap checks). Small mammals caught were identified to species level, sexed, weighed, and marked with permanent ear tags, in the case of rodents (Style 1005–1, National Band Co., Ltd. Newport, KY, USA), and with fur clips, in the case of shrews [44]. After handling, all animals were released at the point of capture [45]. Research on live animals followed ethical guidelines [44]. Vegetation cover was estimated on a visual basis, determining the height and the surface covered by each vegetation strata in a 5 m radius centered on each trap [46]. Despite the fact that this method is time-consuming and subjective, it was suggested that it provides good concordance with modern objective methods for sampling vegetation [47]. We estimated the cover (surface occupied in %) of five variables: tree canopy, tall shrub (>1.5 m), short shrub (<1.5 m), herbaceous, and branch cover. The height of the vegetation was not considered to avoid redundancy. Vegetation cover was estimated by the same person to avoid biases.

2.3. Data Analyses

We used generalized linear mixed models with a Poisson distribution of errors for relative abundance data [48,49], including two fixed factors (Treatment, with four levels; Season, with two levels) and a covariate (Time since the last fire, in months). The sampling plot was included as a random factor, and all independent predictors were scaled before fitting the models [48,49]. Species density was also considered as a response variable [50]. For each response variable, the R function *glmer* was used to build the models, including all the explanatory variables, and we calculated pseudo-R^2 values by means of the function

r.squaredGLMM [51]. In the case of vegetation, we performed a GLM assuming Gaussian distribution errors, and only considering one fixed factor (Treatment). A log-linear model was performed to ascertain changes in the small mammal community structure between treatments, that is, changes in frequencies of occurrence of the three species.

3. Results

Post-fire treatments (PFT) significantly affected the vegetation cover (Table 1, Figure 3a): the tree cover was reduced (from 34% in the unburned control to 0% in the managed PFT), the short shrub cover was reduced (from 46% in the unburned control to 2–10% in the PFT), the cover of branches increased in managed PFT (from 6% to 29–40%), but herbaceous cover was unaffected (from 55% to 33–39%). The short shrub cover was negatively affected by fires, but the increased cover of branches counteracted this loss in PFT (Figure 3a).

Table 1. GLMs of five vegetation cover strata between post-fire treatments, showing the estimates and SE, and their statistical significance. The unburned control is the reference for comparison between treatments.

		Tree Cover (%)		Shrub Cover (<1.5 m, %)		Shrub Cover (>1.5 m, %)		Herb Cover (%)		Branch Cover (%)	
		Estimate	**SE**	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**
	(Intercept)	1.62	0.08	1.63 ***	0.19	0.95	0.75	0.47	0.68	−0.87	0.45
Treatment	Burned_Control	−1.69 ***	0.12	−2.42 ***	0.26	−1.44	1.06	0.35	0.97	0.14	0.63
	Burned_Managed_PFT1	−2.40 ***	0.12	−1.97 **	0.26	−1.06	1.06	−0.83	0.97	1.29	0.63
	Burned_Managed_PFT2	−2.40 ***	0.12	−2.22 **	0.26	−1.44	1.06	−1.30	0.97	2.20 *	0.63

Significance codes: *** 0.001; ** 0.01; * 0.05.

