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Burn severity and land-use legacy influence bird abundance in the Atlantic-Mediterranean biogeographic transition

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ABSTRACT

Fire regimes in mountain landscapes of southern Europe have been shifting from their baselines due to rural abandonment and fire exclusion policies. Understanding the effects of fire on biodiversity is paramount to implement adequate management. Herein, we evaluated the relative role of burn severity and heterogeneity on bird abundance in an abandoned mountain range located in the biogeographic transition between the Eurosiberian and Mediterranean region (the Natural Park 'Baixa Limia–Serra do Xurés'). We surveyed the bird community in 206 census plots distributed across the Natural Park, both inside and outside areas affected by wildfires over the last 11 years (from 2010 to 2020). We used satellite images of Sentinel 2 and Landsat missions to quantify the burn severity and heterogeneity of each fire within each surveyed plot. We also accounted for the past land use (forestry or agropastoral use) by using a land cover information for year 2010 derived from satellite image classification. We recorded 1735 contacts from 28 bird species. Our models, fitted by using GLMs with Poisson error distribution (pseudo-$R^2_{average}$ of 0.22 ± 0.13), showed that up to 71% of the modeled species were linearly correlated with at least one attribute of the fire regime. The spatiotemporal variation in burnt area and severity were relevant factors for explaining the local abundance of our target species (39% of the species; Akaike weights >0.75). We also found a quadratic effect of at least one fire regime attribute on bird abundance for 60% of the modeled species. The past land use, and its legacy after 10 years, was critical to understand the role of fire (Akaike weights >0.75). Our findings confirm the importance of incorporating remotely sensed indicators of burn severity into the toolkit of decision makers to accurately anticipate the response of birds to fire management.

1. Introduction

Fire is a major ecological driver of biodiversity in Mediterranean-type ecosystems, widely recognized by fire ecology as a dynamic force with evolutionary implications (He et al., 2019; Kelly et al., 2020; McLauchlan et al., 2020). It is acknowledged that fire regimes, acting as

selective forces, have ecological effects at various levels, impacting species traits, populations, communities, and ecosystems. The effects of fire on biodiversity have been studied across different taxa (plants, vertebrates and invertebrates; see e.g., Clavero et al., 2011; Mateos et al., 2011; Pausas and Ribeiro, 2017; Santos et al., 2022), considering different species traits (McLauchlan et al., 2020; Pausas, 2015), pre-fire

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conditions (Jones et al., 2016; Taillie et al., 2018), and biogeographic contexts (Farnsworth et al., 2014; Martínez et al., 2022; Parr and Andersen, 2006; Tingley et al., 2016). However, land managers are facing new challenges due to novel fire regimes, land-use and climate change (Kelly et al., 2020; Regos et al., 2016a). In southern Europe, rural landscapes are complex socioecological systems, shaped by traditional agricultural and pastoral activities since millennia. Fire regimes are shifting from their baselines due to cross-scale interactions between global climate change, regional land-use and fire suppression policies (Batllori et al., 2013; Moreira et al., 2020). Over the last decades, these extensive agroforestry activities have been gradually lost, affecting biodiversity patterns and fire (Lehikoinen et al., 2019; Wretenberg et al., 2007; Zakkak et al., 2014). In addition, the traditional use of fire by rural communities – commonly used to open spaces for pastures – has being eradicated as tool to manage landscapes, which has led to profound changes in fire ignition and fuel load patterns (Loepfe et al., 2010; Uyttewaal et al., 2023). The lack of a deep knowledge of the possible and complex responses of biodiversity to altered fire regimes undermines the capacity of managers to decide when, where and how to implement fire management. Besides, the impacts of fire on biodiversity is often evaluated through *proxies* for patch-mosaic configurations and post-fire vegetation regeneration (e.g., through 'burnt area' or 'time since fire') (Chalmandrier et al., 2013; Taillie et al., 2018; Watson et al., 2012). Despite being a critical descriptor of fire regime, burn severity is an aspect not easily accessible for ecologists or land managers, being an under-studied issue of the fire–biodiversity relationships (see meta-analysis in Fontaine and Kennedy, 2012).

Biodiversity patterns are largely influenced by past land uses (Foley et al., 2005; Herrando et al., 2016). For instance, forest birds are benefited from vegetation encroachment and forest spread (Gil-Tena et al., 2009; Regos et al., 2016a, 2016b), being the species more dependent on open habitats (such as grasslands and farmlands) the most negatively affected by agricultural abandonment (Scozzafava and De Sanctis, 2006; Wretenberg et al., 2007; Zakkak et al., 2014). In these abandoned landscapes, wildfires offer a window opportunity for early successional habitat species (Brotons et al., 2005; Campos et al., 2021; Regos et al., 2015a) —an adaptative response that strongly depends on burn severity and post-fire vegetation recovery (Lindenmayer et al., 2014; Puig-Gironès et al., 2022; Taillie et al., 2018). In areas with large-scale land-use changes, legacies from previous land-use can persist and affect post-fire vegetation dynamics (Puerta-Piñero et al., 2012). In fact, past land use was found to be even more important than propagule source distance or pine tree density in explaining levels of native forest regeneration in Mediterranean forests (Navarro-González et al., 2013). Historical land-use change and fire suppression were predicted to drive regional bird distributions in directions opposite to those expected from climatic trends (De Cáceres et al., 2013). Thereby, understanding the role of fire on biodiversity in these complex socioecological systems (driven by altered fire regimes and land abandonment processes) is paramount for implementing adequate management —especially for endangered species in protected areas (see e.g. Maillard et al., 2022; Pérez-Granados et al., 2013; Regos et al., 2016b).

This study assesses the effect of wildfires on bird abundance in the Natural Park 'Baixa Limia–Serra do Xurés' (NW Iberia), a mountain range located in the biogeographic transition between the Eurosiberian and Mediterranean region, strongly affected by rural abandonment and human-caused fires (Regos et al., 2016b). Considering the high fire frequency and rapid post-fire vegetation recoveries in the region, we expect that wildfires had largely influenced local bird abundance. In particular, we evaluated the relative role of burn severity and heterogeneity on bird abundance while accounting for legacy factors such as previous land uses and past fires [see e.g. (Puig-Gironès et al., 2022; Watson et al., 2012; Zozaya et al., 2010)]. To assess the role of these factors on bird abundance, we surveyed local bird community in 206 census plots distributed across the Natural Park, both inside and outside areas affected by wildfires over the last 11 years (from 2010 to 2020).

We used satellite images of Sentinel 2 and Landsat missions (freely available from European Space Agency and NASA, respectively) to measure the burn severity and heterogeneity of each fire that took place within each surveyed plot. We also accounted for the past land use (forestry or agropastoral use) by using land cover information for year 2010 derived from image classification of Landsat satellite.

2. Materials and methods

2.1. Study area

This study was carried out in the Natural Park 'Baixa Limia-Serra do Xurés' (29,345 ha), a mountain rural area located in the south-west of Galicia (NW Spain, 42°–8°; Fig. 1), included in the Transboundary Biosphere Reserve 'Gerês-Xurés' (Macedo et al., 2009). The elevation ranges from 323 to 1529 m a.s.l. with an average slope of 13°. The region is located at the crossroads of the Mediterranean and Eurosiberian biogeographic zones, in the vicinity of the Atlantic coast. Its climate can be described as a temperate oceanic sub-Mediterranean regime. In June, the hottest month, the average maximum temperature reaches 22.8 °C, while the coldest month, January, experiences an average minimum temperature of 0.29 °C. The region receives an annual average rainfall of 1223 mm (Martínez-Cortizas and Pérez-Alberti, 1999). The landscape in the study area is dominated by shrubs (broom, gorse and heath, c.a. 32% of the study area) and sparsely vegetated areas (rocky areas with poor soils and little vegetation, 25%), maintained by fire and extensive agropastoral activities; followed by a variety of fragmented forests, such as deciduous woodlands (mostly represented by *Quercus robur* and *Q. pyrenaica*; 18%) and coniferous plantations (dominated by *Pinus sylvestris* and *P. pinaster*; 11%) (Regos et al., 2015b). The study area has been subjected to land abandonment processes (i.e. vegetation encroachment and forest spread) since the second part of the last century due to rural exodus (Regos et al., 2015b).

The Natural park 'Baixa Limia-Serra do Xurés' is included in the Natura 2000 network, since it holds high levels of biodiversity and serves as refuge for several emblematic species of conservation concern such as Golden eagle (*Aquila chrysaetos*), Eagle owl (*Bubo bubo*), Red-backed Shrike (*Lanius collurio*), Skylark (*Alauda arvensis*) or Dartford warbler (*Curruca undata*), among others; being designated as Special Protection Area (Directive, 2009/147/CE) (Domínguez et al., 2005, 2012).

