ARTICLE IN PRESS

STOTEN-142897; No of Pages 10

Science of the Total Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Using fire to enhance rewilding when agricultural policies fail

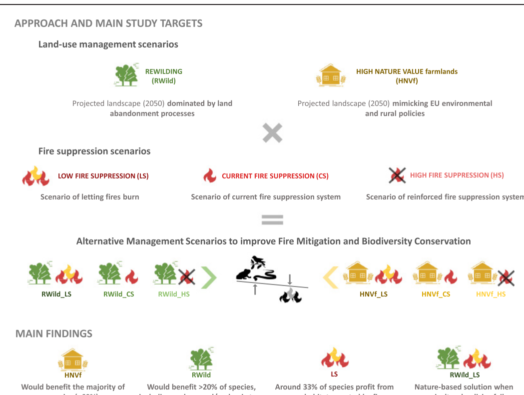
João C. Campos [a,*], Julia Bernhardt [b], Núria Aquilué [c,d], Lluís Brotons [d,e,f], Jesús Domínguez [g], Ângela Lomba [a,h], Bruno Marcos [a,h], Fernando Martínez-Freiría [a], Francisco Moreira [a,i], Silvana Pais [a,j], João P. Honrado [a,h], Adrián Regos [a,g]

[a] InBIO/CIBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos, Campus Agrário de Vairão, Rua Padre Armando Quintas, n° 7, 4485-661 Vairão, Portugal
[b] Universität Leipzig, Ritterstraße 30, 36 04109 Leipzig, Germany
[c] Centre d'Étude de la Forêt, Université du Québec à Montréal, Montréal, Canada
[d] InForest Jru (CTFC-CREAF), Crta. Antiga St Llorenç de Morunys km. 2, 25280 Solsona, Spain
[e] CREAF, 08193 Cerdanyola del Vallès, Spain
[f] CSIC, 08193 Cerdanyola del Vallès, Spain
[g] Departamento de Zooloxía, Xenética e Antropoloxía Física, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain
[h] Departamento de Biologia, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, S/N, Edifício FC4, 4169-007 Porto, Portugal
[i] InBIO/CIBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos, Laboratório Associado, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal
[j] proMetheus, Research Unit in Materials, Energy and Environment for Sustainability, Instituto Politécnico of Viana do Castelo, 4990-706 Ponte de Lima, Portugal

HIGHLIGHTS

- HNVf is a long-term opportunity for fire suppression and biodiversity conservation.
- HNVf management would benefit the majority of species (more than 60%).
- Rewilding benefits up to 20% of species, including endangered/endemic taxa.
- Up to 33% of species profit from open habitats created by fire.
- Fire-mediated rewilding is a nature-based solution when agricultural policies fail.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 July 2020
Received in revised form 13 September 2020
Accepted 2 October 2020
Available online xxxx

Editor: Paulo Pereira

Keywords:
Biodiversity conservation
High Nature Value farmlands
Land abandonment

ABSTRACT

Rewilding has been proposed as an opportunity for biodiversity conservation in abandoned landscapes. However, rewilding is challenged by the increasing fire risk associated with more flammable landscapes, and the loss of open-habitat specialist species. Contrastingly, supporting High Nature Value farmlands (HNVf) has been also highlighted as a valuable option, but the effective implementation of agricultural policies often fails leading to uncertain scenarios wherein the effects of wildfire management remain largely unexplored. Herein, we simulated fire-landscape dynamics to evaluate how fire suppression scenarios affect fire regime and biodiversity (102 species of vertebrates) under rewilding and HNVf policies in the future (2050), in a transnational biosphere reserve (Gerês-Xurés Mountains, Portugal-Spain). Rewilding and HNVf scenarios were modulated by three different levels of fire suppression effectiveness. Then, we quantified scenario effects on fire regime (burned and suppressed areas) and biodiversity (habitat suitability change for 2050). Simulations confirm HNVf as a long-term opportunity for fire suppression (up to 30,000 ha of additional suppressed areas between 2031 and 2050

* Corresponding author.
E-mail addresses: jc_campos@cibio.up.pt (J.C. Campos), nuria.aquilue@ctfc.cat (N. Aquilué), lluis.brotons@ctfc.cat (L. Brotons), jesus.dominguez@usc.es (J. Domínguez), angelalomba@fc.up.pt (Â. Lomba), bruno.marcos@cibio.up.pt (B. Marcos), fmartinez-freiria@cibio.up.pt (F. Martínez-Freiría), fmoreira@cibio.up.pt (F. Moreira), jhonrado@fc.up.pt (J.P. Honrado), adrian.regos@cibio.up.pt, adrian.regos@usc.es (A. Regos).

https://doi.org/10.1016/j.scitotenv.2020.142897

Please cite this article as: J.C. Campos, J. Bernhardt, N. Aquilué, et al., Using fire to enhance rewilding when agricultural policies fail, Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2020.142897

Land-use
Southern Europe
Wildfires

in comparison to rewilding scenario) and for conservation (benefiting around 60% of species). Rewilding benefits some species (20%), including critically endangered, vulnerable and endemic taxa, while several species (33%) also profit from open habitats created by fire. Although HNVf remains the best scenario, rewilding reinforced by low fire suppression management may provide a nature-based solution when societal support through agricultural policies fails.

1. Introduction

Land abandonment in rural landscapes is one of the most important drivers of regional land-use change (Estoque et al., 2019), and has been suggested as an opportunity for biodiversity conservation and the reinstatement of natural ecological processes (e.g. Queiroz et al., 2014; Merckx and Pereira, 2015). Rewilding approaches rely on this assumption as they intend to reestablish natural self-sustained ecosystems with reduced human intervention (Gillson et al., 2011). In Europe, rewilding initiatives (e.g. Rewilding Europe Network; https://rewildingeurope.com) might benefit biodiversity by providing renewed suitable habitats and dispersal corridors, alleviating forest habitat fragmentation (Perino et al., 2019). This management strategy might be particularly beneficial for a diversity of forest-adapted species, including emblematic taxa of conservation concern such as wolfs and bears (Navarro and Pereira, 2015). Additionally, rewilded landscapes might potentiate various ecosystem functions and services (Perino et al., 2019), such as the support of soil, nutrients and water cycles, the provisioning of biomass and climate regulation (Navarro and Pereira, 2015).

However, rewilding holds some constraints that may limit its successful implementation. The inherent homogenization of rewilded landscapes leads to loss and fragmentation of open habitats, mainly due to shrub encroachment and forest expansion (Moreira et al., 2011). Studies also indicated that the gradual cessation of traditional farming areas, many of which known to support "High Nature Value farmlands" (hereafter HNVf), is a major cause of local biodiversity losses, accelerating population declines of species adapted to wet grasslands, pastures and other extensive agricultural areas (Franks et al., 2018; Lomba et al., 2020). Furthermore, shrub encroachment caused by land abandonment contributes to fuel accumulations and higher connectivity of flammable vegetation, increasing the potential incidence, severity and impacts of large wildfires (see Moreira et al., 2011 and references therein). These changes in the fire-vegetation dynamics could cause severe impacts on local ecosystem processes and associated biodiversity, particularly in regions where landscapes and biota have endured a long-term relation with human activities and fire regimes.

The Mediterranean regions of southern Europe are paradigmatic cases of human- and fire-mediated landscapes (Loepfe et al., 2010; Fernandes et al., 2011; Viedma et al., 2015). The marked climate seasonality of Mediterranean regions, characterized by warm-dry summers and cold-humid winters, provides optimal conditions for frequent and intense fire events, mostly concentrated in the summer season. The number of extreme fire events has escalated in southern Europe during the last decades (San-Miguel-Ayanz et al., 2013; Tedim et al., 2013; Williams, 2013), mainly due to intensified effects of climate change (warmer and drier climatic conditions, and more frequent heath waves) and increased fuel accumulation and connectivity caused by rural land abandonment (Fernandes et al., 2016a; Turco et al., 2019). For these reasons, southern European countries have invested vast resources in fire suppression (Fernandes et al., 2016b). However, exhaustive fire suppression might be counter-productive in fire-prone ecosystems, since vegetation will become denser and provide more fuel for larger, more intense and more severe fires — a process described as the "firefighting trap" (Moreira et al., 2020). Consequently, alternative management strategies have been recommended, highlighting the urgency for a wide-ranging policy shift towards fire mitigation and adaptation (Fernandes, 2013; Moritz et al., 2014; Moreira et al., 2020).