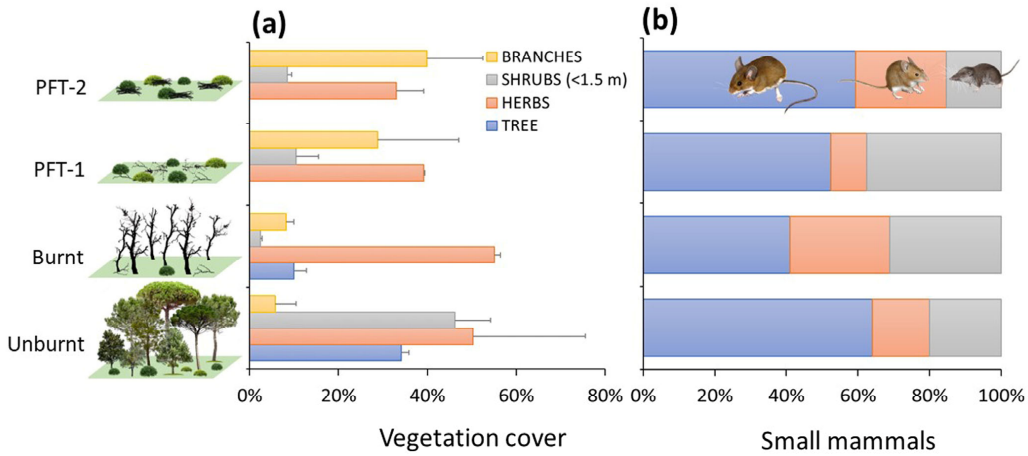

Figure 3. Cover (%) ± SE of the four main vegetation strata (**a**), and frequency of occurrence of the three small mammal species in different regimes of post-fire treatment (**b**); wood mouse shown in blue, Algerian mouse shown in orange, greater white-toothed shrew in gray colors.

During the study period, we captured 217 small mammals of three species. The wood mouse (*Apodemus sylvaticus*) was dominant, with 116 individuals (53.4%), followed by the greater white-tooothed shrew (*Crocidura russula*), with 53 individuals (24.4%), and the Algerian mouse (*Mus spretus*), with 48 individuals (22.1%). The post-fire treatments affected the community structure (Chi^2 = 14.51, p = 0.02, $d.f.$ = 3), showing an increase in *M. spretus* and *C. russula* in burned plots (burned control + PFT) and a decrease in *A. sylvaticus*, compared to the unburned control (Table 2, Figure 3b). Considering only the four plots, unburned and burned without treatment, *A. sylvaticus* was more frequent in the unburned

plots (64% vs. 41%), and *M. spretus* and *C. russula* were more frequent in the burned plots (28% vs. 16% and 31% vs. 20%, respectively).

Table 2. GLMMs for the relative abundance of the three small mammal species captured, the total number of captures, and the species richness (=density) between post-fire treatments. The estimates and SE, as well as their statistical significance, are shown. The unburned control is the reference for comparison between treatments.

		A. sylvaticus		*M. spretus*		*C. russula*		**Total**		**Richness**	
		Estimate	**SE**	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**
	(Intercept)	1.08 ***	0.26	−1.39 *	0.55	−0.56	0.5	11.28 **	2.16	2.40 ***	0.47
Treatment	Burned_Control	0.45	0.32	1.45 **	0.56	1.3 *	0.54	4.5 **	1.60	1.37 ***	0.35
	Burned_Managed_PFT1	0.93 **	0.34	0.3	0.71	1.29 *	0.56	4.84 *	1.75	1.19 **	0.38
	Burned_Managed_PFT2	0.82 **	0.29	1.52 **	0.54	0.85	0.55	5.20 **	1.53	1.08 **	0.33
Season	Spring	−1.09 ***	0.23			−0.13	0.33	−5.65 ***	1.31	−0.99 **	0.28
Time	Months since the last fire	−0.47 ***	0.12	−1.32 ***	0.25	0.50 **	0.17	−2.13 **	0.58	−0.41 **	0.12

Significance codes: *** 0.001; ** 0.01; * 0.05.

Nonetheless, differences in species relative abundance and frequency were observed between post-fire treatments. Indeed, wood mice showed a positive response to treatments affecting the cover of trees (trunks removed, PFT1 and PFT2) that increased the understory cover with branch piles, Algerian mice showed a positive response to the burned (without treatment) and PFT2 areas, and shrews increased in abundance in the burned and PFT2 areas. Both rodents showed a decline in abundance along the study period, whereas a contrasting pattern was observed for the shrew (Figure 4). Wood mice also showed a decline of abundance during late spring. Small mammal abundance and species density (richness) were positively influenced by fire and PFT, and negatively influenced by time since the last fire.