The study area is classified within the intermediate-cool-small pyrome (characterized by intermediate fire return but fairly small fires, see Archibald et al., 2013). The study area exhibits a fire regime primarily characterized by numerous small-to medium-sized fires (Pais et al., 2020). The majority of these fires, accounting for 87%, are attributed to human activity, specifically classified as arson. Among the land covers affected by fire in the Natural Park from 2000 to 2010, sparsely vegetated areas and closed shrubland were the most impacted, comprising 49% and 15% respectively. Additionally, pine plantations and oak woodlands were affected to a lesser extent, accounting for 8.8% and 8.7% respectively (Regos et al., 2015b). The speed of initial post-fire recovery is related to differences in fire–response traits of vegetation and to climatic conditions immediately following fire. The mid-term recovery is mainly influenced by fire traits and post-fire climatic conditions. However, the long-term recovery is more influenced by burn severity than by vegetation type and structure or by post-fire climatic conditions (Torres et al., 2018).

2.2. Bird sampling design

We surveyed the local abundance of birds breeding in the Natural Park by using a standard methodology which consisted of 206 point counts of 5 min duration with unlimited distance (Bibby et al., 1992; Gregory et al., 2004). The censuses were undertaken during the breeding season (from mid-May to mid-July) of 2021. The censuses were carried
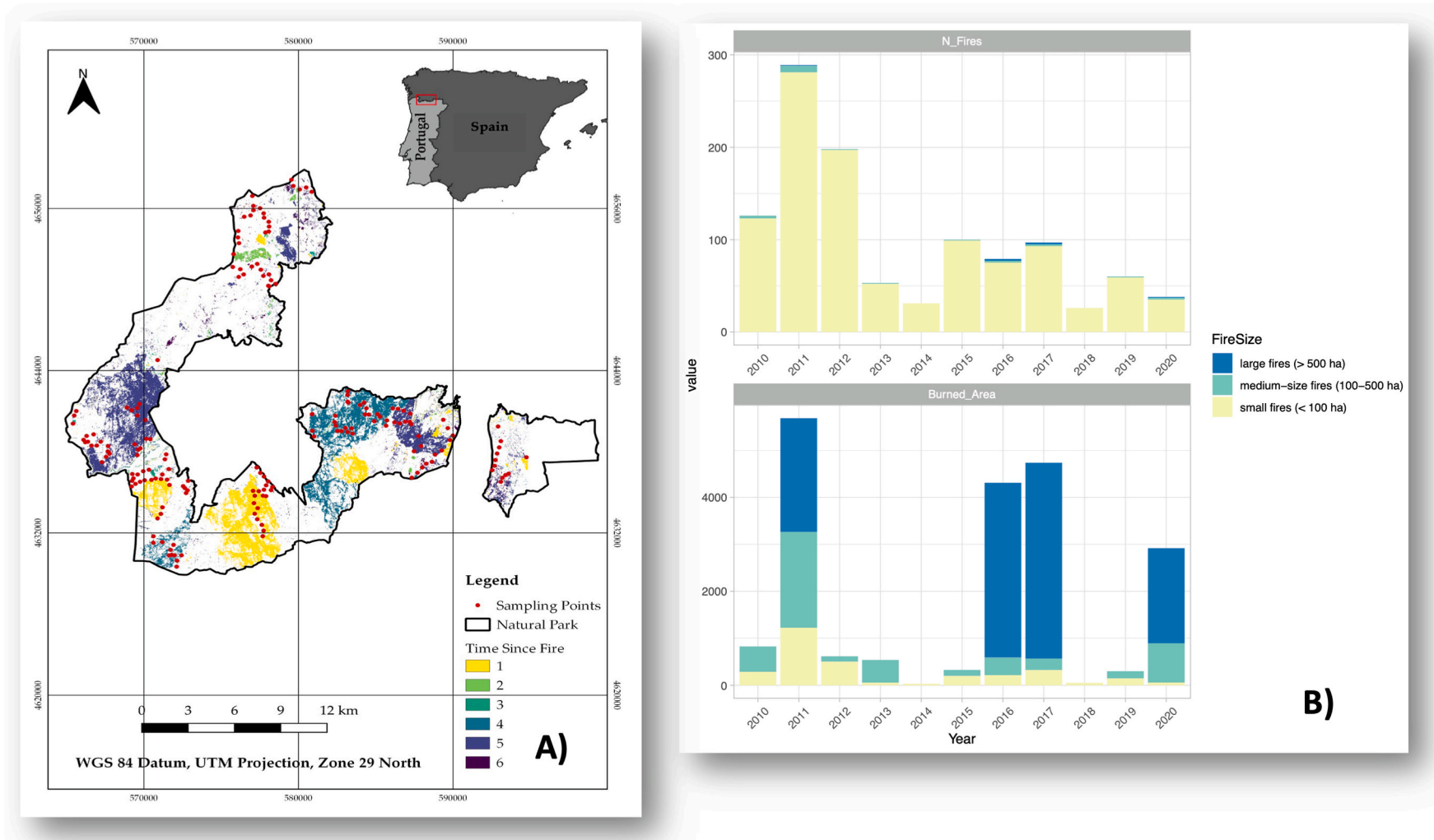
Fig. 1. Location of the Natural Park 'Baixa Limia-Serra do Xurés' and 'Time Since Fire' for the period 2010–2020. Red dots represent the point counts used to estimate bird density at species level (**A**). Number of fires and burned area (in hectares) classified by fire size (**B**).

out during the 4 h after sunrise (peak vocal activity) and under uniform weather conditions (days without marked rainfall or wind) to avoid possible detection biases caused by the time of survey, wind speed or cloud cover (Gregory et al., 2004). We considered a 100-m buffer from the central point of each sampling unit since most bird songs can be effectively detected and accurately identified within this range (Bibby et al., 1992; Gregory et al., 2004). Moreover, it enables a reliable characterization of the average home range of the targeted bird species (see e.g., Regos et al., 2016). To ensure the accuracy of the analysis, certain species were excluded from consideration due to limitations associated with this census method. Specifically, raptors and crepuscular species were not included, as this method is not optimal for estimating their abundance (Bibby et al., 1992). Similarly, migrants and rare species were intentionally excluded to maintain focus on the more reliably surveyed species.

The survey design involved the strategic selection of census plots to ensure comprehensive coverage of all land-cover types within each 10-km square of the study area (Fig. 1). This approach facilitated standardized and intensive surveys, enabling the capture of a wide range of environmental conditions in terms of burn severity and time since the fire event (see Fig. 1). To prevent any issues of pseudo-replication and overlapping data, a minimum distance of 250 m was maintained between census plots. Additionally, the analysis excluded the European Green Woodpecker (*Picus viridis*) due to its distinctive song, which can be easily detected over long distances exceeding the 250 m threshold.

2.3. Fire regime

We created a set of fire-related variables to characterize the fire regime. These fire-related variables were based on burn severity indices derived from satellite imagery and the official database of fire perimeters of the Galician Government (Xunta de Galicia). For each year between 2010 and 2020, we used a pair of satellite images, one before (April–July) and one after (September–November) the fire season. To do so, we used the best available information for each year from the United States Geological Survey (available at https://earth.explorer.usgs.gov/): Landsat 5 imagery for years 2010 and 2011, Landsat 7 for year 2012, since Landsat 5 imagery was not useful due to high cloudiness. Since its launch in 2013, we shifted to Landsat 8 data, and finally to Sentinel 2 data from 2015 onwards (Table 1).All downloaded images were L1T (a processing level that includes a geometric correction performed with ground control points (GCP) and the use of a digital elevation model) and were re-projected to the UTM coordinate system (WGS 84 datum, UTM projection, Zone 29 North). To ensure consistency and accuracy, we employed a radiometric correction method on all images. The widely used 'Dark Object Subtraction' methodology (available in the R-package 'RStoolbox') was applied. This methodology assumes that the radiometric minimum within the image corresponds to pixels entirely covered by shadow or underwater (Chavez, 1996). By considering the reflectance values of these pixels solely as a result of atmospheric effects, the method performs a correction across the entire image, converting the values from top-of-atmosphere (TOA) reflectance to surface reflectance. This correction accounts for atmospheric influences and enhances the reliability of the data.

For each of these years, we calculated the Normalized Burn Ratio (NBR), which is the normalized ratio between near-infrared (NIR) and

short-wave infrared (SWIR) radiation (Eq. (1)). NIR and SWIR bands of satellite sensors respond in opposite ways to burned vegetation, allowing to identify burned areas (Key and Benson, 2006).

$$NBR = (NIR - SWIR) \ / \ (NIR + SWIR) \tag{1}$$

To obtain a quantitative measure of change, we calculated the dNBR for each year by subtracting the NBR of the post-fire season image from the NBR of the pre-fire season image (Eq. (2)). Finally, dNBR values were used as an estimate for fire severity of each fire season (see Fig. 2).

$$dNBR = NBR_{prefire} - NBR_{postfire} \tag{2}$$

We computed several metrics within the buffer of 100 m around each point count to characterize the burn severity at census-plot level for each year (i.e., spatial component): the average, minimum, and maximum values within the buffer. The inter-quartile range (i.e., the difference between the 5% and 95% quartile values) and the standard deviation were calculated to measure the heterogeneity in burn severity within the census plot (i.e., spatial variation; *sensu* Kelly et al., 2016) (Table S1). In addition, we estimated the percentage of burnt area in each census plot from the fire scars, available in vectorial format from official data of the Galicia Government (Xunta de Galicia) for the 2010–2020 period. Vectorial data was rasterized at the same spatial resolution as satellite images (30 m). From the raster maps of annual burnt area and burn severity (Fig. S1), we estimated the average value along the 11-year period in order to account for post-fire vegetation recovery and subsequent fire events (i.e., temporal component) (Fig. 2; Table S1). To characterize other important attributes of fire regime over that period, we calculated fire recurrence (i.e., times each plot was affected by a fire event) and time since a fire event took place at each plot (hereafter, TSF) (Table S2).