The intricate links between land abandonment and fire regimes complexify the selection of appropriate alternative scenarios, and subsequently decision-making in fire management and planning (Moreira et al., 2011; McLauchlan et al., 2020). Considering the different proneness of land cover (LC) types to burn, agricultural policies implemented under the European Union's Common Agricultural Policy have been claimed as an opportunity to reduce fire risk by promoting HNVf in detriment of more flammable LC types, such as dense scrublands (Moreira and Pe'er, 2018). Alternative fire management strategies have been evaluated in the last decades to increase fire suppression effectiveness under the ongoing land abandonment trends. For instance, since wildfires might reduce fuel load and connectivity between flammable vegetation, several studies have suggested that allowing unplanned fires to burn (under safe conditions) would help suppressing future large forest fires under adverse climatic conditions (e.g. Houtman et al., 2013; Regos et al., 2014; Duane et al., 2019).

Allowing low-intensity wildfires to burn might also contribute to biodiversity conservation, an idea advocated by the "pyrodiversity hypothesis", a prominent concept in fire ecology (Kelly and Brotons, 2017; Kelly et al., 2017). This hypothesis relies on the assumption that a high level of landscape heterogeneity, related to spatial-temporal variations of resources and conditions mediated by the intensity and severity of fire regimes, benefits biodiversity (see Kelly and Brotons, 2017 and reference therein). This is still a controversial hypothesis since studies have found both positive (e.g. Ponisio et al., 2016; Tingley et al., 2016) and negative (e.g. Taylor et al., 2012; Berry et al., 2015) effects of pyrodiversity on different biological communities. The incongruent outcomes of pyrodiversity underline the complex relations between biodiversity, fire regime, and landscape structure and composition (McLauchlan et al., 2020). Informative assessments should thus consider how land-use change and fire can affect both the diversity, availability and connectivity of suitable habitats for multiple species (Kelly and Brotons, 2017), preferably from different taxonomic groups.

Here, we assess the impacts of alternative landscape trajectories and fire suppression management strategies on future fire regimes and on biodiversity conservation. We focused on changes in burned and suppressed areas and habitat suitability for 102 vertebrate species from three taxonomic groups (amphibians, birds, and reptiles) in a transboundary protected mountain region between Portugal and Spain, representative of the typical southern European mountain landscapes undergoing land abandonment for at least half a century (Regos et al., 2015; Lasanta et al., 2017). We aimed to answer the following questions: 1) How would different land-use and fire suppression management scenarios contribute to future fire mitigation (i.e. fewer areas burned associated with higher suppression efficiency)?; 2) How would those scenarios affect biodiversity?; 3) Which is the best management scenario for promoting fire mitigation and biodiversity conservation?; and 4) With agricultural policies failing to cope with rural abandonment, could a rewilding trajectory integrated with fire suppression policies contribute to enhance biodiversity conservation? We first modelled the fire-vegetation dynamics from 2010 to 2050, under two contrasting land-use management scenarios (rewilding versus HNVf) coupled with three fire management strategies differing in fire suppression levels. Then, based on future projections of fire-vegetation and on species distribution modelling, we quantified the potential impacts of these contrasting policy options on fire regime, landscape structure, and their subsequent effects on biodiversity.

2. Methods

2.1. Study area

The study area is the Transboundary Biosphere Reserve Gerês-Xurés (BR-GX; c.a. 2670 km^2) in the NW Iberian Peninsula (Fig. 1). The reserve encompasses four Natura 2000 sites and two national protected areas: the Peneda-Gerês National Park (PGNP; Portugal) and the Baixa Limia-Serra do Xurés Natural Park (BLXNP; Spain). This mountain region is topographically complex, with altitudes varying between 15 and 1545 m and is composed by a diversified orientation relief, deep valleys, plains and steep slopes. The climate is predominantly Atlantic, characterized by high precipitation levels (around 1000 to 3000 mm/year), mostly concentrated in autumn and winter seasons (October–March), although the varied relief and wide-ranging altitudes afford diverse microclimatic conditions. The reserve is located between the Mediterranean and Eurosiberian biogeographical regions, holding high biodiversity levels and serving as refuge for several emblematic species of conservation concern. The landscape is dominated by scrublands and fragmented forests of deciduous trees (mainly oaks) and conifers (mainly pines). The reserve is experiencing a long-term rural exodus (having a current low population of 29.4 inhabitants/km^2), which has progressively contributed to scrub and woodland expansion at the expense of cropland and pastureland (Regos et al., 2015). The effects of land abandonment are particularly intensified in the mountainous and hardly accessible areas of the reserve, following contemporary tendencies observed across other Mediterranean regions (e.g., García-Ruiz and Lana-Renault, 2011; van Leeuwen et al., 2019). Still, the area is subjected to a high frequency of human-induced wildfires (e.g. traditional use of fire; Chas-Amil et al., 2015), leading to a fire regime characterized by recurrent fire events and considerable total burned areas (195,000 ha burned between 1983 and 2010) with a fire return interval of 37 years. Despite increased investments in fire suppression, these efforts have been proven unsuccessful to alleviate the local fire regime and the impacts of large wildfires, a pattern that has been observed across other mountain rural areas in southern Europe, such as in Portugal (e.g. Fernandes et al., 2016b) and Spain (e.g. Loepfe et al., 2010; Pausas and Fernández-Muñoz, 2012; Viedma et al., 2015), to France (San Roman Sanz et al., 2013), Italy (Ursino and Romano, 2014; Bajocco et al., 2019) and Greece (Xystrakis et al., 2017).

2.2. Scenario design

Two land-use scenarios were established (see Fig. 2 and Table 1 for details concerning annual conversion rates): (1) a rewilding scenario, representing the ongoing trend of land abandonment reported in our study area (see Regos et al., 2015), as well as in other mountain regions across Southern Europe under the current EU Common Agricultural Policy (CAP) (see Lasanta et al., 2017 and references therein); and (2) an HNVf scenario, reflecting the adoption of policies that effectively maintain and expand HNV agricultural areas (i.e. a greener path for the CAP; Pe'er et al., 2014, 2020). For each land-use scenario, three fire management scenarios differing in suppression policies were compared (Fig. 2): (1) a scenario of letting fires burn in forest and scrubland areas while firefighting resources are prioritized towards human assets protection (i.e. firefighting efforts mostly focused on agricultural mosaics, in which human assets are mostly located; low fire suppression-LS; i.e.