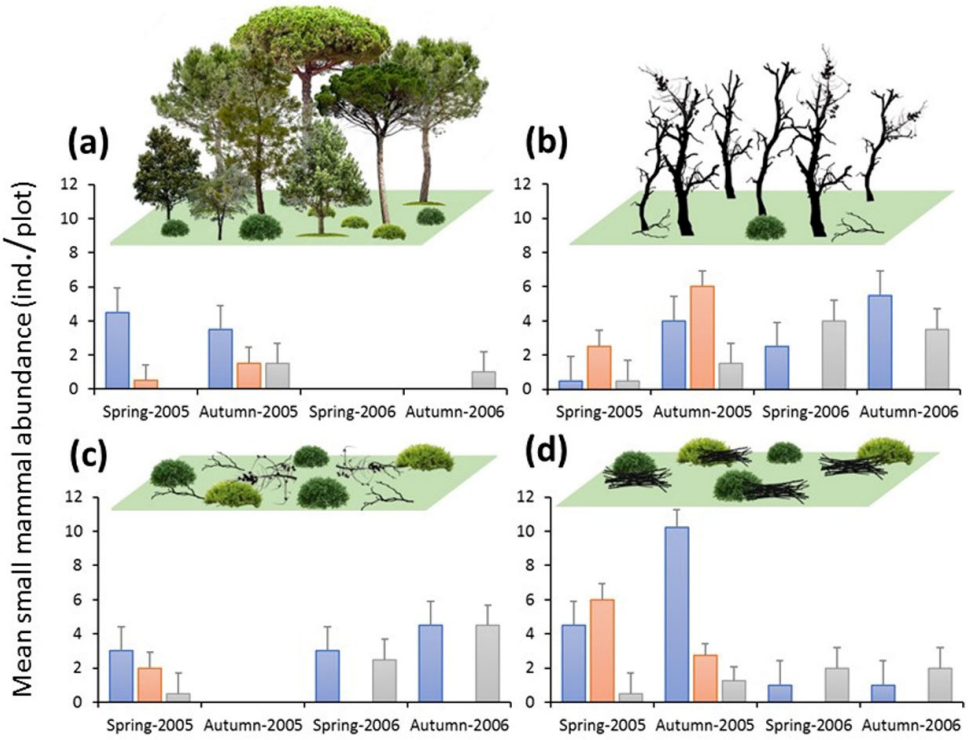

Figure 4. Mean relative abundance (ind./plot ± SE) of the three small mammal species in the four sampling sessions and treatments: (**a**) control-unburned; (**b**) burned not managed; (**c**) burned and managed (PFT1); (**d**) burned and managed (PFT2). Wood mouse shown in blue, Algerian mouse shown in orange, greater white-toothed shrew in gray colors.

4. Discussion

Our results confirmed that small mammal post-fire communities—a short time after the fire—were composed of three common and widespread species. These findings agreed with the results of other studies conducted in NE Spain [7,15,41,52], in which the generalist *A. sylvaticus* was dominant, with a lower relative abundances of *M. spretus* (pioneer open-habitat species) and *C. russula* (late colonizer). The dominance of wood mice can be related to pre-fire occupancy patterns, as well as post-fire landscape configurations (fragmentation, edge effects [15]). At the community level, we observed an increase in overall abundance and species density in post-fire areas, and a consistent decreasing trend of species density and abundance with time elapsed since the last fire, as was observed in long-term studies [41]. These patterns could be related to the decreasing habitat suitability for open-habitat species some years after the fire in the study area [53]. We showed how fire and subsequent salvage logging simplified the original habitat structure, decreasing tree and short shrub cover. However, this simplification may be an opportunity for some species, such as small mammals, whose dispersing individuals can take advantage of the vacant burned territory, lacking competitors and predators [15,41,54]. Immediately after fire, there was a rapid recovery of herbaceous cover, reaching values similar to those of unburned plots, due to the adaptive qualities of plants that allow them to survive or regenerate and reproduce immediately after fires [55]. In addition, resources such as invertebrates and fruits are available and not restrictive for small mammal presence in the burned area [7,56,57]. Thus, wildfires may represent an opportunity for certain opportunistic, generalist, or open-habitat species [58–60], such as some Mediterranean small mammals. For example, *A. sylvaticus* is highly adaptable to new conditions following disturbances in woodland habitats, while forest opening and the presence of sparse woody vegetation and herbs favored the occurrence of *M. spretus* and *C. russula* [52,61]. These results were similar to those observed in fragmented forests, where *A. sylvaticus* showed a preference for productive ecotones, while *M. spretus* showed an affinity for open habitats [62]. In the latter case, the colonization of unburned forest patches can be related to the proximity to the fire edges. However, *C. russula* was documented as the least fire-resistant small mammal species, being absent during the first two years after fire [63,64]. Their reestablishment seemed to be dependent on the litter reconstitution and related to temporal changes in vegetation structure [41,63,64]. Our results, however, pointed out a faster recovery of this shrew (being present two years after fire, see also [52]), its abundance increasing with time elapsed since the last fire.