2.4. Land-use legacy

The inclusion of LULC covariates into the models allows assessing bird abundance variation across sites in relation to fire metrics, thus avoiding possible spurious correlations with other habitat characteristics. Satellite images were captured by Landsat 5 TM (Thematic Mapper) for year 2010 (July 30 and October 18). To generate the Land Use and Land Cover (LULC) map for each image, we employed various supervised classification methods. Within our study site, we identified six main LULC classes: (i) *water bodies* encompassing rivers, lakes, and dams; (ii) *deciduous forests*, primarily oak woodlands; (iii) *evergreen forests*, mainly consisting of pine plantations; (iv) *shrublands* dominated by heath and gorse species; (v) *croplands and grasslands*; and (vi) *sparsely vegetated areas*, typically characterized by shrubs and rocky terrain found at higher elevations. Utilizing two images per year enhanced the spectral separability among the LULC classes, considering the differences in vegetation phenology, thus improving classification accuracy (see Cánibe et al., 2022 for detailed information).

For image supervised classification, we employed four different algorithms: 'Random Forest', 'Least Squared Support Vector Machines with Radial Basis Function Kernel' from the 'Support Vector Machines' family, 'Monotone Multi-Layer Perceptron Neural Network' from the artificial neural network family, and 'adaptive boosting' from the gradient boosting models family. These algorithms were accessed through the 'superClass' function of the 'RStoolbox' R package, (Leutner and Horning, 2017). To assess the accuracy of each algorithm, confusion matrices were used, and sensitivity and positive predictive power were calculated. Ultimately, we selected the LULC map derived from the 'Random Forest' classifier due to its high accuracy (overall accuracy of 0.95; Kappa coefficient of 0.94) (see Cánibe et al., 2022). Finally, we reclassified the six LULC classes into three main land cover/use types of the study area (forest, cropland and grassland, and shrubland), and estimated the percentage of occupancy of each class to account for past land-use effects on bird abundance.

Table 1
Satellite sensors used for each year, spatial resolution, and the corresponding NIR and SWIR bands used to calculate the Normalized Burn Ratio (NBR).

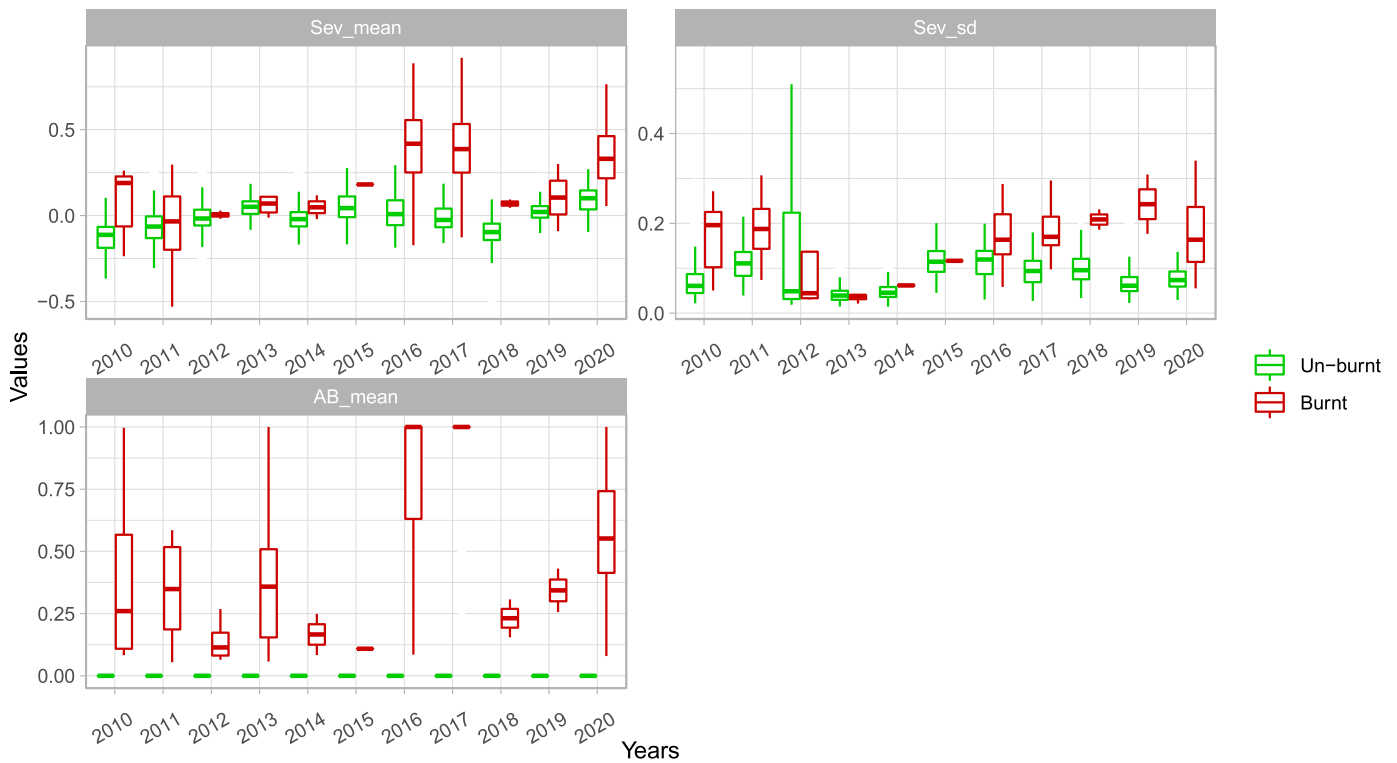| Satellite	Resolution	Years	NIR band	SWIR band
Landsat-5 TM	30 m	2010–2011	B4	B7
Landsat-7 ETM+	30 m	2012	B4	B7
Landsat-8 OLI/TIRS	30 m	2013–2014	B5	B7
Sentinel-2	10 m	2015–2021	B8	B12

Fig. 2. Inter-annual variability ('temporal component') of the percentage of area affected by fire (re-scaled to 0–1 range, 'AB_mean'); and mean ('Sev_mean') and standard deviation of burn severity ('Sev_sd') at plot level (estimated from the annual dNBR values, ranging from −1 to 1). Boxplots show the variability ('spatial component') across the 206 census plots affected ('Burnt') and not affected ('Un-burnt') by fire over the time period (2010–2020). For all boxplots, lower and upper whiskers encompass the 95% interval, lower and upper hinges indicate the first and third quartiles, and the central black line indicates the median value.

2.5. Effects of fire on bird abundance

To assess the effects of fire regime on the abundance of each target species (N = 28; Table 2), we fitted generalized linear models (hereafter:

Table 2
List of modeled species and total number of counts across the census plot carried out in the study area in 2021.

Common Name	Scientific Name	Acronyms	Counts
Common Wood pigeon	*Columba palumbus*	C_palum	20
Common swift	*Apus apus*	Apus	61
Great spotted woodpecker	*Dendrocopos major*	D_major	12
woodlark	*Lullula arborea*	L_arbor	24
Skylark	*Alauda arvensis*	A_rvnss	65
Eurasian wren	*Troglodytes troglodytes*	Trogl	153
European robin	*Erithacus rubecula*	E_rubec	72
European stonechat	*Saxicola rubicola*	S_torq	132
Common blackbird	*Turdus merula*	T_merul	130
Song thrush	*Turdus philomelos*	T_philm	27
Mistle thrush	*Turdus viscivorus*	T_viscv	49
Dartford warbler	*Curruca undata*	S_undat	186
Common whitethroat	*Sylvia communis*	S_comm	26
Eurasian blackcap	*Sylvia atricapilla*	S_atrcp	62
Western Bonelli's warbler	*Phylloscopus bonelli*	P_bonll	36
Iberian chiffchaff	*Phylloscopus ibericus*	P_ibrcs	28
Common firecrest	*Regulus ignicapilla*	R_igncp	56
Coal tit	*Periparus ater*	P_ater	104
Blue tit	*Cyanistes caeruleus*	P_caerl	17
Great tit	*Parus major*	P_major	11
Red-backed shrike	*Lanus collurio*	L_coll	18
Eurasian jay	*Garrulus glandarius*	G_gland	22
Carrion crow	*Corvus corone*	C_coron	34
Common chaffinch	*Fringilla coelebs*	F_colbs	157
European serin	*Serinus serinus*	Serinus	49
Greenfinch	*Carduelis chloris*	C_chlrs	15
Common Linnet	*Carduelis cannabina*	C_cannb	121
Rock bunting	*Emberiza cia*	E_cia	48

