Ecological Processes

RESEARCH

Open Access

Will fire-smart landscape management buffer the effects of climate and land-use changes on fire regimes?

Ângelo Sil[1,2,3,4,5,6*], João C. Azevedo[5,6], Paulo M. Fernandes[4] and João P. Honrado[1,2,3]

Abstract

Background Long-term farmland abandonment has increased fuel build-up in many Euro-Mediterranean mountainous regions. The high fuel hazard in these landscapes, combined with ongoing climate change, is increasing the frequency of extreme wildfires, thus altering contemporary fire regimes. Mitigating the loss of the landscape's capacity to regulate large and intense fires is crucial to prevent future harmful effects of fires. As such, effective strategies to manage these fire-prone landscapes are needed. Yet, further understanding of their performance under global change scenarios is required. This study assessed the effects of fire-smart management strategies on future landscape dynamics, fire regulation capacity (FRC), and fire regime in a Mediterranean fire-prone mountainous landscape in Portugal (30,650 ha) undergoing long-term land abandonment and climate change scenarios. For that, we applied the LANDIS-II model under climate change scenarios (RCP 4.5 and 8.5) and long-term farmland abandonment (2020–2050) according to three fire-smart management strategies focused on fire prevention compared with a business-as-usual (BAU) strategy based on fire suppression.

Results Future fire activity and land dynamics resulted in changes that fostered landscape heterogeneity and fragmentation and favoured fire-adapted forests and agroforestry systems while decreasing the dominance of shrublands and croplands. FRC decreased over time, particularly under RCP 8.5 and the BAU strategy. In turn, fire-smart strategies better prevented large and intense fires than the BAU strategy, but their effectiveness decreased under RCP 8.5. The loss of FRC resulted in increased burned area and fire frequency, which predicts a shift from contemporary fire regimes but more markedly under RCP 8.5 and in the BAU strategy.

Conclusions Fire-smart strategies outperformed BAU in averting current fire regime intensification. Merging forest- and silvopasture-based management is the most promising approach in taming the effects of climate and farmland abandonment on future fire activity. Our study underlines that planning and management policies in fire-prone Mediterranean mountain landscapes must integrate fire-smart strategies to decrease landscape fuel hazard and buffer the impact of global change on future fire regimes.

Keywords Fire management, Global change, LANDIS-II, Landscape dynamics, Mediterranean mountains, Wildfire

*Correspondence:
Ângelo Sil
angelosil@cibio.up.pt
Full list of author information is available at the end of the article

Background

The Euro-Mediterranean region is a highly fire-prone area (Pausas 2022), recording annually approximately 48,000 fires that burn over 438.9 thousand hectares of land (San-Miguel-Ayanz et al. 2022). Over the last decades, landscape fuel build-up driven by land abandonment (Mantero et al. 2020) or wildfire policies (Fernandes et al. 2020), together with higher temperatures and extended drought during summer (Jolly et al. 2015; Turco et al. 2017, 2019) increased the frequency of extreme fire events (Duane et al. 2021a), which led to high ecological and socioeconomic damages (Meier et al. 2023; WWF 2019) in Euro-Mediterranean regions.

Future climate projections for Euro-Mediterranean regions estimate annual warming rates during summer to be larger (20% to 50%) than the global annual average, with more intense and extended temperature extremes and heat waves (Ali et al. 2022). Although there is a decrease in the number of fires in many southern European countries (Turco et al. 2016), these warmer conditions may aggravate fire danger (Carnicer et al. 2022) and the likelihood of future fire activity in southern Europe, particularly in mountainous landscapes with high amounts of hazardous fuels (Dupuy et al. 2020) where farmland abandonment is predicted to continue (Perpiña Castillo et al. 2021; Dax et al. 2021), thus challenging their management (Moreira et al. 2020).

Mitigating the harmful ecological and societal effects of fire is crucial but requires the integration of fire-adapting management policies at various levels of governance, land planning, and landscape management (Gillson et al. 2019; UNEP 2022; Moritz et al. 2014). Europe's policy instruments acknowledge the need to protect people and nature from future threats driven by global change, such as wildfires (EU 2021a, b). Still, the lack of effective fire management policies in Euro-Mediterranean countries demands a balanced shift from the business-as-usual paradigm focused on fire suppression to integrated fire-smart management (Moreira et al. 2020; Faivre et al. 2018; Fernandes 2020).