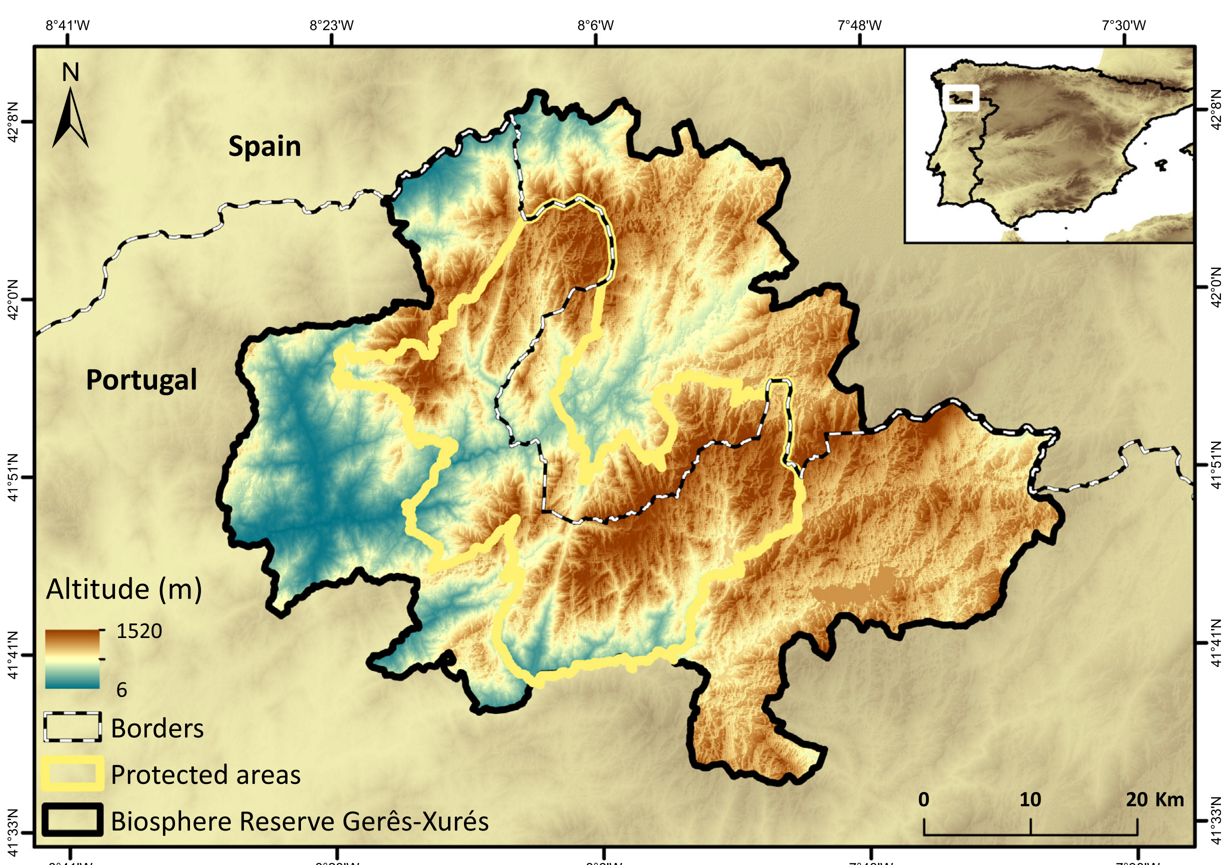


Fig. 1. Location of the Transboundary Biosphere Reserve Gerês-Xurés in the Iberian Peninsula (thick black contours) and of the main protected areas of Peneda-Gerês National Park and the Baixa Limia-Serra do Xurés Natural Park (yellow contours). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

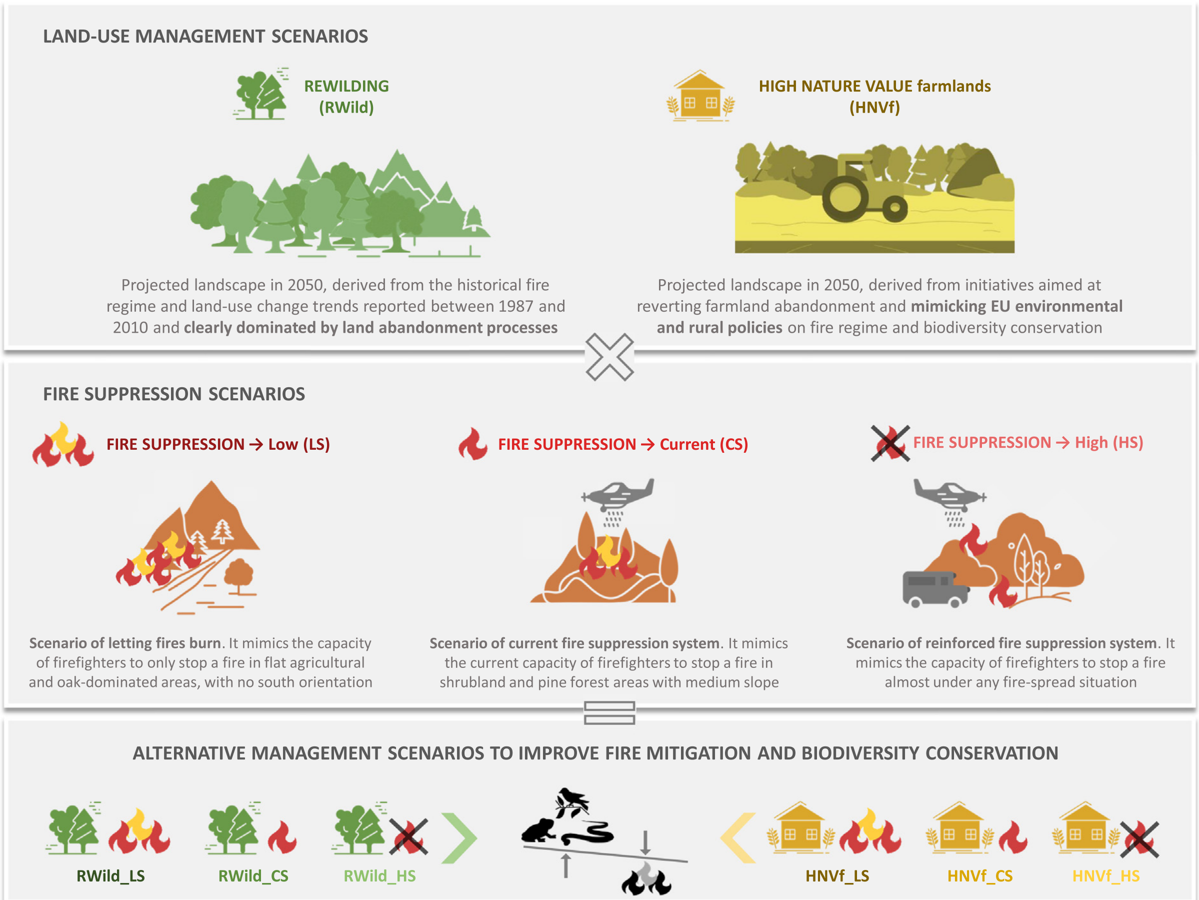


Fig. 2. Schematic representation of the study approach. The land-use and fire suppression management scenarios implemented in this study are presented, as well as the resulting alternative scenarios tested to improve fire mitigation and biodiversity conservation in the study area.

using fire to promote biodiversity; see review in Kelly and Brotons, 2017); (2) a scenario representative of current fire suppression approaches and capabilities (current fire suppression-CS; see model parametrization in Supplementary material in Pais et al., 2020); and (3) a scenario with higher investment in fire suppression (i.e. increased firefighting capacity; high fire suppression-HS).

2.3. Fire-landscape modelling and effects of management scenarios on fire regime

Fire-mediated landscape dynamics were addressed using a landscape dynamic modelling approach based on the REMAINS model (see Pais et al., 2020 concerning REMAINS model). Briefly, the model incorporates landscape change processes driving fire-vegetation dynamics, generating distinct scenarios of landscape dynamics based on previously designed conditions. The model simulates fire ignition, spread and extinction, calibrated under business-as-usual scenarios with the current firefighting effectiveness specifically determined for each administrative region of the study area (please see Supplementary material in Pais et al., 2020), natural succession and post-fire regeneration. Annual burnt areas are quantified to define a burnt area distribution and to consequently incorporate historical fire regime into the model. In addition, the fire-succession model is coupled with a land-use model to implement land-use policies at the landscape level. Particularly, the model used (1) dynamic variables informing about the main LC type, time since last change of LC type and which transitions has recently taken place; and (2) static variables, such as road density, elevation, slope and aspect. The variables were implemented in the model at 30-m resolution for the reserve. Then, the model estimated the fire ignition probability and simulated the fire spread based on three major drivers. Firstly, the land-use changes (e.g. rural abandonment, agricultural intensification and forest conversions) are simulated by using a demand-allocation approach where the quantity of change by time step is based on historical land-use trends, which allows emulating landscape dynamics under current land-use policies. Secondly, wildfire and fire suppression, in which the fire regime was calibrated by previously specifying a target annual burned area based on fire statistical data between 1983 and 2010 at the municipal level of the Spanish Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA, 2018) for Spain, and on fire perimeters for the period 1990–2010 of the Institute of Nature Conservation and Forests (https://www.icnf.pt/) for Portugal. Thirdly, the vegetation dynamics, including natural succession and post-fire regeneration, which was computed by identifying post-fire regeneration curves for each pixel of the study area

Table 1
Land-use and fire suppression scenarios implemented in the modelling simulations. The land-use scenario, the annual vegetation conversion rates under each land-use policy and the fire suppression levels are presented for each scenario.

