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ORIGINAL PAPER

Long-term response of open-habitats species to wildfire salvage logging: the endangered European wild rabbit as example

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Abstract
Salvage logging treatments, a type of logging to economic returns after natural disturbance, are often applied in the aftermath of wildfires. Specialist or dependent species of open-habitat usually increase their populations in the short-term after wildfires and post-fire salvage logging. However, the long-term effects on threatened open-habitat species such as the European wild rabbit (*Oryctolagus cuniculus* L.) are still poorly known. Thus, plant productivity, habitat heterogeneity and rabbit abundance were studied in the north-east Iberian Peninsula in four type of post-fire treatment plots: (1) unburnt, (2) salvage logging with branches left on the ground, (3) salvage logging and manual removal of branches, and (4) recurrent fires. Both the time since the fire and the treatment affected plant productivity and habitat heterogeneity. Plant productivity was quicker in treatments when branches were left on the ground or when branches were removed than in recurrent fire plots. Rabbit relative abundance increased in the short term but dramatically declined over time after fires, especially in the plots where branches were left on the ground and with recurrent fires, in which rabbit abundances fell dramatically. In the long-term, the lack of food availability and adequate habitat structure are the main factors affecting the maintenance of the rabbit population. An appropriate moment for managing burnt areas to favour the persistence of rabbit is between the fifth and sixth year after the fire. These actions also benefit the reduction of environmental biomass and so help prevent future severe wildfires.

Keywords Forest management · Habitat structure, European wild rabbit · Salvage logging · Wildfire

Introduction

Wildfires structure many communities worldwide (Bond et al. 2005) and are an important factor in biodiversity conservation and natural resource management (Kelly and Brotons 2017). After a wildfire, a post-fire management technique, commonly referred as 'salvage logging', consisting of removing burnt trees to minimize economic losses is often applied (Lindenmayer et al. 2008). The immediate ecological consequences of post-fire salvage logging are the subject of intense debate (Lindenmayer et al. 2004; Donato et al. 2006; Hutto 2006; Thorn et al. 2018) since this practice implies a structural simplification of burnt habitats that may slow down vegetation regeneration, reduce the diversity of plant and animal communities, and increase soil erosion (Thorn et al. 2018). Therefore, any animal species depending on the structural components of vegetation for foraging, breeding or shelter (Müller et al. 2007; Puig-Gironès et al. 2018) may be affected (positively or negatively) by this form of logging. Consequently, less severe management options, even including non-intervention, are currently recommended under the assumption that snags and decaying burnt wood are biological legacies that promote ecosystem recovery and diversity (Beschta et al. 2004; Dellasala et al. 2006), especially for dead-wood-dependent species.

The immediate effects of salvage logging have been well studied for different taxa including bryophytes, vascular plants, spiders, bugs, beetles, rodents, bats and birds (Thorn et al. 2018). Although such studies have generally focused on the effects of salvage logging, there is still a knowledge gap

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regarding the long-term effects of this management practice. Kishchuk et al. (2015) found, 11 years after a disturbance in Canada, that significant salvage logging had an impact on the properties of forest soils. Despite this, this impact was not reflected in the productivity (height and diameter) of the regenerating vegetation (Kishchuk et al. 2015). Other studies have also demonstrated that there are no long-term effects on the composition of plant communities (Kramer et al. 2014) and have even found more species in disturbed logged areas than in adjacent unlogged forests, the exception being birds (Georgiev et al. 2021). These positive effects have been attributed to the greater productivity associated with early successional forests, which are species-rich habitats with high resource availability (Swanson et al. 2011; Puig-Gironès et al. 2020; Georgiev et al. 2021) even if there is a notable lack of density or diversity of deadwood (Norvez et al. 2013). Thus, Norvez et al. (2013) were able to show the negative effects of logging on saproxylic beetle communities, 20 years after salvage logging had taken place.

The European wild rabbit (*Oryctolagus cuniculus* L.) is a keystone species in Iberian Mediterranean ecosystems as the main prey item of many predators and is determinant in a number of important ecological processes (Delibes-Mateos et al. 2007, 2008; Gálvez-Bravo et al. 2009); furthermore, it has an important socio-economic value as a game species (MAPA 2020). However, the wild rabbit has undergone a steep decline due to a combination of viral diseases, loss of suitable open habitats, the local predation and unfavourable game management (Calvete et al. 2004; Moreno et al. 2007; Virgós et al. 2007; Williams et al. 2007; Lees and Bell 2008; Delibes-Mateos et al. 2009; Fernandez-de-Simon et al. 2015), and, consequently, has recently been classified by the International Union for Nature Conservation as an endangered species (Villafuerte and Delibes-Mateos 2019). The habitat preferences of this lagomorph are mainly open landscapes, usually composed with scrub and dry open fields with low vegetation cover at ground level, and a first vegetation strata with abundant low herbaceous vegetation, but they avoid dense scrubland and forests (Fa et al. 1999; Beja et al. 2007; Ferreira and Alves 2009). It is thus a specialist or dependent species of open-habitat (henceforth open-habitat species). Wildfires, prescribed fires and some post-fire management strategies have been linked in the short term to an increase in rabbit populations (Moreno and Villafuerte 1995; Rollan and Real 2011; Foster et al. 2016), as well as in other open-habitat species, including threatened birds and bats (Brown 2009; Rost et al. 2012b; Puig-Gironès et al. 2022) and reptiles (Santos and Poquet 2010). In this sense, post-fire managements consisting in the removal of burnt branch can benefit the rabbit by providing it with obstacle-free areas and can enhance the growth of its nurse plant (Rollan and Real 2011).