Fire-smart management is a promising tool for controlling fire regimes through landscape interventions to reduce hazardous fuels and foster fire-resistant and -resilient landscapes (Fernandes 2013; Hirsch et al. 2001; Omi 2015). Yet, their integration into planning and management policies in fire-prone landscapes requires further understanding of the combined effects of ongoing climate change, landscape dynamics, and fire management strategies on fire regimes and their impacts on ecosystems (Castro Rego et al. 2021; Moreira et al. 2023; Fernandes 2013). As such, the concept of fire regime, defined as the spatial and temporal pattern of fires and their effects in a given area over a given period (Oddi 2018), helps characterize when, where, and which types of fires occur. It also addresses the (pre)conditions of fire occurrence and the immediate ecological and societal effects of fire (Krebs et al. 2010).

Moreover, integrating fire within the ecosystem (dis)services conceptual framework allows for a more balanced perspective on fire regimes and effects in the socio-ecological system (Depietri and Orenstein 2019; Sil et al. 2019a). In this sense, the fire regulation capacity (FRC) emerges as a valuable concept to assess and forecast fire regimes. FRC refers to ecosystems and landscapes' capacity to maintain fire impacts under acceptable thresholds for human well-being based on their structure and functioning (e.g., vegetation type, composition, structure, productivity, and spatial configuration) (Guenni et al. 2005; Sil et al. 2019b; Pettorelli et al. 2018). Still, further application and testing of this concept is needed (Depietri and Orenstein 2020).

Indicators derived from fire regime attributes (e.g., burned area and fire intensity) can be useful in assessing FRC and providing insights into how fire-prone landscapes respond to the ongoing set of global pressures (e.g., climate and land use change) in terms of ecological and socioeconomic effects (Sil et al. 2022). In this sense, landscape modelling tools can provide relevant information for landscape management (Keane et al. 2019). For example, fire behaviour modelling systems [e.g., Flammap; Finney (2006)], integrated fire-vegetation models [e.g. REMAINS; Pais et al. (2023)], dynamic global vegetation models (Argles et al. 2022) and landscape models [e.g., LANDIS-II; Scheller et al. (2007)] are suitable to address interactions among climate, fire, and vegetation.

Modelling studies in Euro-Mediterranean ecosystems have addressed the effects of land abandonment (Azevedo et al. 2011) or alternative landscape management strategies (Aquilué et al. 2020; Benali et al. 2021) on fire regime attributes and their impacts on ecosystem services and biodiversity (Pais et al. 2020; Campos et al. 2022; Iglesias et al. 2022). Yet, few have covered feedback between climate-fire-landscape dynamics and management strategies in a spatially explicit manner (Henne et al. 2015; Mairota et al. 2014; Millington et al. 2009; Mouillot et al. 2002).

Our study applies the LANDIS-II forest landscape model (Scheller et al. 2007) to a Mediterranean fire-prone landscape in NE Portugal to assess how alternative fire management strategies affect future landscape dynamics, the fire regulation capacity, and fire regimes under long-term farmland abandonment and climate change scenarios. Ultimately, this research aims to provide relevant information for planning and managing of the Sabor River upper basin and similar fire-prone mountainous landscapes elsewhere in the Euro-Mediterranean region in the context of global change.

Methods

Study area

The study area is the Sabor River upper basin (NE Portugal), a Mediterranean mountainous landscape with a total surface of 30,650 ha [Fig. 1a; EEA (2016)]. The area comprises a variety of land cover types, including native deciduous (e.g., *Quercus pyrenaica*) and evergreen broadleaved woodlands (e.g., *Quercus rotundifolia*), pine (e.g., *Pinus pinaster*) and non-native other conifers (e.g., *Pseudotsuga menziensii*) forests, shrublands (e.g., dominated by *Erica* spp., *Cytisus* spp. or *Cistus* spp.), natural grasslands (e.g., *Festuca elegans*), agroforestry systems (e.g., *Castanea sativa*), and agricultural areas. Seminatural areas of shrublands dominate the area (41%) followed by forests and woodlands (20%), grasslands (13%), and agroforestry (12%) and agricultural (9%) systems [Fig. 1b; DGT (2020)].