GLMs; Burnham and Anderson, 2002). Multicollinearity can inflate the standard errors of regression coefficients, making it difficult to assess the statistical significance of individual explanatory variables. Multicollinearity can also reduce the predictive power of the model, as the intercorrelation between variables can mask the true relationships between explanatory and the response variable (Dormann et al., 2013). To overcome these potential problems, we calculated the variance inflation factor (VIF) with the 'usdm' R package (Naimi, 2017) to estimate how much a regression coefficient's variance is inflated by multicollinearity. The variables with VIF value greater than 3 were excluded from further analyses (Dormann et al., 2013). Therefore, we finally retained: (1) percentage of forest, (2) cropland and grassland, and (3) burned area; (4) TSF, and (5) mean and (6) standard deviation of burn severity, as exploratory variables from the initial set of 18 fire-related and land cover variables (see complete datasets in Tables S1 and S2). Since the response variable (i.e., relative bird abundance index) represents counts of individuals, our models were fitted by using GLMs with Poisson error distribution. The good-of-fitness of each model was measured by the pseudo-R^2 (R^2 Nagelkerke). We also measured the dispersion parameter (deviance/degrees of freedom), which should approximate to 1.0, to ensure no overdispersion within the models. The analyses were performed with the 'MASS' R package. We applied a multimodel inference approach to run the GLMs for all (valid) combinations of explanatory variables (with the dredge function available in the 'MuMIn' R package; Barton, 2016) (Burnham and Anderson, 2002). Models were built assuming linear and non-linear (i.e., second-order polynomial) relationships between the response and exploratory variables. For each model, we calculated the Akaike information criterion (AIC) and Δ_I, where $\Delta_I = AIC_i - AIC_{minimum}$. All the models with $\Delta_I < 4$ were considered to have support. The importance of each variable was obtained by adding the Akaike weights (W_i) to the models in which such variable was present (Burnham and Anderson, 2002).

3. Results

The bird dataset included 2041 records of 61 species, from which only a third had enough records to be modeled (i.e., species with presence in more than 5% of the 206 census plots) (number of species = 28; total contacts = 1735; see Table 2, and Table S3 in Supp. Mat.). The bird abundance models yielded moderate explanatory capacity (i.e., the proportion of the variation in the dependent variable that is predictable from the independent variables) for most of our target species (pseudo-$R^2_{-average}$ of 0.22 ± 0.13, Fig. 3). The abundance models fitted assuming linear relationships showed similar explanatory capacity than those built upon non-linear relationships (hereafter: second-order polynomial GLMs; pseudo-$R^2_{-average}$ of 0.20 ± 0.12), although depending on the target species (Fig. 3; Table S4).

3.1. Linear relationships between bird abundance and fire regime

According to the GLMs, the abundance of 71% of the target species (20/28) were significantly explained by at least one attribute of the fire regime (hereafter: 'fire-sensitive' species) (Fig. 4; Table S5). The abundance of 46% of species (13/28) was found to be affected by at least

one of the two burn severity metrics (Fig. 4; Table S5). The percentage of forest was the main factor driving bird abundance (19/28) (see W_{Akaike} > 0.5 in Fig. 5). Regarding the fire-related variables, the percentage of burnt area was the most important factor affecting the local abundance for 39% of the modeled species (11/28), followed by the spatiotemporal descriptors of burn severity (namely, mean and standard deviation of dNBR) that significantly affected 28% of species (8/28) (see Fig. 4; and W_{Akaike} > 0.5 in Fig. 5). The models showed positive correlations between the standard deviation of burn severity and bird abundance for half of the species (6/13) (Fig. 4), while a third of the species did so with the burned area (4/11) and TSF (4 species; Fig. 4).

3.2. Non-linear relationships between bird abundance and fire regime

For several birds, the relationship between their abundance and fire regime attributes was also nonlinear, even though the explanatory power of second-order polynomial GLMs was slightly lower than assuming linear relationships (Fig. 3). The abundance of 60% of the modeled species were non-linearly influenced by at least one attribute of the fire regime (17/28) (Fig. 4; Table S5). The percentage of forest was also the main factor driving bird abundance (16/28) (see W_{Akaike} > 0.5

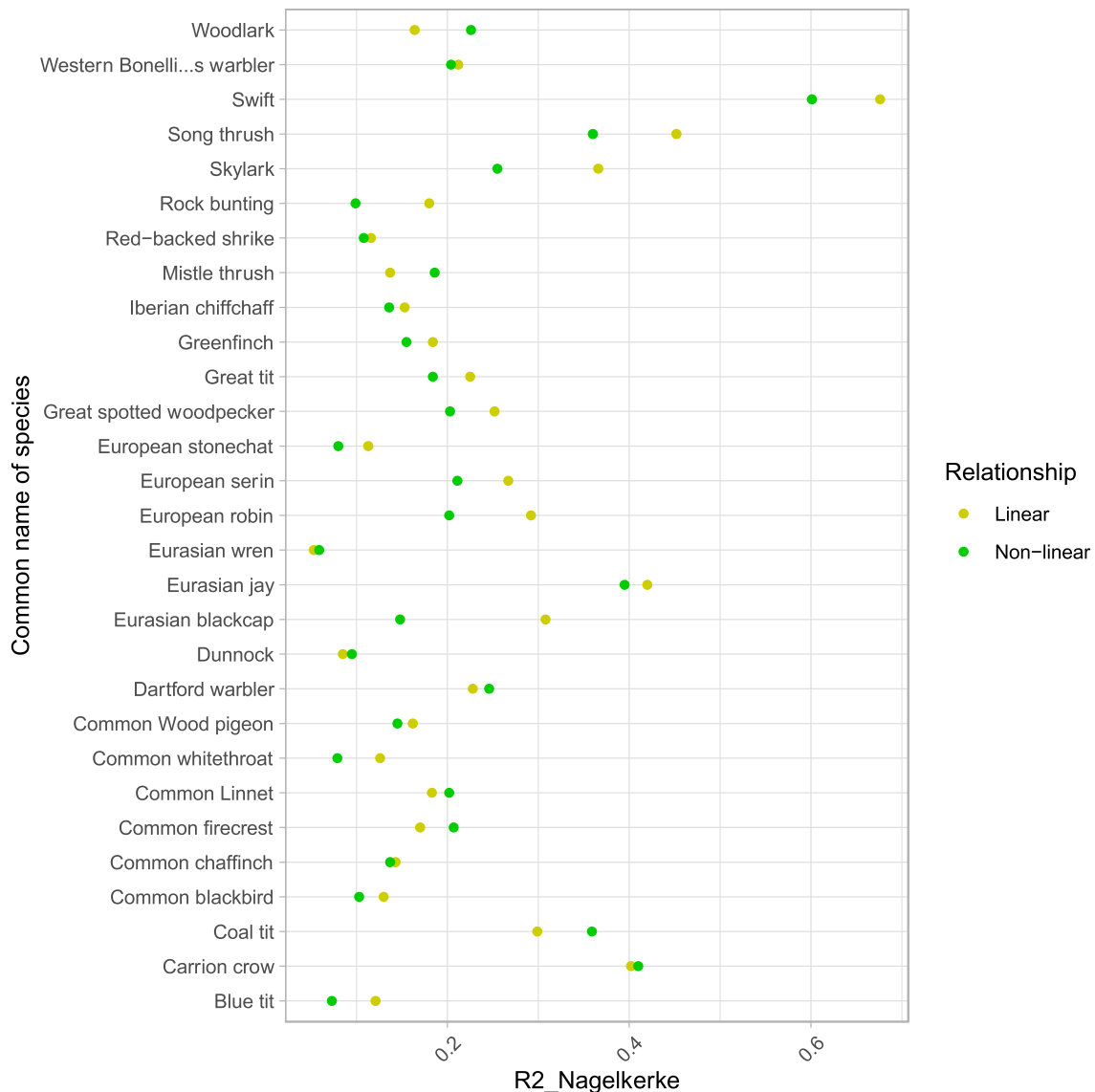**Fig. 3.** Pseudo-R^2 (R^2 Nagelkerke) for linear and second-order polynomial (non-linear) GLMs fitted with Poisson error distribution. Scientific species names available in Table 1.
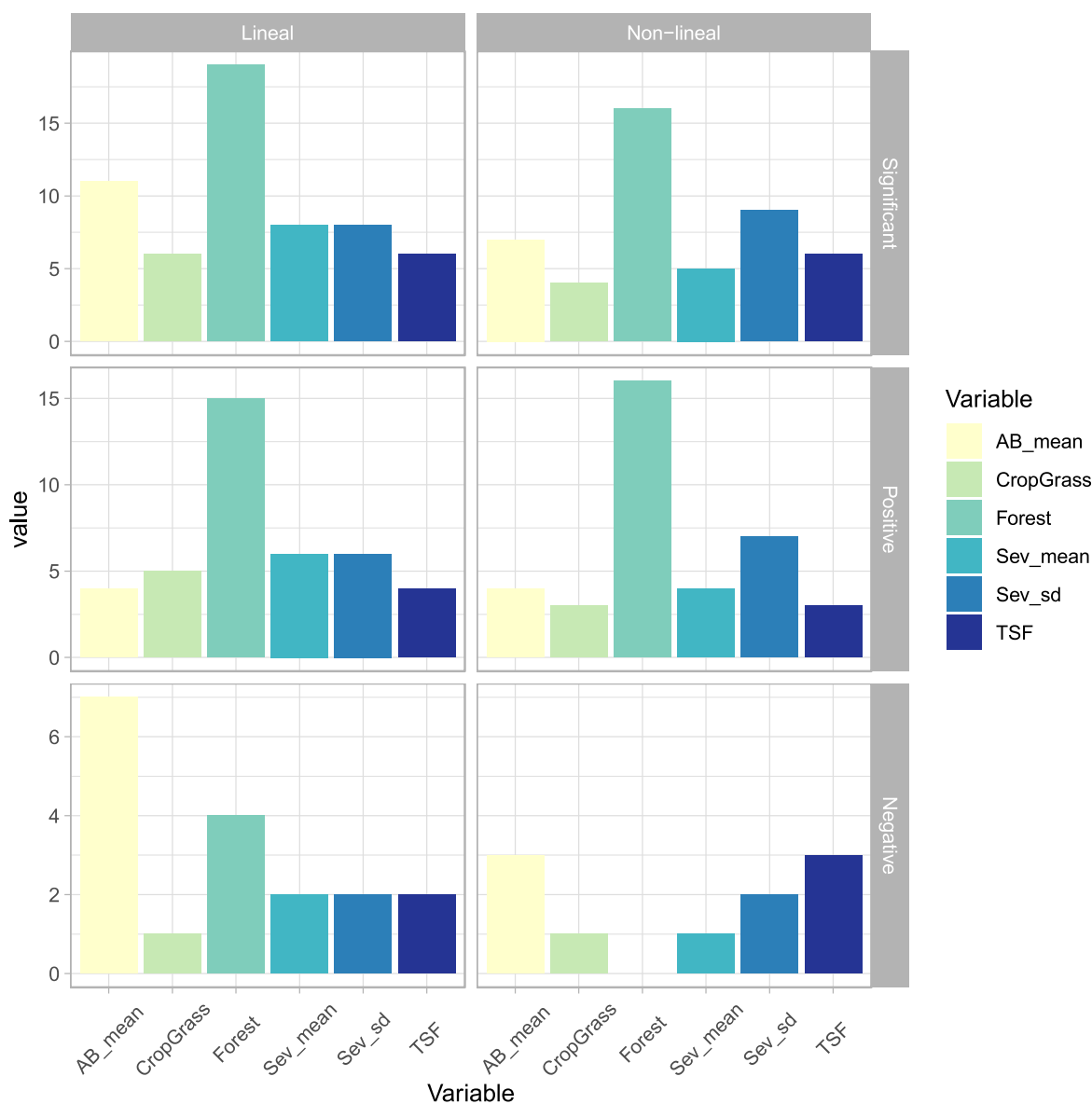
Fig. 4. Number of species significantly correlated (*p*-value <0.05) with each exploratory variable: 'AB_mean' (average value of annual burn area), 'CropGrass' (% of cropland and grassland), 'Forest' (% of forest), 'Sev_mean' (average value of annual burn severity), 'Sev_sd' (standard deviation of burn severity), 'TSF' (time since last fire). 'Positive' and 'Negative' indicate the number of species with positive or negative relationships between the response and exploratory variables (determined by the ß parameter).