The long-term effects of wildfires and salvage logging on open-habitat populations in general and on rabbit populations in particular are still relatively unknown. So, the main novelty of our work is that there are few studies of long-term monitoring of changes in rabbit abundance, and even less after wildfires, one of the most widespread stochastic phenomena in the rabbit's area of distribution, and post-fire salvage logging. Therefore, understanding how threatened open-habitat species respond to the long-term effects of wildfire and salvage logging is the key in decision-making when restoring forest ecosystems and biodiversity and for improving forestry practices. Thus, our aim was to assess in the north-east Iberian Peninsula the long-term effects of wildfires followed by salvage logging on plant productivity and habitat heterogeneity, and the response of relative rabbit abundances. We hypothesized that (1) in the long-term (18 years after a fire), due to vigorous vegetation succession processes, plant productivity is higher in burnt and logged areas than in unlogged areas where wildfires are recurrent over time; (2) long-term plant regeneration negatively affects rabbit abundance; and (3) areas with fire recurrence show greater long-term rabbit abundance because they offer suitable habitat—i.e. less structural complexity and plant productivity—that more closely resembles pre-fire shrubland habitats.

Material and methods

Study context

The study area was in the Sant Llorenç del Munt i l'Obac Natural Park (NE Iberian Peninsula) (Fig. 1). This mountainous area, which forms part of the Catalan Prelitoral Mountain Range, has a mid-altitude Mediterranean montane climate characterized by its great variability, with annual mean rainfall of 500–800 mm and annual mean temperature of 15 °C. The original forest cover is dominated evergreen holm oak (*Quercus ilex* L.), Aleppo pines (*Pinus halepensis* Mill.) and Spanish black pine (*Pinus nigra* subsp. *salzmannii* (Dunal) Franco), generally with an evergreen holm oak understory (Pintó and Panareda 1995). In August 2003, 4543 ha of the eastern part of this Natural Park (10% of its total surface area) and neighbouring areas were burnt by a wildfire (Fig. 1). Of the total area burnt, 3790 ha corresponded to areas of Aleppo pine with holm oak and kermes oak (*Quercus coccifera* L.). understorey. About 440 ha had already been burnt in previous years (335 ha in 1970 and 105 ha in 1994) (Fig. 1). In 2005 different forestry treatments were applied to the burnt area (Rollan and Real 2011; Santos et al. 2014), see the sampling design section for further details.