Scenario acronym	Land-use scenario	Cropland to scrubland (ha)	Scrubland to cropland (ha)	Fire suppression level
RWild_LS	RWild	400	0	Low
RWild_CS	RWild	400	0	Current
RWild_HS	RWild	400	0	High
HNVf_LS	HNVf	0	400	Low
HNVf_CS	HNVf	0	400	Current
HNVf_HS	HNVf	0	400	High

by using a Normalized Difference Vegetation Index time series according to Gutman and Ignatov (1998). Final fire perimeters resulted from the spatio-temporal interactions between the landscape itself and the implementation of firefighting strategies.

2.4. Species distribution modelling and effects of management scenarios on biodiversity

2.4.1. Species data and environmental variables

In order to assess the impacts of alternative management scenarios on biodiversity, we built species distribution models (SDMs) for 102 vertebrates (79 birds, 15 reptiles and 8 amphibians; Appendix A) using a set of environmental variables. To do so, we gathered presence/absence data from the PGNP (Pimenta and Santarém, 1996; Soares et al., 2005) and the BLXNP (Domínguez et al., 2005, 2012) atlases. Birds data were available at 2 km resolution for the PGNP (for 1990–1995) and at 1 km (for 1998–2000) and 2 km resolution (for 2010) for the BLXNP. The data of amphibians and reptiles were available at 1 km resolution for both PGPN (for 1998–2003) and BLXNP (for 2010). SDMs were then conducted onto a 1-km grid covering the entire study area, using a minimum of 30 presences per species (Appendix A).

Environmental variables were selected in accordance with the temporal periods of the atlases data. Altitude, slope and aspect were acquired at 30 m resolution from a Global Digital Elevation Model of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (https://asterweb.jpl.nasa.gov/gdem.asp). LC variables, concretely percentage of evergreen forests, deciduous forests, agricultural areas, rocky areas with sparse vegetation and shrublands, were obtained from Landsat-derived data for 2010, and from REMAINS simulations for the period between 2020 and 2050, under the previously defined six management scenarios (RWild_LS, RWild_CS, RWild_HS, HNVf_LS, HNVf_CS and HNVf_HS). All environmental variables were consequently resampled into 1 km of spatial resolution.

2.4.2. Model fitting and evaluation

We built our SDMs using six modelling techniques (Generalized Linear Models, Generalized Additive Models, Random Forests, Artificial Neural Networks, Generalized Models of Boosted Regression, and Multivariate Adaptive Regression Splines) available in the R package 'biomod2' (http://r-forge.r-project.org/projects/biomod/). The models were fit using 80% of the data, while the remaining 20% were used for model evaluation through the area under the curve (AUC) of a receiver operating characteristics (ROC; Fielding and Bell, 1997). Subsequently, we built consensus predictions based on weighted averages of single-model projections for each species (Marmion et al., 2009; Araújo et al., 2011). Ensemble models were derived using a minimum of 10 model replicates (see Appendix A concerning model replicates and AUC quality thresholds for each species). These models were then projected for 2010 (one projection) and 2050 (using 40 fire-landscape model runs per management scenario, thus totaling 240 projections per species). Finally, consensus predictions were reclassified into presence/absence maps through ROC optimized thresholds available in 'biomod2' (Thuiller et al., 2009).

2.4.3. Effects of management scenarios on biodiversity

To evaluate the effects of land-use and fire suppression management scenarios on biodiversity, we calculated the predicted habitat suitability change between 2010 and 2050 for each species. We fitted multiple linear regression models using the species habitat suitability changes as dependent variables, and fire suppression level (low/curr/high) and land-use management (rewilding/HNVf) as independent variables. The effects of land-use and fire suppression management on species distributions were assessed based on model significance statistics (Appendix B). Finally, habitat suitability changes (between 2010 and 2050) were evaluated according to (i) species groups significantly affected by land-use and fire suppression management; and (ii) species' regional IUCN status (Appendix A).

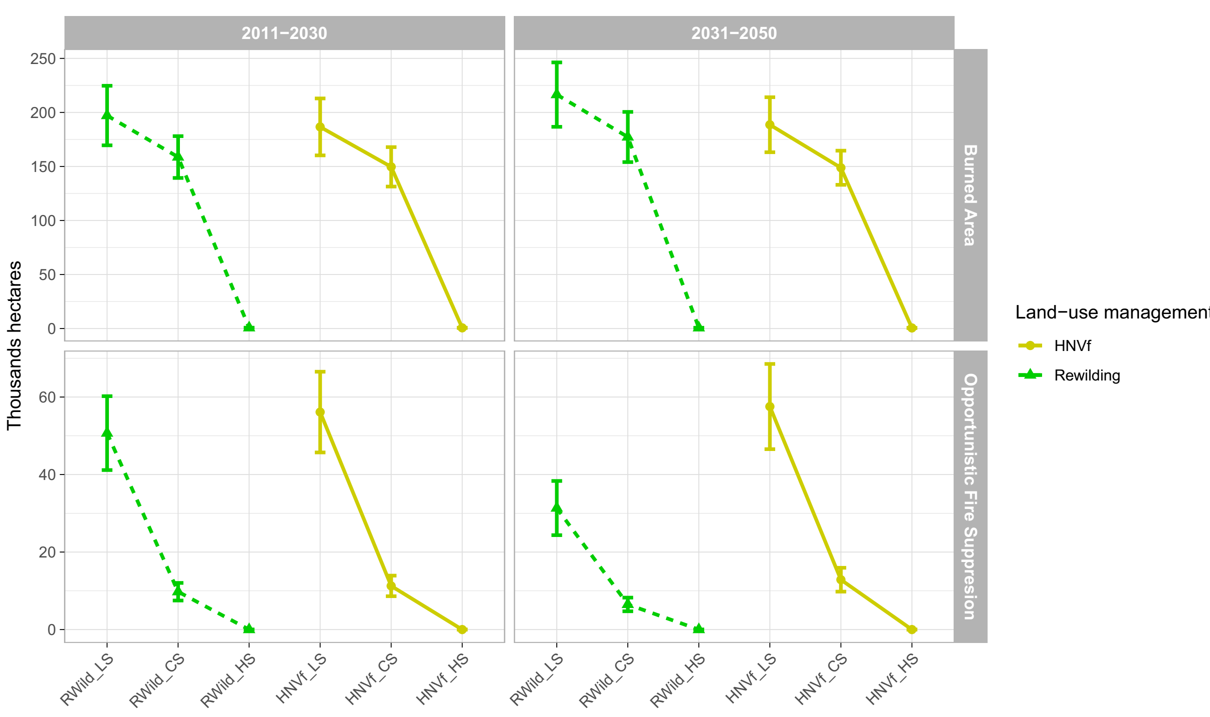


Fig. 3. Estimated burned and suppressed areas (following an opportunistic fire suppression, i.e. adopting open mosaics originated from agricultural activities as opportunities to stop fires) for two future periods (2011–2030 and 2031–2050), according to different land-use and fire management scenarios. Points and bars represent the mean and the mean standard error, respectively.

3. Results

3.1. Effects of management scenarios on fire regime

According to our simulations, future fires would burn around 175,000 (RWild_CS) and 150,000 (HNVf_CS) hectares between 2031 and 2050 under the current fire suppression system (more than 8500 and 7500 ha/year, respectively). Scenarios with the highest fire suppression levels would largely reduce burned areas (Fig. 3). However, firefighting opportunities from open areas generated by agricultural activities would become most impactful under low suppression scenarios (see fire suppression in Fig. 3), with significant differences (up to 30,000 ha; i.e. 1500 ha/year) between rewilding and HNVf scenarios in the long term (2031–2050) as farmland areas gradually increase (see “cropland” in Appendix C).