in Fig. 5). However, in the second-order polynomial GLMs, the standard deviation of burn severity was the most important factor affecting the abundance patterns for 32% of the modeled species (9/28), followed by the burnt area and TSF that significatively affected 7 and 6 species, respectively (Figs. 4 and 5; Table S5). The models showed that the standard deviation of burn severity correlated positively with the abundance of 7 of the 17 species sensitive to fire (Fig. 4). The abundance of a fourth of the species increased with the burnt area (4/17) (Fig. 4). TSF was found to be positively correlated with the abundance of 3 species, while other 3 species did so negatively with this factor (Fig. 4; Table S5).

4. Discussion

Our models showed that the majority of our target species (up to 71%) are correlated with at least one attribute of the fire regime in the 'Baixa Limia – Serra do Xurés' Natural Park (see Figs. 4 and 5). The spatiotemporal variation in the burnt area and its severity were relevant

factors for explaining the local abundance patterns of our target species (up to 39% of the 28 modeled species, see Fig. 4). These results confirm the importance of burn severity and heterogeneity to explain bird abundance (see e.g., Puig-Gironès et al., 2022; Stephens et al., 2015), which has clear implications for fire management (see meta-analysis in Fontaine and Kennedy, 2012). Overall, the spatiotemporal variation of burn severity was positively correlated with the abundance patterns for 6 species (Figs. 4 and 5), which can be explained by an increase in the habitat heterogeneity created by fire (Nimmo et al., 2013; Parr and Andersen, 2006; Zozaya et al., 2010). The amount of burnt area was correlated with the abundance of 39% of species, with both positive and negative effects on bird abundance (see Fig. 4). Overall, open habitat and early successional species were found to be positively affected by fire (i.e., the higher the burnt area, the higher the bird abundance), even though some of them were negatively influenced by its severity (see e.g., Dartford warbler and Skylark in Table S5). These results are in line with previous studies that suggest that early successional species, such as Dartford warbler, have peaks of abundance around 4–8 years after fire in
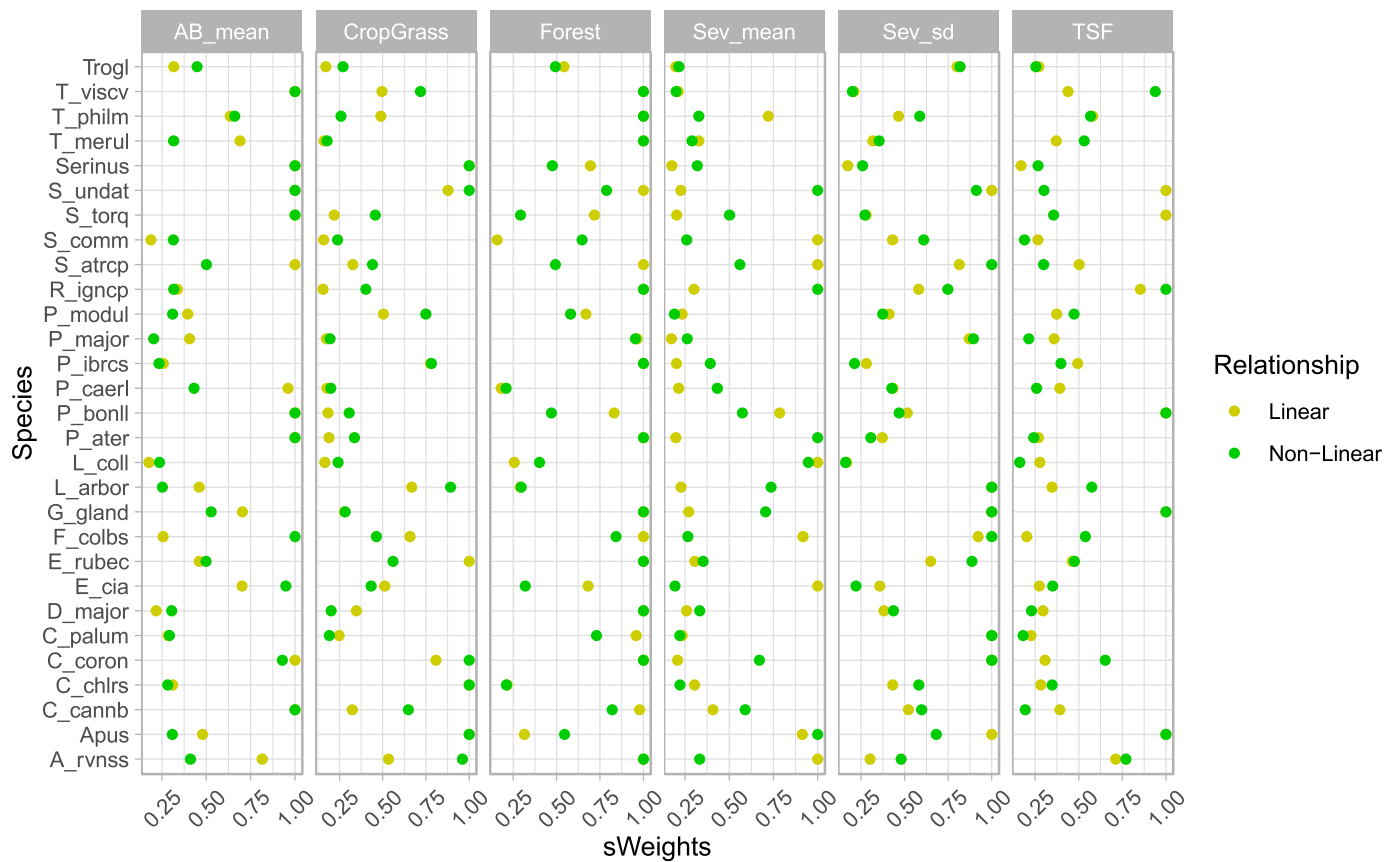
Fig. 5. Relative variable importance obtained by adding the Akaike weights (W$_i$) of the consequential models (Δ$_I$ < 4) in which such variable was present, assuming linear or second-order polynomial (non-linear) relationships. Common and scientific names of the modeled species available in Table 1.