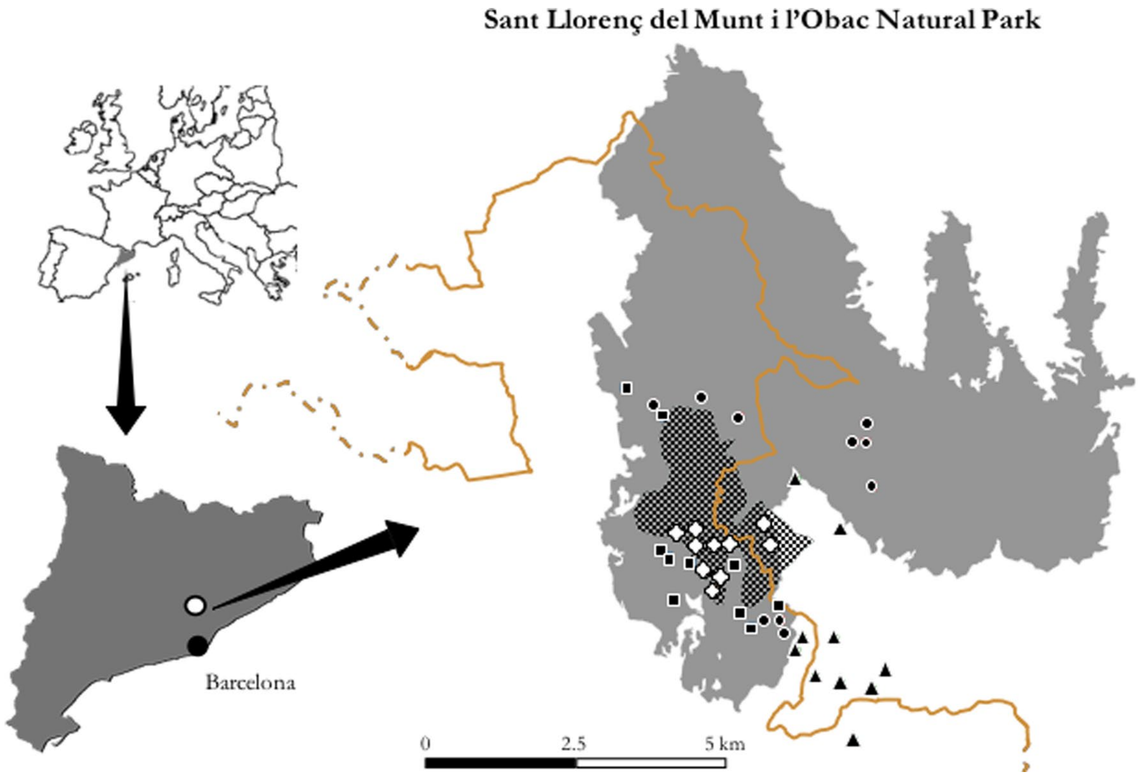

Fig. 1 Location of study area and distribution of sampling plots. Location of the Sant Llorenç del Munt i l'Obac Natural Park, with its border (orange line) in Catalonia (NE Iberian Peninsula), the 2003-burnt shape and size (grey), the historical (1970 and 1994) burnt areas (grated), and the forty 100×100 m plots, where black triangles correspond to unburnt forests, black circles to branches left on the ground, black squares to branches reduction, and white crosses to recurrent burnt areas (plots areas are out of scale). Burnt and protected perimeters was obtained from Sant Llorenç del Munt i l'Obac Natural Park managers (parcs.diba.cat/web/santllorenc)

Sampling design and field methods

Within the burnt area, 40 plots (100×100-m) were randomly established on gentle slopes at altitudes ranging from 440 to 655 m a.s.l. (Rollan and Real 2011). The plot surface area corresponded to the area commonly used by an individual European wild rabbit (Lombardi et al. 2007; Devillard et al. 2008). Four types of plots were established in accordance with the forest types and different post-fire treatments (Fig. 1): (A) unburnt forests ($n=10$) as control plots with pre-fire vegetation; (B) branches left on the ground in burnt forests ($n=10$), with clear cutting and the removal of burnt trees; (C) reduction of branches by manual removal in burnt forests ($n=10$), with clear-cutting, removal of burnt trees and subsequent manual removal of branches from the ground; (D) recurrent fires ($n=10$) corresponding to sites burnt twice, in 1970 or 1994 and in 2003, characterized by shrublands with high percentage of bare ground and little tree cover before the fires.

In order to estimate rabbit abundance, plots were sampled once a year in 2006, 2007, 2008, 2020 and 2021 in June and July, at the end of the breeding season, the moment of the year with the highest rabbit abundances (Cabezas and Moreno 2007; Catalán et al. 2008). Rabbit abundances in each plot were estimated by counting all the pellets noted within 2 m on either side of a 300-m transect (i.e. 1200 m^2) when walking winding at a speed of about 2 km/h and trying to sample all possible plot microhabitats (Rollan and Real 2011). The number of pellets per square metre was used as a variable of the relative abundance of rabbits per itinerary (Table 1) (Fernandez-de-Simon et al. 2011; Guerrero-Casado et al. 2020).

The assessment of vegetation cover regeneration over time depending on the treatment was measured using the Normalized Difference Vegetation Index (hereafter, NDVI) from Landsat (Loveland and Dwyer 2012) for all 40 sampled plots using Google Earth Engine software (Mutanga and Kumar 2019). The NDVI index is a remote-sensing method frequently used in estimates of plant productivity in ecosystems (Tucker 1979; Díaz-Delgado et al. 2002; Virtanen et al. 2010). We used the mean NDVI (Table 1) as a surrogate of primary productivity (hereafter, plant productivity), and the standard deviation as a surrogate of plot vegetation heterogeneity (hereafter, habitat heterogeneity) (Seto et al. 2004). Specifically, the NDVI variables were calculated between 1 March and 31 July every year after the fire (i.e.