3.2. Effects of management scenarios on biodiversity

Our ensemble models presented high predictive accuracy (AUC = 0.92 ± 0.06; TSS = 0.72 ± 0.14; Appendix A) and revealed different responses of biodiversity to land-use and fire suppression management (Fig. 4 and Appendix D).

Land-use management significantly affected more species (83%) than fire suppression management (48%) (Fig. 4 and Appendix B). HNVf scenarios would increase habitat suitability for more than half of the species (N = 64), whereas rewilding scenarios are predicted to increase suitable habitats for 20% of species (N = 21). However, several threatened and endemic species are significantly benefited by rewilding scenarios (Fig. 5), including the only critically endangered species (habitat gains of more than 50%), and most of the endangered (3 out of 5 species; Appendix E) and vulnerable species (6 out of 11 species;

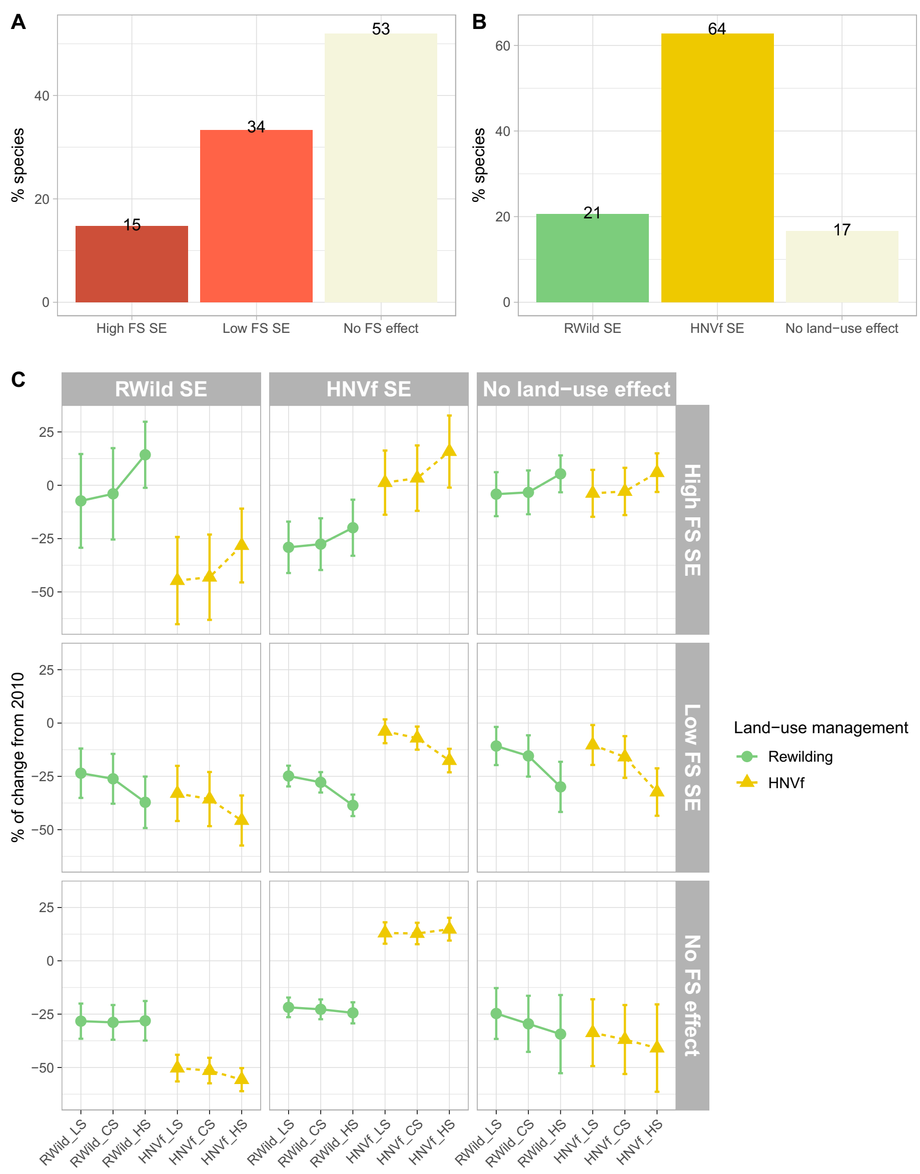


Fig. 4. Effects of management scenarios on biodiversity. (A) Percentage of species benefited by fire suppression (FS) management scenarios (2050), independently of the land-use scenario and (B) percentage of species benefited by land-use management scenarios, independently of the fire management scenarios (2050). (C) Total habitat suitability change (2010–2050) according to species groups significantly affected by (1) land-use management (significant effects - SE; species with no significant effects are plotted as “No FS/land-use effects”) and (2) fire suppression (FS) management scenarios, i.e. species significantly affected by high (High FS SE) and low (Low FS SE) fire suppression tendencies, and with no significant effects (No FS effect). Points and bars are representing the mean and the mean standard error, respectively.

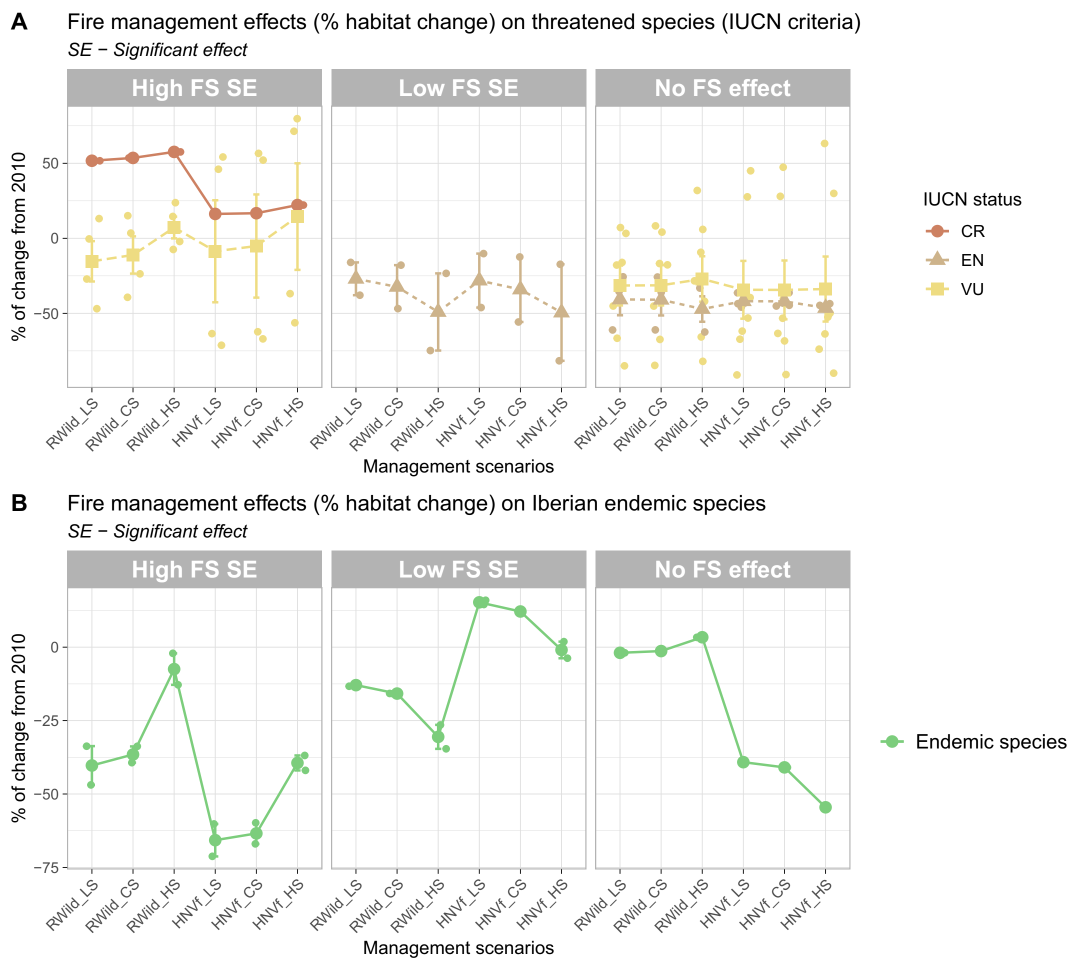


Fig. 5. Effects of management scenarios on threatened and endemic biodiversity. (A) Changes (%) of habitat suitability for 2050 (in comparison to 2010) for threatened (regional IUCN criteria) and (B) endemic species from the Iberian Peninsula. The species are plotted according to the fire suppression (FS) management scenarios significant effects (SE), i.e. species significantly affected by high (High FS SE) and low (Low FS SE) fire suppression tendencies, and with no significant effects (No FS effect). Points and bars represent the mean and the mean standard error, respectively.