Mediterranean ecosystems (Birdlife International, 2014; Pons et al., 2012). Fire creates habitat conditions to allow these species to occupy areas previously lost due to vegetation encroachment or afforestation processes driven by the joint effect of rural abandonment and fire suppression (see e.g., Regos et al., 2015a). In fact, recent studies suggested the use of fire as a tool to enhance bird conservation in this region, since fire could offset the negative effects of land abandonment on ecotone and open-habitat species (Campos et al., 2021; Regos et al., 2016b). On the contrary, forest-dwelling species (see e.g., Eurasian blackcap or Western Bonelli's warbler in Table S5) were negatively affected by fire, being favored by an increasing heterogeneity in burn severity (i.e., the presence of un-burnt patches) (Berry et al., 2014).

Despite the number of studies supporting 'time since fire' as a good predictor of bird abundance (Chalmandrier et al., 2013; Moghli et al., 2021; Pons and Clavero, 2010), this variable only correlated significantly with the abundance of 6 species in our study area (see Figs. 4 and 5). The variable 'time since fire' is often used to delineate successional vegetation states, being a good *proxy* for post-fire recovery, fuel age or vegetation structure (Moritz et al., 2004; Parks et al., 2014). However, our study region is characterized by fast recovery rates (Torres et al., 2018) due to its bioclimatic position, which could explain the less important role of 'time since fire' on bird abundance (see Fig. 5). Nevertheless, future studies in the region should include longer time series for burn severity and fire occurrence in their analyses. Short- and mid-term bird responses to fire can significantly differ from longer-term post-fire conditions and management (Nappi et al., 2010; Rost et al., 2013; Santos et al., 2016; White et al., 2015) —a critical issue that is context-specific.

The relationship between bird abundance and fire regime attributes is not always linear. Some studies have found more complex relationships between fire and bird abundance (Taillie et al., 2018; Watson et al.,

2012). It is therefore important to consider non-linear effects of fire severity and 'time since fire' to fully understand post-wildfire responses for a majority of bird species (see e.g., Taillie et al., 2018). In our case, we found a quadratic effect of at least one of the three fire regime attributes on bird abundance for 60% of the modeled species (see Fig. 3). Yet, the explanatory power of these models was slightly lower than those fitted assuming linear relationships (see Fig. 3; Table S4), which suggests that adding non-linear relationships in our model would not provide additional information. On the contrary, the inclusion of variables on the past land use, and its legacy after 10 years (mainly percentage of 'forest' and, in less extent, 'cropland and grassland' for year 2010), was critical to understand the role of fire (Figs. 4 and 5). Previous studies showed a significant increase for 13 shrubland and forest bird species (including species of conservation concern such as Turtle Dove, Dartford Warbler and Western Bonelli's Warbler), while only 4 ecotone and open-habitat species (e.g., Red-backed Shrike) showed a significant negative trend in the Natural park 'Baixa Limia – Serra do Xurés' between 2000 and 2010, due to vegetation encroachment and forest spread in the region (Corbelle-Rico et al., 2022; Regos et al., 2016b; Salaverri et al., 2019). In this sense, this study confirms the added value of accounting for fire and land-use legacy factors when modelling bird abundance to enhance their predictive capacity (De Cáceres et al., 2013; Vallecillo et al., 2009). The complex relationships found between each fire regime descriptor and the relative bird abundance highlights the need of tailor-made management at species level, and the role that fire can play in such management. The creation of small burnt patches through fire (e.g. prescribed burning) could be a cost-effective management option to maintain open habitats in rural abandoned landscape of NW Iberia, while reducing wildfire hazard (Campos et al., 2021; Regos et al., 2016b).

5. Conclusions

Burn severity and heterogeneity – measured through the spatio-temporal variation of dNBR at plot level for the last 11 years – significatively correlated with bird abundance, being relevant factors affecting bird abundance in the Natural park 'Baixa Limia – Serra do Xurés'. The majority of the 28 modeled species (71%) was found to be sensitive to fire, whose abundance were correlated with at least one fire regime attribute. These results confirm the role that fire can play in the conservation of these species in mountain regions largely affected by rural abandonment. Our burn severity metrics, computed from the interannual variation of satellite images, were useful to explain the abundance of several target species, due to the capacity of such indices to inform about habitat conditions after fire across space and time. These results confirm the usefulness of burn severity indicators to explain bird abundance patterns, which clearly complements the information provided by well-known fire regime descriptors such as the amount of burnt area and 'time since fire'. However, the relative importance of land-use legacy factors to explain the abundance of our target species highlights the need of longer-term analysis to better inform decision making. The particular biogeographic position of our study area – characterized by fast post-fire vegetation recovery rates – calls for caution when extrapolating our results to other socioecological contexts. Despite the context-specific response of birds, our findings confirm the importance of incorporating remotely sensed indicators of burn severity into the toolkit of decision makers to accurately anticipate the response of birds to fire management.

Author contributions

Conceptualization, A.R..; methodology, A.R..; formal analysis, C.G-R and A.R.; bird surveys, L.T and A.G-C.; remote sensing data, P.F-M and M.C.; writing—original draft preparation, A.R and C.G-R.; writing—review and editing, all authors.; visualization, P.F-M. and M.G-R.; supervision, A.R. and M.D-R.; project administration, A.R.; funding acquisition, A.R. All authors have read and agreed to the published version of the manuscript.

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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.

Data availability

Data is avaliable in Supplementary Material

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.116510.

References

Archibald, S., Lehmann, C.E.R., Gomez-Dans, J.L., Bradstock, R.A., 2013. Defining pyromes and global syndromes of fire regimes. Proc. Natl. Acad. Sci. USA 110, 6442–6447. https://doi.org/10.1073/pnas.1211466110.

Barton, K., 2016. MuMIn: multi-model inference. R package version 1.15.6. https://CRAN.R-project.org/package=MuMIn.

Batllori, E., Parisien, M.-A., Krawchuk, M.a., Moritz, M.a., 2013. Climate change-induced shifts in fire for Mediterranean ecosystems. Global Ecol. Biogeogr. 22, 1118–1129. https://doi.org/10.1111/geb.12065.

Berry, L.E., Lindenmayer, D.B., Driscoll, D.a., 2014. Large unburnt areas, not small unburnt patches are needed to conserve avian diversity in fire-prone landscapes. J. Appl. Ecol. https://doi.org/10.1111/1365-2664.12387 n/a-n/a.

Bibby, C.J., Burgess, N.D., Hill, D.A., 1992. Bird Census Techniques. Cambridge University Press, Cambridge (Cambridge University Press, Cambridge, UK).

Birdlife International, 2014. Species Factsheet: Sylvia Undata ([WWW Document]).

Brotons, L., Pons, P., Herrando, S., 2005. Colonization of dynamic Mediterranean landscapes: where do birds come from after fire? J. Biogeogr. 32, 789–798. https://doi.org/10.1111/j.1365-2699.2004.01195.x.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach. Springer, New York.

Campos, J.C., Bernhardt, J., Aquilué, N., Brotons, L., Domínguez, J., Lomba, Â., Marcos, B., Martínez-Freiría, F., Moreira, F., Pais, S., Honrado, J.P., Regos, A., 2021. Using fire to enhance rewilding when agricultural policies fail. Sci. Total Environ. 755, 142897 https://doi.org/10.1016/j.scitotenv.2020.142897.

Cánibe, M., Titeux, N., Domínguez, J., Regos, A., 2022. Assessing the uncertainty arising from standard land-cover mapping procedures when modelling species distributions. Divers. Distrib. 28, 636–648. https://doi.org/10.1111/ddi.13456.

Chalmandrier, L., Midgley, G.F., Barnard, P., Sirami, C., 2013. Effects of time since fire on birds in a plant diversity hotspot. Acta Oecol. 49, 99–106. https://doi.org/10.1016/j.actao.2013.03.008.

Chavez, J., 1996. Image-based atmospheric corrections - revisited and improved. Photogramm. Eng. Rem. Sens. 62, 1025–1036. https://doi.org/10.1111/j.1440-1681.2004.03065.x.

Clavero, M., Brotons, L., Herrando, S., 2011. Bird community specialization, bird conservation and disturbance: the role of wildfires. J. Anim. Ecol. 80, 128–136. https://doi.org/10.1111/j.1365-2656.2010.01748.x.

Corbelle-Rico, E., Sánchez-Fernández, P., López-Iglesias, E., Lago-Peñas, S., Da-Rocha, J. M., 2022. Putting Land to Work: an Evaluation of the Economic Effects of Recultivating Abandoned Farmland. In: Land Use Policy, vol. 112. https://doi.org/10.1016/j.landusepol.2021.105808.