Table 1 List of dependent and predictor variables used, their description and kind of variable (Dependent or Predictor)

Variable	Description
Rabbit abundance	Number of pellets per m^2 counted within 2 m on either side of 300 m itinerary of each plot
NDVI mean	Normalized Difference Vegetation Index (NDVI) mean of each plot. Variable used as plant productivity proxy
NDVI standard deviation	Normalized Difference Vegetation Index (NDVI) standard deviation of each plot. Variable used as habitat heterogeneity proxy
Treatment	Kind of treatment on each plot, where (A) correspond to unburnt plots; (B) to salvage logging plots with branches left on the ground; (C) to salvage logging plots with reduction of branches; (D) to plots with recurrent fires
Time since fire	Number of years elapsed since the fire (first spring = 1, and so on)
Time since fire category	Time since fire grouped in two categories: short-term (from 1 to 6) and long-term (from 12 years after fire)
Plot slope	Mean percentage of the inclination (in %) of each plot

from 2004 to 2021) on days with cloud cover equal to or less than 5%. These 5 months coincide with both the European wild rabbit breeding season and the mean persistence time of droppings in the environment during the dry season (Fernandez-de-Simon et al. 2011). The time since the fire was measured as the number of years that had elapsed since the fire (first spring = 1, and so forth) and was grouped into two categories: short-term (less than 6 years) or long-term (more than 18 years after fire). Finally, the slope was calculated as the mean percentage of the inclination (in %) of each plot (Table 1).

Statistical analyses

To understand the effect of the treatments on the recovery of the vegetation (plant productivity and habitat heterogeneity) and rabbit abundance, three complementary analyses were carried out. To detect the possible effects of long-term treatments on plant productivity (NDVI mean) and habitat heterogeneity (NDVI standard deviation), generalized additive mixed models (GAMM) with Gaussian error distribution were used with treatment, plot slope, time since fire (0–18 years), and the interaction between treatment and time as predictor variables (Table 1). The plot was included as a random factor to control possible site-based differences. Subsequently, to test the effect on rabbit abundance, GAMM were used with treatment, habitat heterogeneity, plant productivity (as smooth variables), plot slope and the time since fire category as predictor variables (Table 1). In this case, the data distribution was negative binomial because rabbit variance was greater than the mean (i.e. there was overdispersion) due to an excess of zeros (Martin et al. 2005); each plot and calendar year were included as random factors to control possible site-based differences and temporal pseudoreplication. GAMM is a powerful and flexible way of performing a regression analysis (Wood 2017) and consists of a generalized linear mixed models (GLMM) using smoothing splines fitted to the explanatory variables rather than the original values of the variables. Due to the duality between smooth and random effects, random effects may act as smooth terms in the model (Wood 2017).

We used a multi-model inference approach to select the most important variables in the GAMM. This approach uses all possible sub-models derived from a set of explanatory variables, which limits model selection bias and provides a relative measure of each predictor's importance (weight of evidence) (Millington and Perry 2011). All possible models were ranked according to their Akaike Information Criteria corrected for small samples (AICc) (Burnham and Anderson 2002) in a series of hierarchical steps. Then, we analysed the diagnostic plots of the fitted values, residuals and the fitted splines for each term of each model to assess their goodness of fit. Multicollinearity diagnostics were performed by quantifying generalized variance-inflation factors (GVIF) calculated for each fixed factor (Fox and Monette 1992), where large GVIF values (arbitrary threshold of ≤ 2.5 suggesting collinearity) were sequentially dropped from each subsequent analysis (Zuur et al. 2010). For each model, the AIC weight (AICω) was calculated (total AICω adds 1) (Wagenmakers and Farrell 2004). If there was no clear most-parsimonious model (one or more models showing an AIC difference of less than two from the best model), we proceeded to estimate the average final model of all these models (Burnham and Anderson 2002). To interpret the magnitude of each variable in the average final model, the relative importance of each variable (RVI) was weighted based on the sum of ωi for each variable (Supplementary Table S1). The RIV ranges from 0 to 1, so that the explanatory variable was considered robust if it had an RIV > 0.9; a moderate effect between 0.6 and 0.9; a weak effect between 0.5 and 0.6; and no effect below 0.5 (Kennedy et al. 2013; Chiaradia et al. 2016). To perform these analyses, we used R software (R Development Core Team 2017) with the *car* (Fox and Weisberg 2011), *gamm4* (Wood and Scheipl 2014), *lme4* (Bates et al. 2015), MuMIn (Bartoń 2016) and *ggplot2* (Wickham 2009) packages.

Results

Plant productivity and habitat heterogeneity

Both analysed plant components (plant productivity and habitat heterogeneity) showed positive relationships for the time since a fire (Table 2). This relationship with plant productivity consisted of immediate rapid plant growth in the first 5 years after a fire, followed by a constant but slow increase (Fig. 2). However, plant productivity exhibited a variety of regeneration patterns depending on the specific treatment and time (time-treatment interaction; Table 2). For example, the increase in productivity was more rapid in the plots with the branches left on the ground and manual removal of branch treatments than in the recurrent fire plots (Fig. 2 and Supplementary Fig. S1). Even so, after 18 years productivity after both these logging treatments exceeded the productivity recorded in the unburnt habitats (Supplementary Fig. S1). Habitat heterogeneity was also higher and was more rapidly attained in the branches left on the ground treatment; the manual removal branch treatment showed a continuous and consistent positive trend, while in recurrent fire areas practically no change occurred over the time since the fire (Supplementary Fig. S1).