Appendix F). Iberian endemics would be particularly benefited by HNVf under low fire suppression levels (15% of habitat gain). Still, several endemic species also profit from rewilding scenarios, concretely those significantly affected by high suppression strategies and those not affected by fire suppression management (Fig. 5).

Concerning the effects of fire suppression management, a high proportion of species (33%) is predicted to benefit from low fire suppression (i.e., fire-mediated landscapes), while only 15% profit from high fire suppression, both in detriment of the current fire suppression system (Fig. 4).

4. Discussion

4.1. Effects of management strategies on fire mitigation

The current tendency of land abandonment would increase the impacts of future fires (Fig. 3), which might be explained by encroachment of vegetation dominated by more flammable species in areas previously occupied by farmlands and sparse vegetation (Appendix D). The implementation of an HNVf scenario could represent a more efficient (and cost-effective) fire mitigation strategy in the long-term (Fig. 3), as also demonstrated in other regions of the Iberian Peninsula (Aquilué et al., 2020). Our fire-vegetation simulations reinforce these assumptions, by demonstrating potential advantages of letting unplanned fires burn to increase fire suppression opportunities derived from new open areas (Fig. 3). Letting unplanned fires burn under favorable weather conditions in landscapes with higher availability of semi-open areas might contribute to increase fire-suppression opportunities by reducing fuel accumulation and promoting accessibility for firefighting (Duane et al., 2019).

4.2. Effects of management strategies on biodiversity

Three main findings should be highlighted from our results: 1) there is a high variability of biodiversity responses to different combinations of land-use and fire suppression management strategies; 2) HNVf management would benefit the majority of species (more than 60%) in detriment of rewilding scenarios (Fig. 4); and 3) a substantial number of species (more than a third) would profit from scenarios with more fire in the landscape (i.e., low fire suppression levels; Fig. 4). The majority of the studied species profited from HNVf scenarios, reinforcing that maintaining some agricultural areas contributes to biodiversity at the landscape level (Halada et al., 2011; Lomba et al., 2020). The effective implementation of HNVf policies could have an impactful repercussion on biodiversity conservation in our study area, given the small extent of agricultural areas in comparison to other LC types such as shrublands (c.a. 60%) and forests (c.a. 20%). Land abandonment and subsequent vegetation encroachment leads to habitat losses for farmland specialists and other species adapted to open and semi-open areas (Appendices B and D). However, other species would benefit from these conditions, especially when associated with high fire suppression strategies (Fig. 4; Appendices B and D). These species are mostly represented by forest bird specialists and amphibians (Appendices B and D), which are more dependent on wetter and cooler habitats with dense vegetation.

The importance of fire lies in the creation and maintenance of open habitats, particularly in areas susceptible to gradual farmland abandonment that would produce more homogeneous and flammable landscapes. In fact, the positive response of a large group of species to lower fire suppression levels (Fig. 4; Appendices B and D) might be precisely related to the creation of open spaces (and fragmentation of wood and scrub matrices) promoted by wildfires. New open habitats can be potentially recolonized from surrounding habitat patches, a pattern already acknowledged for reptiles and early successional bird species (Regos et al., 2016; Chergui et al., 2019). Still, previous studies have observed distinct responses of biodiversity communities to fire according to different post-fire recovery and recolonization trajectories in Mediterranean burnt areas (Bros et al., 2011; Mateos et al., 2011; Santos et al., 2016). All these contrasting patterns suggest a context-dependent response (i.e. habitat dominance at the landscape level and habitat preference of the species) of biodiversity and biotic communities to fire-landscape dynamics (Pausas and Parr, 2018).

4.3. Implications for biodiversity conservation and landscape management

4.3.1. Optimal management scenario: HNVf with high fire suppression

The implementation of HNVf combined with high fire suppression strategies, although demanding a careful strategic planning to avoid extreme fire hazards derived from firefighting trap effects, would represent an optimal management approach that could contribute to both fire mitigation and biodiversity conservation (Fig. 4). The historical human interventions that shaped Mediterranean landscapes over millennia sustained high levels of biodiversity. The promotion of HNVf would benefit several species adapted to these semi-natural habitats and dependent on the continuation of specific farming systems (Fig. 4 and Appendix D), including many taxa of conservation concern currently threatened by land abandonment processes (Franks et al., 2018; Pais et al., 2020; Fig. 5). The continuous abandonment of these practices will cause negative impacts for several species (Fig. 4 and Appendix D), which highlights the need for stable rural policies and long-term socio-economic projects to sustain agricultural activities in rural mountain areas.

Nonetheless, the success and continuation of HNVf demands tailored socio-economic and political strategies exploring alternative and more efficient solutions than economic incentives (Lomba et al., 2020). Increasing capacity building, societal cooperation and raising awareness for the values of biodiversity and ecosystem services in these regions are paramount for sustaining the natural and cultural heritage associated with these traditional activities. Still, given the currently dominating tendencies of land abandonment and the difficulties to reinforce the current fire suppression system (due to the high costs involved and the low accessibility in steep mountainous areas), HNVf should be considered as complementary to other alternative management scenarios to assure cost-effectiveness and adequate implementation.

4.3.2. Alternative management scenario: using fire to enhance rewilding

Our simulations support rewilding as a beneficial scenario for forest-adapted species and taxonomic groups considered most vulnerable to environmental and landscape disturbances (e.g. amphibians). Moreover, rewilding scenarios would promote stabilization of suitable areas and considerable increases of available habitats for several threatened and endemic species inside the reserve (Fig. 5). The habitat gains are particularly noticeable for critically endangered (Appendix E) and vulnerable taxa (Appendix F), highlighting the potential of rewilding policies for protecting unique biodiversity of conservation concern.

According to these results, and given the overall ineffectiveness of current European agricultural policies (Pe'er et al., 2014, 2019), our study suggests an alternative and practicable scenario centered on fire-mediated rewilding, consistent with the continuous trend of depopulation in the study area. In such a scenario, the potential hazards of rewilding would be buffered by low fire suppression strategies, both by controlling the effects of unplanned fires and by using strategic prescribed fires. This scenario would contribute to an opportunistic fire mitigation and to potential increases in pyrodiversity for supporting biodiversity conservation (Kelly et al., 2015, 2017).

Alternative scenarios integrating both rewilding and HNVf management at the landscape level should also be considered (Merckx and Pereira, 2015; Lomba et al., 2020), since their combined implementation would potentially contribute to achieve different conservation goals (e.g. conservation of biodiversity adapted to agricultural and forested areas) and to secure a wider range of ecosystem services (Pais et al., 2020). Future strategic planning and decision-making in the region, however, should consider the prospective trade-offs between fire mitigation, ecosystem services and conservation of different facets of biodiversity.