The Sabor River upper basin is a fire-prone landscape (Oliveira et al. 2021). Fire activity (1989–2019) is characterized by 35 fires/year that burn 1.7% of the area annually, with a fire rotation period of 58 years. Fires are usually small and low-intensity linked to agricultural or pastoral activities (Pereira et al. 2022). Large fires (> 100 ha) average 1 fire/year and are responsible for ca. 60% of the total burned area (Fig. 1c; ICNF (2021)).

Rural depopulation over the last decades (Azevedo et al. 2011) resulted in significant landscape changes, such as the decrease of croplands (24%) by conversion to seminatural areas (8%) and agroforestry systems (10%) or the expansion of forests (12%) at the expense of seminatural (6%) and former croplands (4%) areas (DGT 2019). Simultaneously, these changes increased the landscape's fire-proneness, leading to larger and more intense fires (Azevedo et al. 2011; Sil et al. 2019b).

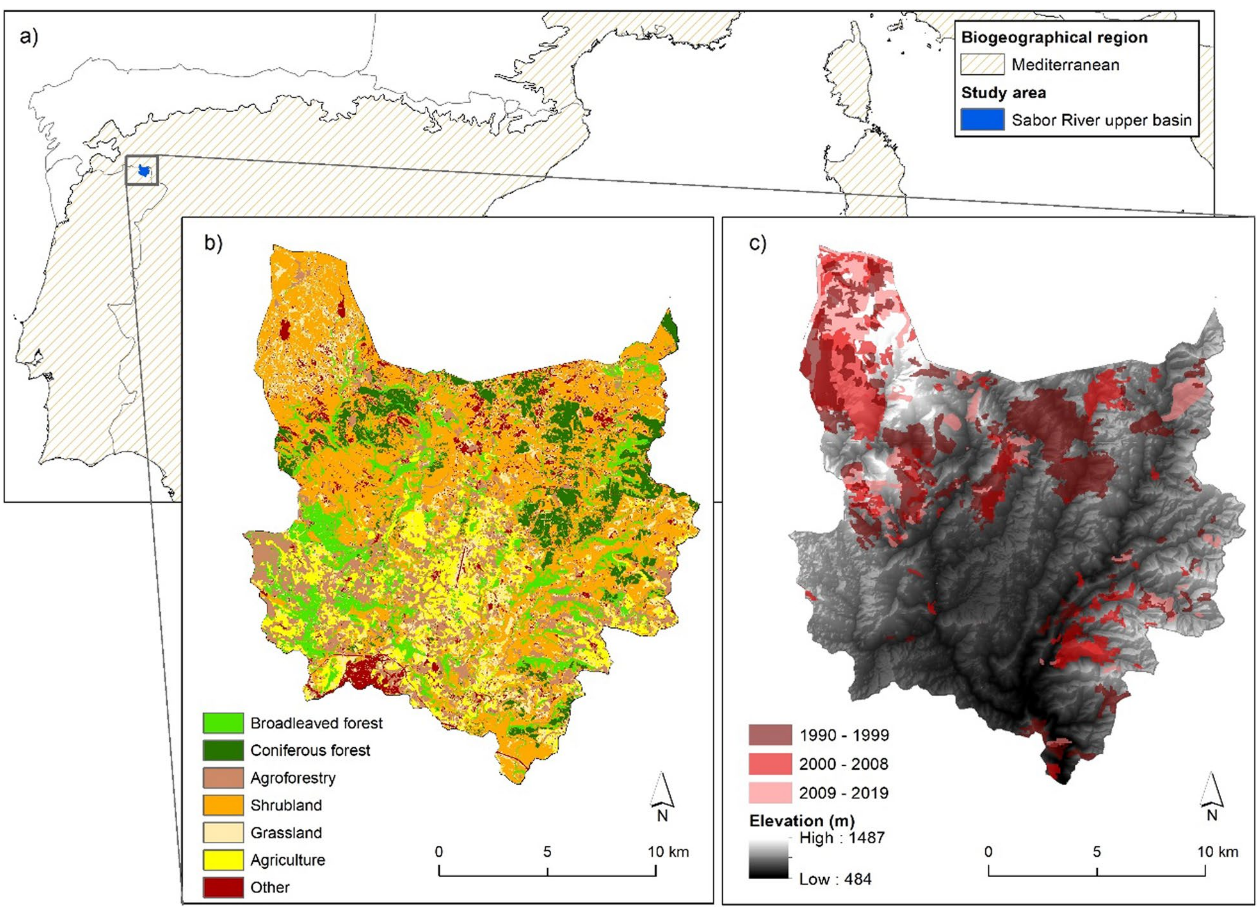

Fig. 1 **a** Location of the Sabor River upper basin in NE Portugal, including the distribution of the Mediterranean biogeographical region in the NW Iberian Peninsula (EEA 2016); **b** Land cover map with indication of major land cover types in 2020 (DGT 2020); **c** Elevation map with indication of burned areas in three-time intervals between 1990 and 2019 (ICNF 2021)

General approach and modelling framework

We applied a modelling and simulation approach using the LANDIS-II forest landscape model (FLM) (Scheller et al. 2007). LANDIS-II model is suitable for the development of this research because it simulates interactively the dynamics of several ecological and social processes at large temporal and spatial scales, incorporating climate and climate change within the simulated processes (Scheller et al. 2007). In our application, LANDIS-II was used to simulate at the site and landscape levels fire disturbance, vegetation succession, post-fire regeneration, and socio-ecological processes such as LULC change driven by farmland abandonment or fire management strategies over 30 years (2020–2050) under two climate change scenarios (Fig. 2). To do so, we coupled three LANDIS-II model extensions: the BFOLDS-FRM, the Boreal Forest Landscape Disturbance Simulator—Fire Regime Module v.2.1 (Ouellette et al. 2020; Perera et al. 2014), the Age-Only Succession v.5 (Scheller and Domingo 2019), and the Base Harvest v.5 (Scheller et al. 2019). Based on LANDIS-II FLM outputs, we assessed landscape dynamics (changes in composition and configuration), the capacity of the landscape to regulate potentially large and intense fires (FRC), and the fire regimes considering spatial and temporal patterns of fires (Fig. 2).

LANDIS-II FLM overview and setup