European wild rabbit relative abundance

European wild rabbit relative abundance was affected by the time elapsed since the fire (Table 2). Although in the short-term rabbit abundances were high, they dramatically declined in the long-term (18 years after fire) (Fig. 3); nevertheless, this decline is closely related to the post-fire treatments. Branches left on the ground and recurrent fire treatments caused high short-term abundances (Fig. 3) and so led to extraordinary falls in rabbit abundances. On the other hand, in unburnt forests uniform but low rabbit abundances were maintained over time (Supplementary Fig. S2). Plant productivity was also closely related to the fall in relative rabbit abundance. This relationship with plant productivity showed that rabbit abundances increase smoothly as the habitat becomes more productive, but that when the NDVI value exceeds 0.4, rabbit abundances decline rapidly and steadily (Fig. 3).

Discussion

Long-term effects of salvage logging on plant productivity and habitat heterogeneity

There was an increase in plant productivity and habitat heterogeneity over time in the sampling plots after fires regardless of the post-fire treatment. Most plant species growing in ecosystems where fire is common have adaptive qualities that permit them to survive or regenerate and reproduce after fires (Pausas and Keeley 2014). However, our results show how plant regeneration is slightly slower in areas with recurrent fires than in burnt and logged areas, as other studies have shown, and only becomes evident several years—rather than immediately—after a fire (Díaz-Delgado et al. 2002; Eugenio and Lloret 2004). This fact may be a consequence

Table 2 Summary of the selected generalized additive mixed models (GAMM), on plant productivity (NDVI mean), habitat heterogeneity (NDVI standard deviation) and European wild rabbit relative abundance (expressed as the density of pellets per m^2 of transect) in Sant Llorenç del Munt i l'Obac burnt area

Fixed effects		Plant productivity			Habitat heterogeneity			Rabbit abundance		
		Coefficient ± SE	*P* value	RVI	Coefficient ± SE	*P* value	RVI	Coefficient ± SE	*P* value	RVI
Intercept		0.3±0.01	<0.001		0.05±0.005	<0.001		6.09±1.14	<0.001	
Time Since Fire		8.55*	<0.001	1.0	8.59*	<0.001	1.0	–2.16±0.61	<0.001	1.0
Unburnt		0.12±0.02	<0.001	1.0	0.005±0.006	0.41	1.0	–0.99±0.30	<0.001	1.0
Reduction of branches		0.02±0.02	0.27	1.0	0.008±0.006	0.23	1.0	–0.63±0.26	0.01	1.0
Recurrent fires		0.01±0.02	0.46	1.0	0.002±0.006	0.77	1.0	–0.16±0.24	0.51	1.0
Time treatment interaction	Unburnt	–0.007±0.0009	<0.001	1.0	–0.001±0.0002	< 0.001	1.0			
	Reduction of branches	–0.0006±0.0009	0.47	1.0	–0.0009±0.0002	< 0.001	1.0			
	Recurrent fires	–0.002±0.0009	0.02	1.0	–0.001±0.0002	< 0.001	1.0			
Plant productivity								1.0*	0.01	0.65
Slope		–0.0003±0.0006	0.67	0.28	–0.0001±0.0002	0.57	0.31	–0.02±0.01	0.09	0.58

The table shows the model coefficient, its standard error (±SE) and the associated *p* values. For smooth variables (*) we present the edf coefficient. If no model was clearly most parsimonious (one or more models show a difference in AIC less than 2 from the best model), we include the relative variable importance (RVI; the sum of the Akaike Information Criterion weights (AICω+) of the models) on the average final model. Intercept is the value of response variables into branches left on the ground treatment when all the covariates are = 0, while *p* value indicates whether it is significantly different from 0. Grey rows indicate that the variable was not used in the analysis