5. Conclusions

This study contributes to the increasing evidence of agricultural policies as essential tools to ensure biodiversity while reducing fire hazard, an aspect that has been frequently neglected when assessing the beneficial effects of agricultural policies. Also, our study suggests using fire to enhance rewilding as an alternative management strategy in our study area — an issue that decision makers and managers should consider when implementing rewilding initiatives in other fire-prone regions. Additionally, our study highlights the need for renewed political and socio-economic efforts exploring different solutions to economic incentives and/or management strategies integrating both rewilding and HNVf. In this context, our study demonstrates how an effective implementation of European agricultural policies could benefit biodiversity (through the creation of new open habitats for endangered species) while providing further fire-suppression opportunities. Our study also shows how fire suppression policies can help the implementation of rewilding initiatives in other abandoned, fire-prone mountain areas across Southern Europe. It also goes beyond the business-as-usual scenarios and provides plausible future pathways wherein rewilding modulated by fire suppression can emerge as nature-based solution if the new EU Common Agricultural Policy continues to fail at reversing rural abandonment trends. From a methodological perspective, our study highlights the need of taking into account the landscape dynamics and fire-vegetation feedbacks when modelling future management scenarios in mountain landscapes of Southern Europe — highly dynamic areas historically driven by the spatial interaction between fire-related processes (such as fire and post-fire recovery) and human interventions (land-use and fire suppression policies).

CRediT authorship contribution statement

Conceived and designed the experiments: JCC, AR. Experiments and data analyses: JCC, JB, AR. Contributed data/analysis tools: NA, JD, BM, FM-F. Draft preparation: JCC. Visualization: JCC. Writing, review and editing: all authors.

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.

Acknowledgements

The authors thank Adrián Lamosa Torres, Xosé Pardavila and Alberto Gil for their help during fieldwork in Xurés; and Rafael Vázquez for providing additional data of amphibians and reptiles.

Funding

This research was supported by Portuguese national funds through FCT - Foundation for Science and Technology, I.P., under the FirESmart project (PCIF/MOG/0083/2017), and by project INMODES (CGL2017-89999-C2-2-R) funded by the Spanish Ministry of Science and Innovation.

AL, FM and FM-F were supported by FCT (DL57/2016/CP1440/CT0001, IF/01053/2015; and DL57/2016/CP1440/CT0010, respectively). AR was supported by the Xunta de Galicia (ED481B2016/084-0) and IACOBUS program (INTERREG V-A España–Portugal, POCTEP 2014–2020).

Appendix A–F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142897.

References

Aquilué, N., Fortin, M.-J., Messier, C., Brotons, L., 2020. The potential of agricultural conversion to shape forest fire regimes in Mediterranean landscapes. Ecosystems 23, 34–51. https://doi.org/10.1007/s10021-019-00385-7.

Araújo, M.B., Alagador, D., Cabeza, M., Nogués-Bravo, D., Thuiller, W., 2011. Climate change threatens European conservation areas. Ecol. Lett. 14, 484–492. https://doi.org/10.1111/j.1461-0248.2011.01610.x.

Bajocco, S., Ferrara, C., Guglietta, D., Ricotta, C., 2019. Fifteen years of changes in fire ignition frequency in Sardinia (Italy): a rich-get-richer process. Ecol. Indic. 104, 543–548. https://doi.org/10.1016/j.ecolind.2019.05.030.

Berry, L.E., Lindenmayer, D.B., Driscoll, D.A., 2015. Large unburnt areas, not small unburnt patches, are needed to conserve avian diversity in fire-prone landscapes. J. Appl. Ecol. 52, 486–495. https://doi.org/10.1111/1365-2664.12387.

Bros, V., Moreno-Rueda, G., Santos, X., 2011. Does postfire management affect the recovery of Mediterranean communities? The case study of terrestrial gastropods. For. Ecol. Manag. 261, 611–619. https://doi.org/10.1016/j.foreco.2010.11.014.

Chas-Amil, M.L., Prestemon, J.P., McClean, C.J., Touza, J., 2015. Human-ignited wildfire patterns and responses to policy shifts. Appl. Geogr. 56, 164–176. https://doi.org/10.1016/j.apgeog.2014.11.025.

Chergui, B., Fahd, S., Santos, X., 2019. Are reptile responses to fire shaped by forest type and vegetation structure? Insights from the Mediterranean basin. For. Ecol. Manag. 437, 340–347. https://doi.org/10.1016/j.foreco.2019.01.046.

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.

Domínguez, J., Lamosa, A., Pardavila, X., Martınez-Freirıa, 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. p. 423.

Duane, A., Aquilué, N., Canelles, Q., Morán-Ordoñez, A., De Cáceres, M., Brotons, L., 2019. Adapting prescribed burns to future climate change in Mediterranean landscapes. Sci. Total Environ. 677, 68–83. https://doi.org/10.1016/j.scitotenv.2019.04.348.

Estoque, R.C., Gomi, K., Togawa, T., Ooba, M., Hijioka, Y., Akiyama, C.M., Kuroda, K., 2019. Scenario-based land abandonment projections: method, application and implications. Sci. Total Environ. 692, 903–916. https://doi.org/10.1016/j.scitotenv.2019.07.204.

Fernandes, P.M., 2013. Fire-smart management of forest landscapes in the Mediterranean basin under global change. Landsc. Urban Plan. 110, 175–182. https://doi.org/10.1016/j.landurbplan.2012.10.014.

Fernandes, P.M., Rego, F.C., Rigolot, E., 2011. The FIRE PARADOX project: towards science-based fire management in Europe. For. Ecol. Manag. 261, 2177–2178. https://doi.org/10.1016/j.foreco.2010.12.024.

Fernandes, P.M., Monteiro-Henriques, T., Guiomar, N., Loureiro, C., Barros, A.M., 2016a. Bottom-up variables govern large-fire size in Portugal. Ecosystems 19, 1362–1375. https://doi.org/10.1007/s10021-016-0010-2.

Fernandes, P.M., Pacheco, A.P., Almeida, R., Claro, J., 2016b. The role of fire-suppression force in limiting the spread of extremely large forest fires in Portugal. Eur. J. For. Res. 135, 253–262. https://doi.org/10.1007/s10342-015-0933-8.

Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ. Conserv. 24, 38–49. https://doi.org/10.1017/S0376892997000088.

Franks, S.E., Roodbergen, M., Teunissen, W., Carrington Cotton, A., Pearce-Higgins, J.W., 2018. Evaluating the effectiveness of conservation measures for European grassland-breeding waders. Ecology and Evolution 8, 10555–10568. https://doi.org/10.1002/ece3.4532.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region—a review. Agric. Ecosyst. Environ. 140, 317–338. https://doi.org/10.1016/j.agee.2011.01.003.

Gillson, L., Ladle, R.J., Araújo, M.B., 2011. Baselines, patterns and process. Conservation Biogeography. Wiley-Blackwell, Oxford, pp. 31–44.

Gutman, G., Ignatov, A., 1998. The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. Int. J. Remote Sens. 19, 1533–1543. https://doi.org/10.1080/014311698215333.

Halada, L., Evans, D., Romão, C., Petersen, J.E., 2011. Which habitats of European importance depend on agricultural practices? Biodivers. Conserv. 20, 2365–2378. https://doi.org/10.1007/s10531-011-9989-z.

Houtman, R.M., Montgomery, C.A., Gagnon, A.R., Calkin, D.E., Dietterich, T.G., McGregor, S., Crowley, M., 2013. Allowing a wildfire to burn: estimating the effect on future fire suppression costs. Int. J. Wildland Fire 22, 871–882. https://doi.org/10.1071/WF12157.

Kelly, L.T., Brotons, L., 2017. Using fire to promote biodiversity. Science 355, 1264–1265. https://doi.org/10.1126/science.aam7672.

Kelly, L.T., Bennett, A.F., Clarke, M.F., McCarthy, M.A., 2015. Optimal fire histories for biodiversity conservation. Conserv. Biol. 29, 473–481. https://doi.org/10.1111/cobi.12384.

Kelly, L.T., Brotons, L., McCarthy, M.A., 2017. Putting pyrodiversity to work for animal conservation. Conserv. Biol. 31, 952–955. https://doi.org/10.1111/cobi.12861.

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M.P., Lana-Renault, N., 2017. Space–time process and drivers of land abandonment in Europe. Catena 149, 810–823. https://doi.org/10.1016/j.catena.2016.02.024.