LANDIS-II FLM simulates temporal and spatial landscape dynamics through several ecological and social processes, such as fire and harvest disturbances, vegetation succession, and recovery after disturbance (Scheller et al. 2007). LANDIS-II FLM has been applied worldwide, although its application in Euro-Mediterranean ecosystems is scarce (Mairota et al. 2014; Sil et al. 2022; Suárez-Muñoz et al. 2021). Ecological and social processes run as software extensions (plug-ins) that operate at individual time steps and interact through the LANDIS-II core modelling platform during the simulation process in a grid cell environment (Figure A1—Appendix A). Feedback between landscape processes and spatial patterns allows continuous spatiotemporal outputs to assess disturbances and vegetation dynamics.

We coupled three LANDIS-II FLM extensions to develop landscape scenarios that simulate the outcome of fire management strategies in the context of the ongoing trend of farmland abandonment and under two climate change scenarios:

i) the Age-Only succession (Scheller and Domingo 2019) simulates ecological succession and post-disturbance regeneration based on spatially and non-spatially explicit processes. Model parameters, e.g., initial communities, species life history attributes, and species probability of establishment, were calibrated and validated for the study area based on several data sources, including spatial databases for the analysis of land cover changes and an extensive literature review for each species or vegetation types modelled (Appendix A—Sect. 1.1). Also, we conducted model sensitivity analysis to test assumptions on seed dispersal distance parameters (Appendix A—Sect. 1.1, Table A1.3);
ii) the BFOLDS-FRM (Ouellette et al. 2020; Perera et al. 2014) is a spatially explicit process-based model that simulates fire ignition, growth, and extinguishment at hourly time steps based on daily ignitions and weather conditions, fuel type, and terrain conditions as well as user-defined assumptions to derive spatial and temporal patterns of fire regime indicators. Model parameters were retrieved from a previous study for the Sabor River upper basin (Sil et al. 2022), wherein we tested model sensitivity against different assumptions in input data quality and conducted model calibration and validation by adjusting model parameters to emulate key fire regime attributes accurately (Appendix A—Sect. 1.2);
iii) the Base-Harvest (Scheller et al. 2019) simulates landscape disturbance driven by vegetation-management activities by combining spatial, temporal, and cohort removal components (Gustafson et al. 2000). We parametrized model extension (Appendix A—Sect. 1.3) to simulate potential land cover transitions driven by farmland abandonment and cropland conversion based on scientific literature addressing the influence of land use changes on farmland abandonment in mountainous regions of northern Portugal (Aguiar et al. 2009; Azevedo et al. 2011) and land cover change analysis in the study area. Also, model parameters to simulate fire management strategies were based on a previous study assessing the influence of land use and topography on wildfire occurrence in northern Portugal (Carmo et al. 2011).