De Cáceres, M., Brotons, L., Aquilué, N., Fortin, M.-J., 2013. The combined effects of land-use legacies and novel fire regimes on bird distributions in the Mediterranean. J. Biogeogr. 40, 1535–1547. https://doi.org/10.1111/jbi.12111.

Domínguez, J., Arenas, M., Tapia, L., 2005. Guía de las Aves del Parque Natural Baixa Limia-Serra do Xurés y Lic Baixa Limia. Consellería de Medio Ambiente, Xunta de Galicia (Santiago de Compostela).

Domínguez, J., Lamosa, A., Pardavila, X., Martínez-Freiría, F., Regos, A., Gil, A., Vidal, M., 2012. Atlas de los vertebrados terrestres reproductores en el Parque Natural Baixa Limia-Serra do Xurés y ZEPVN-LIC Baixa Limia. Xunta de Galicia.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography (Cop.). 36, 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x.

Farnsworth, L.M., Nimmo, D.G., Kelly, L.T., Bennett, A.F., Clarke, M.F., 2014. Does pyrodiversity beget alpha, beta or gamma diversity? A case study using reptiles from semi-arid Australia. Divers. Distrib. 20, 663–673. https://doi.org/10.1111/ddi.12181.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K.,

2005. Global consequences of land use. Science (80 309, 570–574. https://doi.org/10.1126/science.1111772.

Fontaine, J.B., Kennedy, P.L., 2012. Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in U.S. Fire-prone forests. Ecol. Appl. 22, 1547–1561. https://doi.org/10.1890/12-0009.1.

Gil-Tena, A., Brotons, L., Saura, S., 2009. Mediterranean forest dynamics and forest bird distribution changes in the late 20th century. Global Change Biol. 15, 474–485. https://doi.org/10.1111/j.1365-2486.2008.01730.x.

Gregory, R.D., Gibbons, D.W., Donald, P.F., 2004. Bird census and survey techniques. Bird Ecol. Conserv. 17–56.

He, T., Lamont, B.B., Pausas, J.G., 2019. Fire as a key driver of Earth's biodiversity. Biol. Rev. 3, 1983–2010. https://doi.org/10.1111/brv.12544.

Herrando, S., Brotons, L., Anton, M., Páramo, F., Villero, D., Titeaux, N., Quesada, J., Stefanescu, C., 2016. Assessing impacts of land abandonment on Mediterranean biodiversity using indicators based on bird and butterfly monitoring data. Environ. Conserv. 43, 69–78. https://doi.org/10.1017/S0376892915000260.

Jones, G.M., Gutiérrez, R.J., Tempel, D.J., Whitmore, S.A., Berigan, W.J., Peery, M.Z., 2016. Megafires: an emerging threat to old-forest species. Front. Ecol. Environ. 14, 300–306. https://doi.org/10.1002/fee.1298.

Kelly, L.T., Brotons, L., McCarthy, M.A., 2016. Putting pyrodiversity to work for animal conservation. Conserv. Biol. https://doi.org/10.1111/cobi.12861 (This).

Kelly, L.T., Giljohann, K.M., Duane, A., Aquilué, N., Archibald, S., Batllori, E., Bennett, A. F., Buckland, S.T., Canelles, Q., Clarke, M.F., Fortin, M., Hermoso, V., Herrando, S., Keane, R.E., Lake, F.K., Mccarthy, M.A., Morán-ordóñez, A., Parr, C.L., Pausas, J.G., Penman, T.D., Regos, A., Rumpff, L., Santos, J.L., Smith, A.L., Syphard, A.D., Tingley, M.W., Brotons, L., 2020. Fire and biodiversity in the anthropocene. Science 80, 370. https://doi.org/10.1126/science.abb0355 eabb0355.

Key, C.H., Benson, N.C., 2006. Landscape assessment: ground measure of severity, the composite burn index; and remote sensing of severity, the normalized burn ratio. In: Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., L.J.G (Eds.), FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service, Rocky Mountain Research Station, Gen. Tech, Ogden, UT (Rep).

Lehikoinen, A., Brotons, L., Calladine, J., Campedelli, T., Escandell, V., Flousek, J., Grueneberg, C., Haas, F., Harris, S., Herrando, S., Husby, M., Jiguet, F., Kålås, J.A., Lindström, Å., Lorrillière, R., Molina, B., Pladevall, C., Calvi, G., Sattler, T., Schmid, H., Sirkiä, P.M., Teufelbauer, N., Trautmann, S., 2019. Declining population trends of European mountain birds. Global Change Biol. 25, 577–588. https://doi.org/10.1111/gcb.14522.

Leutner, B., Horning, N., 2017. RStoolbox: Tools for Remote Sensing Data Analysis. R package version 0.1.8. https://CRAN.R-project.org/package=RStoolbox.

Lindenmayer, D.B., Blanchard, W., McBurney, L., Blair, D., Banks, S.C., Driscoll, D.a., Smith, A.L., Gill, a.M., 2014. Complex responses of birds to landscape-level fire extent, fire severity and environmental drivers. Divers. Distrib. https://doi.org/10.1111/ddi.12172 n/a-n/a.

Loepfe, L., Martinez-Vilalta, J., Oliveres, J., Piñol, J., Lloret, F., 2010. Feedbacks between fuel reduction and landscape homogenisation determine fire regimes in three Mediterranean areas. For. Ecol. Manage. 259, 2366–2374. https://doi.org/10.1016/j.foreco.2010.03.009.

Macedo, A., Tavares, A., Fontes, A., Pinto, C., Rodrigues, C., Machado, C., Figueiredo, D., Silva, D., Carvalho, H., Regalo, H., Osório, M., Santarém, M., Gonzalez, R., Formoso, J.C., Gonzalez, F.J., Fernández, M.A., Gil, A., Veloso, N., 2009. Propuesta para la creación de la Reserva de la Biosfera Transfronteriza Gerês/Xurés. Xunta de Galicia, Comissão de Coordenação e Desenvolvimento Regional do Norte, Instituto de Conservação da Natureza e da Biodiversidade. Xunta de Galicia, Comissão de Coordenação e Desenvolvimento Regional do Norte. Instituto de Conservação da Natureza e da Biodiversidade.

Maillard, O., Herzog, S.K., Soria-Auza, R.W., Vides-Almonacid, R., 2022. Impact of fires on key biodiversity areas (KBAs) and priority bird species for conservation in Bolivia. Fire 5, 1–20. https://doi.org/10.3390/fire5010004.

Martínez-Cortizas, A., Pérez-Alberti, A., 1999. Atlas Bioclimático de Galicia. Xunta de Galicia, Santiago de Compostela.

Martínez, F.J., Cheli, G.H., Grismado, C.J., Bisigato, A.J., 2022. Ground-dwelling arachnids and fire disturbance: a case study in northeastern patagonia (Argentina). Fire 5. https://doi.org/10.3390/fire5040091.

Mateos, E., Santos, X., Pujade-Villar, J., 2011. Taxonomic and functional responses to fire and post-fire management of a Mediterranean Hymenoptera community. Environ. Manag. 48, 1000–1012. https://doi.org/10.1007/s00267-011-9750-0.

McLauchlan, K.K., Higuera, P.E., Miesel, J., Rogers, B.M., Schweitzer, J., Shuman, J.K., Tepley, A.J., Varner, J.M., Veblen, T.T., Adalsteinsson, S.A., Balch, J.K., Baker, P., Batllori, E., Bigio, E., Brando, P., Cattau, M., Chipman, M.L., Coen, J., Crandall, R., Daniels, L., Enright, N., Gross, W.S., Harvey, B.J., Hatten, J.A., Hermann, S., Hewitt, R.E., Kobziar, L.N., Landesmann, J.B., Loranty, M.M., Maezumi, S.Y., Mearns, L., Moritz, M., Myers, J.A., Pausas, J.G., Pellegrini, A.F.A., Platt, W.J., Roozeboom, J., Safford, H., Santos, F., Scheller, R.M., Sherriff, R.L., Smith, K.G., Smith, M.D., Watts, A.C., 2020. Fire as a fundamental ecological process: research advances and frontiers. J. Ecol. 108, 2047–2069. https://doi.org/10.1111/1365-2745.13403.

Moghli, A., Santana, V.M., Baeza, M.J., Pastor, E., Soliveres, S., 2021. Fire recurrence and time since last fire interact to determine the supply of multiple ecosystem services by mediterranean forests. Ecosystems 25, 1358–1370. https://doi.org/10.1007/s10021-021-00720-x.

Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M.C., Catry, F. X., Armesto, J., Bond, W., González, M.E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J.G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V.R., Van Wilgen, B. W., Xanthopoulos, G., Fernandes, P.M., 2020. Wildfire management in

Mediterranean-type regions: paradigm change needed. Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab541e.

Moritz, M.A., Keeley, J.E., Johnson, E.A., Schaffner, A.A., 2004. Testing a basic assumption of shrubland fire management: how important is fuel age? Front. Ecol. Environ. 2, 67–72.