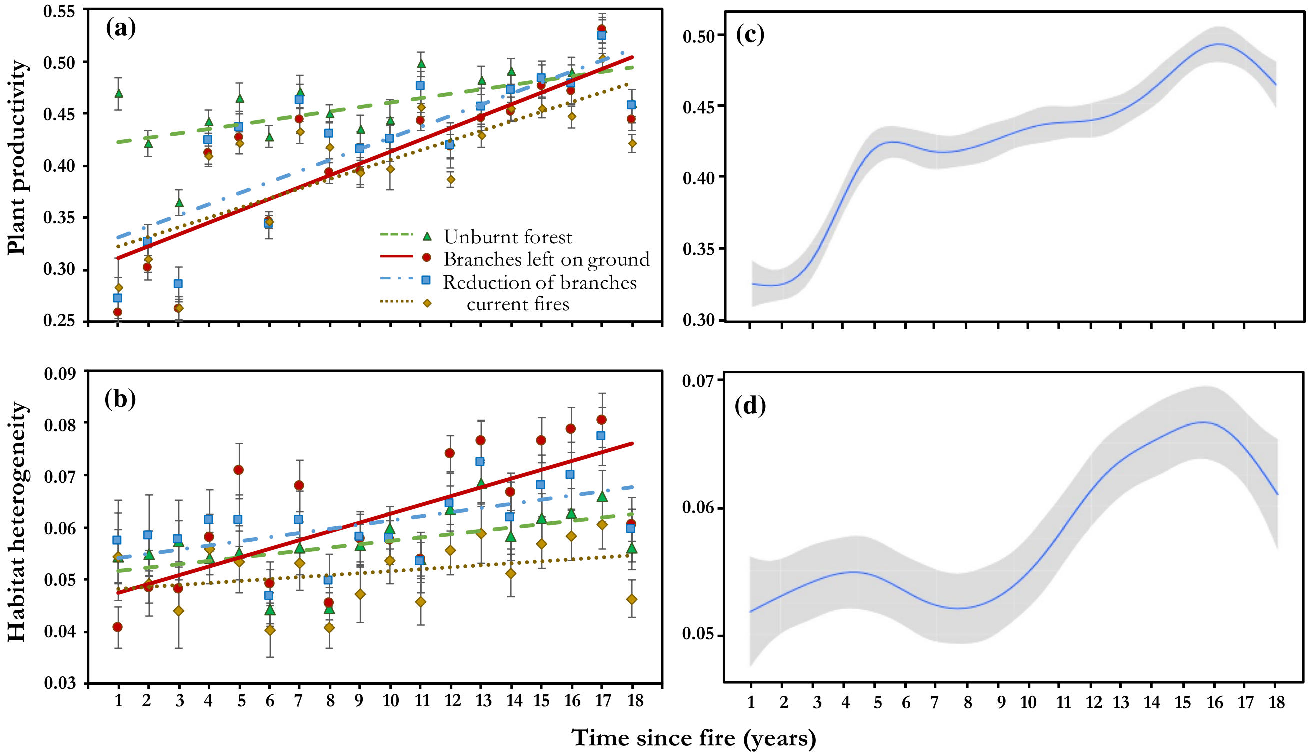

Fig. 2 Model predictions of plant production and habitat heterogeneity over time. Responses of **a** plant productivity (NDVI mean) and **b** habitat heterogeneity (NDVI standard deviation) to time since fire and each treatment (Unburnt forest, branches left on the ground, reduction of branches and recurrent fires). Marginal effects (i.e. measure the instantaneous rate of change) of the time since fire on the **c** plant productivity and **d** habitat heterogeneity. Trend line and standard error shown were obtained from model estimates

of the poorer capacity of the soil to recover its pre-fire characteristics and nutrient availability, and erosion (Kishchuk et al. 2015), although these characteristics are geological-substrate dependent. In this sense, resprouting species such as kermes oak may decrease in stem, total biomass and net primary production after recurrent fires (Delitti et al. 2005). Likewise, long-lived seeder species such as Aleppo pine may be sensitive to recurrent fires that limit seed storage (Trabaud 2000; Pausas and Keeley 2014).

We detected greater plant productivity in burnt than in unburnt areas 18 years after the fire, which probably reflects the long-term effects found in other regions whereby both the number of plant species (Georgiev et al. 2021) and productivity (Kishchuk et al. 2015) were higher in areas that had been salvage logged. This fact may also be related to plant regeneration strategies (Pausas and Keeley 2014). Although several studies have shown that the logging and hauling of burnt trees may hamper the regeneration of plant communities (Beschta et al. 2004), seedling survival is higher in the areas where logs and branches are left on the ground, due to the greater the protection from herbivory and erosion they provide, and the better microclimatic conditions created by the piles of dead wood (Rost et al. 2012a; Marzano et al. 2013). In our study, we found no differences in plant production between the branches left on the ground and the manual removal branch treatments.

Trends in rabbit abundance related to time, treatment type and plant regeneration

Rabbits live in a wide variety of habitats, from agricultural landscapes to woodlands. However, they prefer open areas of grassland, farmland and Mediterranean shrubland (Virgós et al. 2003). The rapid response after fire by rabbits is attributable to the great diversity of herbaceous plants that appears immediately after a fire and better access at ground level (Rollan and Real 2011). Communities with an important herbaceous layer grow rapidly, even in recurrent fire areas (Vilà et al. 2001), and attract rabbits to logged and recurrent burnt areas (personal observation). Here, we found that the time since a fire, together with the treatment type and plant productivity, were determinant in the evolution of rabbit abundances in the study area over time. These results imply that the time since a fire is a useful surrogate for predicting the response in rabbit abundances to fire and salvage logging. It is important to note that, although there are greater rabbit abundances in areas where branches are left on the ground, the rate of change found by Rollan and