We ran each extension at 1-year time steps and prepared spatial inputs at 10-m resolution. Also, we conducted a sample size study (Appendix A—Sect. 2, Figure A2), based on which 15 replicates for each combination of landscape/fire management and climate scenarios were run to account for model variability.

Farmland abandonment modelling

Long-term land abandonment in European regions is predicted to continue in the future, particularly in Mediterranean mountainous areas due to socio-ecological factors (Perpiña Castillo et al. 2021; Dax et al.

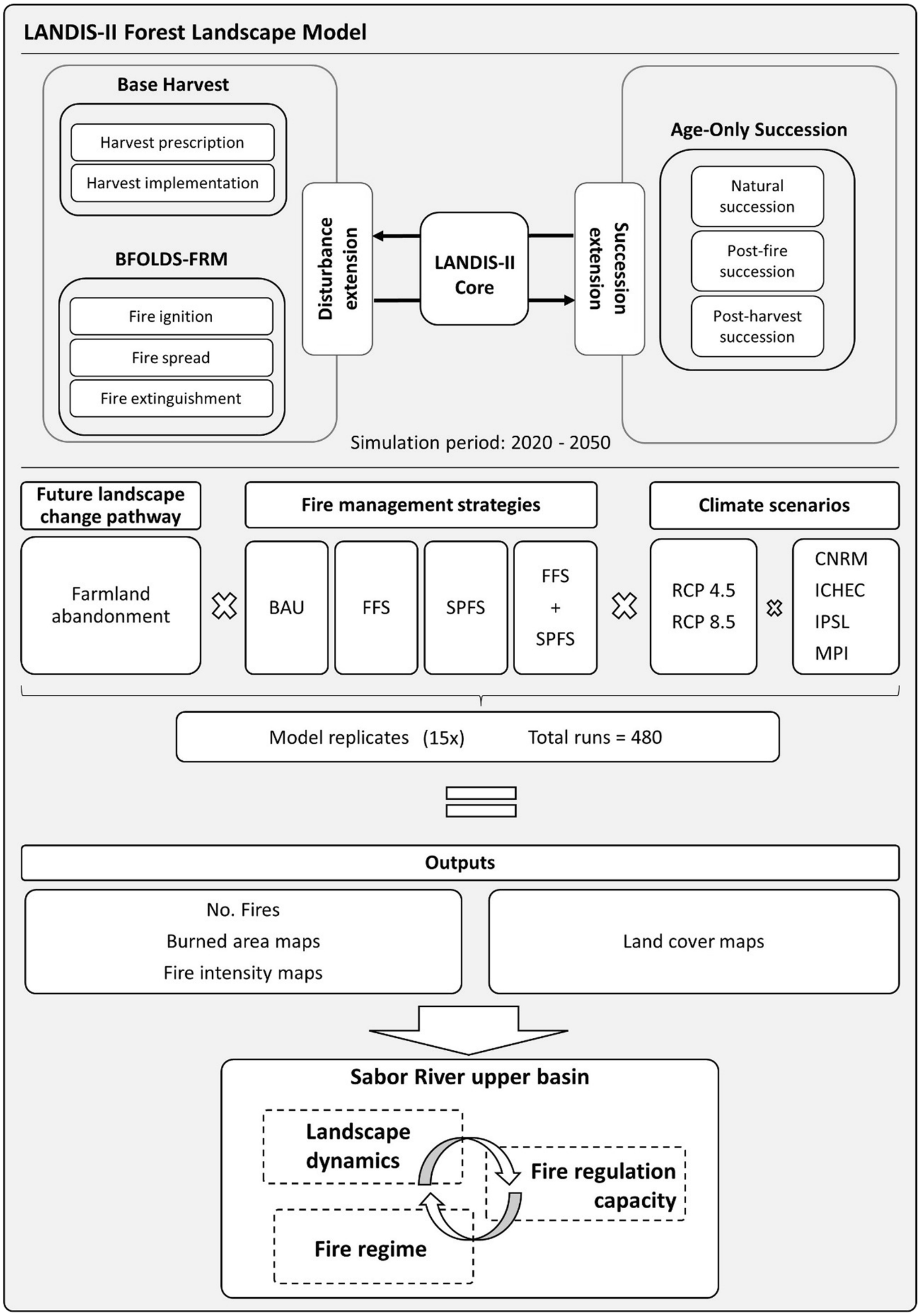

Fig. 2 Modelling workflow on the LANDIS-II FLM platform for the combination of long-term landscape trajectory, fire management scenarios (*BAU* Business-as-usual, *FFS* Forest-based fire-smart, *SPFS* Silvopasture-based fire-smart, *FFS* + *SPFS* Forest- and Silvopasture-based fire-smart), and climate change scenarios (*RCP* Representative Concentration Pathways 4.5 and 8.5) under four climate models (CNRM, ICHEC, IPSL, and MPI), and outputs used to assess landscape dynamics and fire regulation capacity, and characterize fire regimes in the Sabor River upper basin

2021). For example, the farmland abandonment rate for the NUTS 3—Terras de Trás-os-Montes region, of which the study area is part of, is projected between 0.6 and 1%/year until 2030 (Perpiña Castillo et al. 2021). Likewise, in the Sabor River upper basin, the loss in population in rural areas observed between 2011 and 2021 (INE 2021) along with the decrease in croplands observed between 1995 and 2018 (DGT 2019), suggests that the ongoing process of farmland abandonment will prevail in the area.

Based on these trends, we designed a farmland abandonment scenario, assuming the landscape pathway observed in the study area between 1995 and 2018 will continue over the simulation period. To do this, we analysed the land use and land cover changes observed in the area between 1995 and 2018, from which we identified the main transitions involving the loss of croplands. Specifically, we considered the conversion of marginal agricultural land into grassland and shrubland caused by vegetation