While the high availability of resources, along with a decrease in competition and predation pressure [41], could be the main explanations for the increased relative abundance of small mammals in burned compared to unburned areas, the habitat structure complexity at the floor level seemed to be the major explanation in salvage-logged areas. Some studies have found higher seedling survival in areas where logs and branches were left on the ground, due to the protection against herbivory and erosion, as well as better microclimatic conditions created by the piles of dead wood [38,65]; our results showed less regeneration (e.g., resprouting shrubs) in burned plots, regardless of treatment, but this was probably related to the short time elapsed since the last fire (< three years). However, salvage-logged areas presented higher branch cover than unburned and unlogged areas. Branches, either scattered on the ground or piled up, may provide shelter and facilitate the recolonization of the logged area by small mammals that are highly dependent on short woody vegetation [16,66].

Our results showed that small mammal responses to post-fire management were species-specific, although normally, the generalist species colonized more recently disturbed areas (e.g., salvage logged), while specialist species are more abundant in more mature forest habitats [67]. *A. sylvaticus* is the most abundant mammal in the study area, and it seems resilient to habitat modification [52]. This mouse was more abundant in logged areas because it used the piles of woody debris for shelter against predators [8,68] where natural short woody vegetation was lacking. *M. spretus* showed a preference for open

sites, with a combination of herbaceous, shrub, and dead vegetation cover, and avoided woodland [52,69]. Therefore, it was more abundant in post-fire plots with large open areas interspersed with piles of woody debris, and in the unlogged area, with greater cover of undergrowth [7]. Both mice are strong colonizers who are able to forage efficiently in salvage-logged sites with less vegetation but are not as successful as *C. russula* in later successional stages when food becomes scarce and ground cover becomes more complex. On the other hand, this shrew is mainly found in Mediterranean open and shrubland habitats [61].

A. sylvaticus showed lower relative abundance in spring than autumn, which is contrary to the normal seasonal pattern [70]. *C. russula* showed no seasonal trend in abundance during the two study years, but its population dynamics exhibited autumn peaks, after the spring-summer reproductive period [61]. Observed differences in seasonal dynamics could be caused by the alteration of breeding cycles and demography in post-fire habitats. Small mammal responses to disturbance can vary widely by year and by location [71,72]. In this sense, the retention of non-commercial woody debris in the logged stands seems fundamental to attract and retain mice, if vegetation regrowth has not started, in addition to facilitating the population connectivity between burned and unburned areas and providing a shelter from predation as an alternative to plant cover [7,73]. Because the diversity, abundance, and stability of Mediterranean small mammal communities can be negatively affected by vegetation structural complexity [16], managing forest fires by removing trunks would be beneficial for small mammals. In the context of climate change, increasing warming and drought conditions will produce changes to fire regimes and fire recurrence in the Mediterranean-basin and in many world regions [5,74], and salvage logging operations are expected to increase. However, large post-fire salvage logging operations risk the homogenization of forest ecosystems and the stability of wildlife populations on a landscape scale. In the specific case studied here, it seems evident that generating a heterogeneous landscape, through unlogged burned patches and patches logged through different management strategies, can be an appropriate strategy to improve habitat suitability and to increase the biodiversity of small mammals and other key open-land species (such as rabbits [31] or birds [38]) in the entire burned area. Indeed, wildfires (either natural or prescribed) could be the only way to fight against the process of land abandonment and rewilding at large spatial scales, reversing the decline in habitat suitability for open-land species due to habitat loss by the natural afforestation process and the subsequent recovery of small mammal predators [24,75].

In summary, our results agree with our previous findings regarding the positive effects of post-fire environments for small mammals [15,41]. Nonetheless, the combination of different post-fire management strategies is necessary to recover populations of small mammal species showing different habitat requirements. Indeed, our results suggested that increasing structural complexity at the floor level (e.g., adding piles of branches) in recently burned areas without natural vegetation cover will benefit some pioneer and generalist small mammal species; at the same time, simplifying the structural complexity at the canopy level (e.g., removing burned trees) will indirectly benefit common small mammals by decreasing habitat suitability for predators (e.g., lack of perches for aerial predators) and competitors (e.g., black rats and squirrels) [16]. The latter species are forest dwellers, but their presence in unburned forests is scarce [22], and they were not detected in this study. Although more investigations on the role of post-fire management strategies are needed to corroborate our results, this approach shows the benefits of managing logged areas heterogeneously to preserve small mammal biodiversity.

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