Naimi, B., 2017. Usdm: uncertainty analysis for species distribution models. R Package. Version 1.1–18. [WWW Document].

Nappi, A., Drapeau, P., Saint-Germain, M., Angers, V.A., 2010. Effect of fire severity on long-term occupancy of burned boreal conifer forests by saproxylic insects and wood-foraging birds. Int. J. Wildland Fire 19, 500–511. https://doi.org/10.1071/WF08109.

Navarro-González, I., Pérez-Luque, A.J., Bonet, F.J., Zamora, R., 2013. The weight of the past: land-use legacies and recolonization of pine plantations by oak trees. Ecol. Appl. 23, 1267–1276.

Nimmo, D.G., Kelly, L.T., Spence-Bailey, L.M., Watson, S.J., Taylor, R.S., Clarke, M.F., Bennett, a F., 2013. Fire mosaics and reptile conservation in a fire-prone region. Conserv. Biol. 27, 345–353. https://doi.org/10.1111/j.1523-1739.2012.01958.x.

Pais, S., Aquilué, N., Campos, J., Sil, À., Marcos, B., Martínez-freiría, F., Domínguez, J., Brotons, L., Honrado, J.P., Regos, A., 2020. Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. Ecosyst. Serv. 44, 101143 https://doi.org/10.1016/j.ecoser.2020.101143.

Parks, S.a., Miller, C., Nelson, C.R., Holden, Z.a., 2014. Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. Ecosystems 17, 29–42. https://doi.org/10.1007/s10021-013-9704-x.

Parr, C.L., Andersen, A.N., 2006. Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. Conserv. Biol. 20, 1610–1619. https://doi.org/10.1111/j.1523-1739.2006.00492.x.

Pausas, J.G., 2015. Evolutionary fire ecology: lessons learned from pines. Trends Ecol. Evol. 20, 318–323. https://doi.org/10.1016/j.tplants.2015.03.001.

Pausas, J.G., Ribeiro, E., 2017. Fire and plant diversity at the global scale. Global Ecol. Biogeogr. 5, 1–17. https://doi.org/10.1111/geb.12596.

Pérez-Granados, C., López-Iborra, G.M., Serrano-Davies, E., Noguerales, V., Garza, V., Justribó, J.H., Suárez, F., 2013. Short-term effects of a wildfire on the endangered dupont's lark chersophilus duponti in an arid shrub-steppe of Central Spain. Acta Ornithol 48, 201–210. https://doi.org/10.3161/000164513X678856.

Pons, P., Clavero, M., 2010. Bird responses to fire severity and time since fire in managed mountain rangelands. Anim. Conserv. 13, 294–305. https://doi.org/10.1111/j.1469-1795.2009.00337.x.

Pons, P., Clavero, M., Bas, J.M., Prodon, R., 2012. Time-window of occurrence and vegetation cover preferences of Dartford and Sardinian Warblers after fire. J. Ornithol. 153, 921–930. https://doi.org/10.1007/s10336-012-0822-6.

Puerta-Piñero, C., Espelta, J.M., Sánchez-Humanes, B., Rodrigo, A., Coll, L., Brotons, L., 2012. History matters: previous land use changes determine post-fire vegetation recovery in forested Mediterranean landscapes. For. Ecol. Manage. 279, 121–127. https://doi.org/10.1016/j.foreco.2012.05.020.

Puig-Gironès, R., Brotons, L., Pons, P., 2022. Aridity, fire severity and proximity of populations affect the temporal responses of open-habitat birds to wildfires. Biol. Conserv. 272 https://doi.org/10.1016/j.biocon.2022.109661.

Regos, A., D'Amen, M., Herrando, S., Guisan, A., Brotons, L., 2015a. Fire management, climate change and their interacting effects on birds in complex Mediterranean landscapes: dynamic distribution modelling of an early-successional species—the near-threatened Dartford Warbler (Sylvia undata). J. Ornithol. 156, 275–286. https://doi.org/10.1007/s10336-015-1174-9.

Regos, A., D'Amen, M., Titeux, N., Herrando, S., Guisan, A., Brotons, L., 2016a. Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios. Divers. Distrib. 22, 83–96. https://doi.org/10.1111/ddi.12375.

Regos, A., Domínguez, J., Gil-Tena, A., Brotons, L., Ninyerola, M., Pons, X., 2016b. Rural abandoned landscapes and bird assemblages: winners and losers in the rewilding of a marginal mountain area (NW Spain). Reg. Environ. Change 16, 199–211. https://doi.org/10.1007/s10113-014-0740-7.

Regos, A., Ninyerola, M., Moré, G., Pons, X., 2015b. Linking land cover dynamics with driving forces in mountain landscape of the Northwestern Iberian Peninsula. Int. J. Appl. Earth Obs. Geoinf. 38, 1–14. https://doi.org/10.1016/j.jag.2014.11.010.

Rost, J., Hutto, R.L., Brotons, L., Pons, P., 2013. Comparing the effect of salvage logging on birds in the Mediterranean Basin and the Rocky Mountains: common patterns, different conservation implications. Biol. Conserv. 158, 7–13.

Salaverri, L., Guitián, J., Munilla, I., Sobral, M., 2019. Bird richness decreases with the abandonment of agriculture in a rural region of SW Europe. Reg. Environ. Change 19, 245–250.

Santos, X., Badiane, A., Matos, C., 2016. Contrasts in short- and long-term responses of Mediterranean reptile species to fire and habitat structure. Oecologia 180, 205–216. https://doi.org/10.1007/s00442-015-3453-9.

Santos, X., Belliure, J., Gonçalves, J.F., Pausas, J.G., 2022. Resilience of reptiles to megafires. Ecol. Appl. 32, 1–14. https://doi.org/10.1002/eap.2518.

Scozzafava, S., De Sanctis, A., 2006. Exploring the effects of land abandonment on habitat structures and on habitat suitability for three passerine species in a highland area of Central Italy. Landsc. Urban Plann. 75, 23–33. https://doi.org/10.1016/j.landurbanplan.2004.10.006.

Stephens, J.L., Ausprey, I.J., Seavy, N.E., Alexander, J.D., 2015. Fire severity affects mixed broadleaf–conifer forest bird communities: results for 9 years following fire. Condor. https://doi.org/10.1650/CONDOR-14-58.1.

Taillie, P.J., Burnett, R.D., Roberts, L.J., Campos, B.R., Peterson, M.N., Moorman, C.E., 2018. Interacting and non-linear avian responses to mixed-severity wildfire and time since fire. Ecosphere 9. https://doi.org/10.1002/ecs2.2291.

Tingley, M.W., Ruiz-Gutiérrez, V., Wilkerson, R.L., Howell, C.A., Siegel, R.B., 2016. Pyrodiversity promotes avian diversity over the decade following forest fire. Proc. R. Soc. B Biol. Sci. https://doi.org/10.1098/rspb.2016.1703.

Torres, J., Gonçalves, J., Marcos, B., Honrado, J., 2018. Indicator-based assessment of post-fire recovery dynamics using satellite NDVI time-series. Ecol. Indicat. 89, 199–212. https://doi.org/10.1016/j.ecolind.2018.02.008.

Uyttewaal, K., Prat-Guitart, N., Ludwig, F., Kroeze, C., Langer, E.R., Lisa, 2023. Territories in Transition: how social contexts influence wildland fire adaptive capacity in rural Northwestern European Mediterranean areas. Fire Ecol 19. https://doi.org/10.1186/s42408-023-00168-5.

Vallecillo, S., Brotons, L., Thuiller, W., 2009. Dangers of predicting bird species distributions in response to land-cover changes. Ecol. Appl. 19, 538–549. https://doi.org/10.1890/08-0348.1.

Watson, S.J., Taylor, R.S., Nimmo, D.G., Kelly, L.T., Haslem, A., Clarke, M.F., Bennett, A. F., 2012. Effects of time since fire on birds: how informative are generalized fire response curves for conservation management? Ecol. Appl. 22, 685–696.

White, A.M., Manley, P.N., Tarbill, G.L., Richardson, T.W., Russell, R.E., Safford, H.D., Dobrowski, S.Z., 2015. Avian community responses to post-fire forest structure: implications for fire management in mixed conifer forests. Anim. Conserv. 19, 256–264. https://doi.org/10.1111/acv.12237.

Wretenberg, J., Lindstrom, A., Svensson, S., Part, T., 2007. Linking agricultural policies to population trends of Swedish farmland birds in different agricultural regions. J. Appl. Ecol. 44, 933–941.

Zakkak, S., Kakalis, E., Radovic, A., Halley, J.M., Kati, V., 2014. The impact of forest encroachment after agricultural land abandonment on passerine bird communities: the case of Greece. J. Nat. Conserv. 22, 157–165. https://doi.org/10.1016/j.jnc.2013.11.001.

Zozaya, E.L., Brotons, L., Herrando, S., Pons, P., Rost, J., Clavero, M., 2010. Monitoring Spatial and temporal dynamics of bird communities in Mediterranean Landscapes affected by large wildfires. ARDEOLA 57, 33–50.