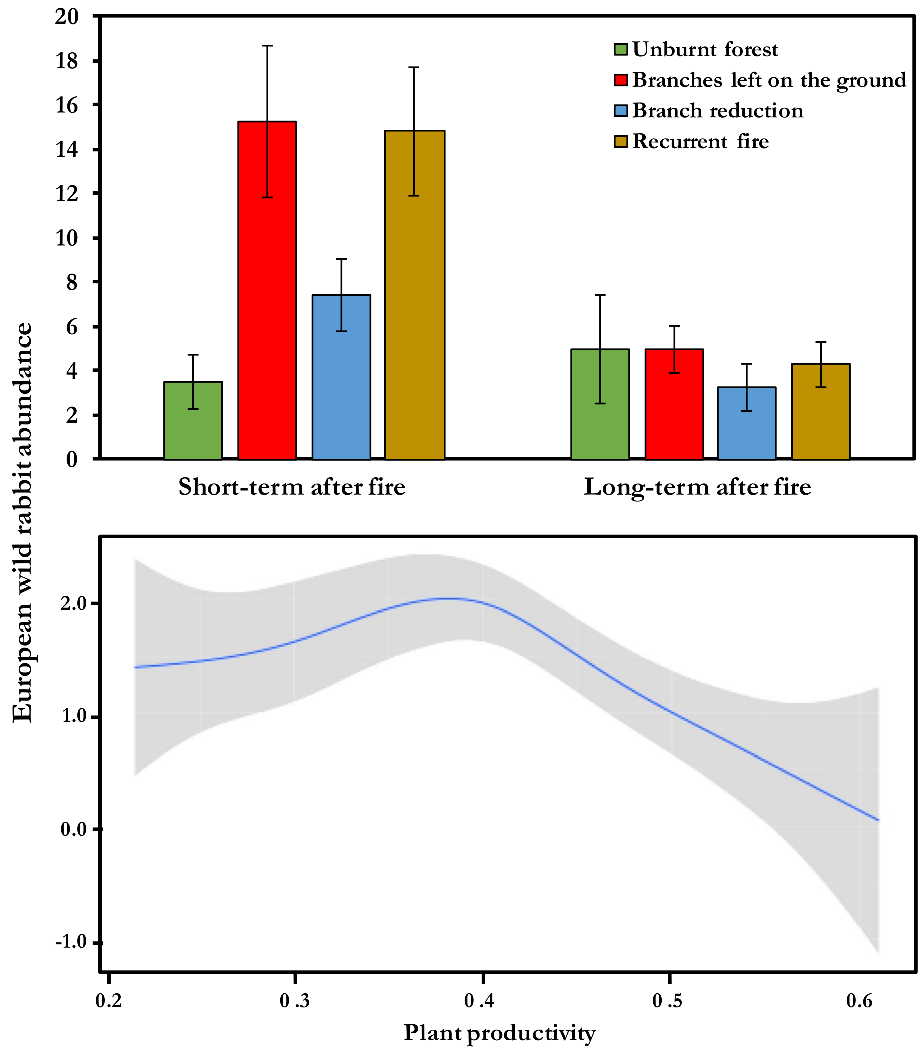

Fig. 3 Model predictions of European wild rabbit abundance after fire and logging. Effects of the time since fire (short and long term) and treatment (Unburnt forest, branches left on the ground, branch reduction and recurrent fires) interaction on **a** European wild rabbit relative abundance (expressed as the density of pellets per m2 of transect). Marginal effects (measure the instantaneous rate of change) on **b** rabbit relative abundance by plant productivity (NDVI mean). Trend line and standard error shown were obtained from model estimates

Real (2011) were higher in areas with the manual removal branch treatment. However, the long-term decrease in and even disappearance of rabbits from burnt plots where they were abundant in the aftermath of a fire (Rollan and Real 2011) show how rapid vegetation growth affects rabbit abundance over time. In the long-term, although logged areas are heterogeneous, the main factors influencing the maintenance of rabbit populations may be the open microhabitats present between large shrubs, the lack of food availability (Rollan and Real 2011) or an adequate habitat structure (shrub strata) allowing for free movement (Beja et al. 2007; Ferreira and Alves 2009). This also occurs in other species with similar requirements (Pons and Prodon 1996; Herrando et al. 2002, 2003; Puig-Gironès et al. 2017). The low abundances found in the recurrent fire plots were unexpected and we believe that this is due to the more than 11 years that had elapsed between fires. This fire recurrence may not allow for the presence of an adequate habitat with the necessary resources (shelter and food) for rabbits. Furthermore, other stochastic factors including viruses and their new variants (Monterroso et al. 2016) or the fact that certain areas are isolated in the middle of unsuitable habitats for rabbits may affect rabbit abundances in fire recurrence areas (Calvete et al. 2004, 2006).