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. Manag. 259, 2366–2374. https://doi.org/10.1016/j.foreco.2010.03.009.

Lomba, A., Moreira, F., Klimek, S., Jongman, R.H., Sullivan, C., Moran, J., McCracken, D.I., 2020. Back to the future: rethinking socioecological systems underlying high nature value farmlands. Front. Ecol. Environ. 18, 36–42. https://doi.org/10.1002/fee.2116.

MAPAMA, 2018. Estadísticas de incendios forestales. Consultado en Marzo de 2018. http://www.mapama.gob.es/es/desarrollo-rural/estadisticas/Incendios_default.aspx.

Marmion, M., Parviainen, M., Luoto, M., Heikkinen, R.K., Thuiller, W., 2009. Evaluation of consensus methods in predictive species distribution modelling. Divers. Distrib. 15, 59–69. https://doi.org/10.1111/j.1472-4642.2008.00491.x.

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. 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., Balch, J.K., 2020. Fire as a fundamental ecological process: research advances and frontiers. J. Ecol. 108, 2047–2069. https://doi.org/10.1111/1365-2745.13403.

Merckx, T., Pereira, H.M., 2015. Reshaping agri-environmental subsidies: from marginal farming to large-scale rewilding. Basic and Applied Ecology 16, 95–103. https://doi.org/10.1016/j.baae.2014.12.003.

Moreira, F., Pe'er, G., 2018. Agricultural policy can reduce wildfires. Science 359, 1001. https://doi.org/10.1126/science.aar8120.

Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Bilgili, E., 2011. Landscape - wildfire interactions in southern Europe: implications for landscape management. J. Environ. Manag. 92, 2389–2402. https://doi.org/10.1016/j.jenvman.2011.06.028.

Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M., Curt, T., 2020. Wildfire management in Mediterranean-type regions: paradigm change needed. Environ. Res. Lett. 15, 011001. https://doi.org/10.1088/1748-9326/ab541e.

Moritz, M.A., Batllori, E., Bradstock, R.A., Gill, A.M., Handmer, J., Hessburg, P.F., Syphard, A.D., 2014. Learning to coexist with wildfire. Nature 515, 58–66. https://doi.org/10.1038/nature13946.

Navarro, L.M., Pereira, H.M., 2015. Rewilding abandoned landscapes in Europe. Rewilding European Landscapes. Springer, Cham https://doi.org/10.1007/s10021-012-9558-7.

Pais, S., Aqlué, N., Campos, J., Sil, Â., Marcos, B., Martínez-Freiría, F., ... Regos, A., 2020. Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. Ecosystem Services 44, 101143. https://doi.org/10.1016/j.ecoser.2020.101143.

Pausas, J.G., Fernández-Muñoz, S., 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Clim. Chang. 110, 215–226. https://doi.org/10.1016/j.landusepol.2019.01.018.

Pausas, J.G., Parr, C.L., 2018. Towards an understanding of the evolutionary role of fire in animals. Evol. Ecol. 32, 113–125. https://doi.org/10.1007/s10682-018-9927-6.

Pe'er, G., Dicks, L.V., Visconti, P., Arlettaz, R., Báldi, A., Benton, T.G., Scott, A.V., 2014. EU agricultural reform fails on biodiversity. Science 344, 1090–1092. https://doi.org/10.1126/science.1253425.

Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Hansjürgens, B., 2019. A greener path for the EU Common Agricultural Policy. Science 365, 449–451. https://doi.org/10.1126/science.aax3146.

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P.H., Marquard, E., 2020. Action needed for the EU Common Agricultural Policy to address sustainability challenges. People and Nature 2, 305–316. https://doi.org/10.1002/pan3.10080.

Perino, A., Pereira, H.M., Navarro, L.M., Fernández, N., Bullock, J.M., Ceaușu, S., ... Wheeler, H.C., 2019. Rewilding complex ecosystems. Science 80 (364), eaav5570. https://doi.org/10.1126/science.aav5570.

Pimenta, M., Santarém, M.L., 1996. Atlas das Aves do Parque Nacional da Peneda-Gerês.

Ponisio, L.C., Wilkin, K., M'Gonigle, L.K., Kulhanek, K., Cook, L., Thorp, R., Kremen, C., 2016. Pyrodiversity begets plant-pollinator community diversity. Glob. Chang. Biol. 22, 1794–1808. https://doi.org/10.1111/gcb.13236.

Queiroz, C., Beilin, R., Folke, C., Lindborg, R., 2014. Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. Front. Ecol. Environ. 12, 288–296. https://doi.org/10.1890/120348.

Regos, A., Aquilué, N., Retana, J., De Cáceres, M., Brotons, L., 2014. Using unplanned fires to help suppressing future large fires in mediterranean forests. PLoS One 9, 1–10. https://doi.org/10.1371/journal.pone.0094906.

Regos, A., Ninyerola, M., Moré, G., Pons, X., 2015. 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.

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

San Roman Sanz, A., Fernandez, C., Mouillot, F., Ferrat, L., Istria, D., Pasqualini, V., 2013. Long-term forest dynamics and land-use abandonment in the Mediterranean mountains, Corsica, France. Ecol. Soc. 18.

San-Miguel-Ayanz, J., Moreno, J.M., Camia, A., 2013. Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. For. Ecol. Manag. 294, 11–22. https://doi.org/10.1016/j.foreco.2012.10.050.

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.

Soares, C., Álvares, F., Loureiro, A., Sillero, N., Arntzen, J.W., Brito, J.C., 2005. Atlas of the Amphibians and Reptiles of Peneda-Gerês National Park, Portugal.

Taylor, R.S., Watson, S.J., Nimmo, D.G., Kelly, L.T., Bennett, A.F., Clarke, M.F., 2012. Landscape-scale effects of fire on bird assemblages: does pyrodiversity beget biodiversity? Divers. Distrib. 18, 519529. https://doi.org/10.1111/j.1472-4642.2011.00842.x.

Tedim, F., Remelgado, R., Borges, C., Carvalho, S., Martins, J., 2013. Exploring the occurrence of mega-fires in Portugal. For. Ecol. Manag. 294, 86–96. https://doi.org/10.1016/j.foreco.2012.07.031.

Thuiller, W., Lafourcade, B., Engler, R., Araújo, M.B., 2009. BIOMOD - a platform for ensemble forecasting of species distributions. Ecography 32, 369–373. https://doi.org/10.1111/j.1600-0587.2008.05742.x.

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. 283. https://doi.org/10.1098/rspb.2016.1703.

Turco, M., Jerez, S., Augusto, S., Tarín-Carrasco, P., Ratola, N., Jiménez-Guerrero, P., Trigo, R.M., 2019. Climate drivers of the 2017 devastating fires in Portugal. Sci. Rep. 9, 1–8. https://doi.org/10.1038/s41598-019-50281-2.

Ursino, N., Romano, N., 2014. Wild forest fire regime following land abandonment in the Mediterranean region. Geophys. Res. Lett. 41, 8359–8368. https://doi.org/10.1002/2014GL061560.

van Leeuwen, C.C., Cammeraat, E.L., de Vente, J., Boix-Fayos, C., 2019. The evolution of soil conservation policies targeting land abandonment and soil erosion in Spain: a review. Land Use Policy 83, 174–186. https://doi.org/10.1016/j.landusepol.2019.01.018.

Viedma, O., Moity, N., Moreno, J.M., 2015. Changes in landscape fire-hazard during the second half of the 20th century: agriculture abandonment and the changing role of driving factors. Agric. Ecosyst. Environ. 207, 126–140. https://doi.org/10.1016/j.agee.2015.04.011.

Williams, J., 2013. Exploring the onset of high-impact mega-fires through a forest land management prism. For. Ecol. Manag. 294, 4–10. https://doi.org/10.1016/j.foreco.2012.06.030.

Xystrakis, F., Psarras, T., Koutsias, N., 2017. A process-based land use/land cover change assessment on a mountainous area of Greece during 1945–2009: signs of socio-economic drivers. Sci. Total Environ. 587, 360–370. https://doi.org/10.1016/j.scitotenv.2017.02.161.