Rabbit populations declined once plant production (NDVI mean) reached a value of about 0.4. Before reaching this figure, rabbit abundances increased slightly; however, once this limit was surpassed, rabbit abundances decreased rapidly. This value was attained between the fifth and sixth year after fire in all treatments (except the unburned forest, where abundances remained constantly low), coinciding with the moment in which the increase in post-fire plant productivity stabilizes. This temporary decline after 5 or 6 years in open habitat species has also been reported by Jacquet and Prodon (2009). At regional scale, fire history and floristic composition will determine the recovery of each vegetation layer after a fire. In addition, abiotic factors such as fire severity, precipitation, altitude and topography will also have an important effect on the recovery (Díaz-Delgado et al. 2002; Puig-Gironès et al. 2017).

Management implications and recommendations

In recent years, wildfires have become more frequent around the world due to human activity and changes in land use, climate and atmospheric conditions (Pausas and Keeley 2009; Kelly et al. 2020; Moreira et al. 2020). However, fires may still generate open areas that can benefit populations of endangered species (Prodon 1994; Brotons et al. 2008; Rost et al. 2012b; Kelly and Brotons 2017). Indeed, some post-fire treatments may be favourable to rabbit populations and may help increase the conservation value of burnt areas. In the short-term, we recommend removing branches from the ground to favour open-habitat species like the rabbit, whose populations had a short-term greater rate of change after this treatment, as Rollan and Real (2011) found. This recommendation is aimed at promoting the abundance of open-habitat species (Brown 2009; Santos and Poquet 2010; Puig-Gironès et al. 2022), without prejudice to the rest of biodiversity. Therefore, we also suggest that the removed branches may be piled up to act as refuges for other species (Rost et al. 2012a; Puig-Gironès et al. 2020).

In the long term, to preserve endangered open-habitat species, prescribed fires and livestock are recommended as a means of keeping vegetation in early succession stages and maintaining open shrublands—a largely forgotten habitat in ecosystem conservation—that are favourable for rabbit populations (Virgós et al. 2003). However, we recommend maintain the habitat heterogeneity with a mixture of open and forest habitats to not negative affect other forestry-specialist species. We observed that rabbit populations began to decline when the NDVI reaches a value of about 0.4, around 5 or 6 years after a fire, coinciding with the moment in which post-fire plant productivity stabilizes its initial increase so coinciding with a maximum of vegetation coverage. Thus, we believe that this is the correct time to manage burnt areas in order to favour the persistence of open-habitat species. These actions will also help to reduce the environmental biomass, thereby mitigating the possibility of future severe wildfires. These permanent open-habitat areas should be connected to prevent rabbit populations from becoming isolated given that, if populations are disconnected from each other, there is a risk that a disease could locally extinguish a whole population (Calvete et al. 2006) as the vacant area will never be recolonized by a neighbouring population.

Integrated fire management can help generating a landscape matrix and maintains vegetation in early successional stages (Pons et al. 2003; Virgós et al. 2003) with patches of different fire ages, to host a rich open-habitat ecological community (Rainsford et al. 2022). However, in the case of prescribed burns, may not be associated completely with wildfire effects because are generally of lower severity, while wildfires in the Mediterranean area occur in summer with high severity. In these sense, recent studies show associations between open-habitat species and high severity fires (Puig-Gironès et al. 2022). On the other hand, prescribed fires may increase rabbit abundance but not sufficient to achieve abundances to sustain specialist predator populations (Ferreira et al. 2014). Therefore, this can be a challenge to the effective use of burning to create an appropriate mix of post-fire successional stages across the landscape and increase open-habitat species, as rabbit abundances, and conservation value. Finally, it would also be interesting to integrate the livestock in the matrix to keep the pastures green and free of shrub competition.

The European wild rabbit is a keystone species in Iberian Mediterranean ecosystems since it is the main prey item of many predators (some endangered) and it is determinant in many important ecological processes. Consequently, fires and subsequent appropriate forest management are the key for improving rabbit numbers, which in turn can have positive socio-economic consequences (hunting and farms) and strengthen their predator populations. However, we are fully aware that the conservation of the European rabbit—as is the case of other open-habitat species—depends not only on post-fire forest management practices but also on other, wide-ranging socio-economic policies. We hope that this study will provide a comprehensive understanding of the short- and long-term effects of post-fire salvage logging on European wild rabbit conservation.

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Author contribution ÀR, AF and RP-G collected the data. ÀR, RP-G and JR planned the sampling design and methodology. RP-G designed the research layout; carried out the statistical analyses and wrote the manuscript with support from ÀR and JR. All authors discussed the results and contributed to the final manuscript.

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