encroachment and the conversion of croplands into agroforestry systems (sweet-chestnut groves). Simulated cropland transitions to mimic farmland abandonment were designed through the Base Harvest extension (Table A1.7—Appendix A) and applied to each combination of fire management strategy and climate change scenarios based on the rate of conversion of agricultural land to seminatural areas (shrubland and grasslands) and agroforestry systems observed between 1995 and 2018 in the study area (DGT 2019) as shown in Table 1.

Fire management strategies modelling

Three fire-smart management strategies focused on fire prevention were contrasted against a business-as-usual (BAU) management strategy focused on fire suppression.

We assumed that the BAU strategy reflects the current fire management policy in Euro-Mediterranean countries focused on fire suppression (Fernandes et al. 2020). In this sense, the BAU strategy assumes that fire-preventive management (i.e., landscape interventions to reduce wildfire hazard) remains negligible over time.

Fire-smart strategies were assumed as fire-preventive measures, i.e., aim to regulate the fire regime by decreasing fire behaviour potential (fire spread and intensity) as determined by vegetation, thus enabling more fire-resistant and fire-resilient landscapes (Fernandes 2013; Hirsch et al. 2001; Omi 2015). We modelled fire-smart management strategies based on a previous regional study on stakeholders' perceptions regarding fire management, where forest-based management (e.g., fuel types conversion, prescribed fire and vegetation thinning) and silvopasture-based management (e.g., livestock grazing and mechanical methods) were perceived as highly necessary to prevent large wildfires (Lecina-Diaz et al. 2023a). Three strategies were designed:

1. Forest-based fire-smart (FFS): applies fuel management by treating forest stands and seminatural areas to decrease fuel load and its vertical and horizontal continuity or by increasing the presence of less flammable and more fire-resilient forest types in the landscape (e.g., conversion of shrubland and conifer forests to evergreen oak woodlands);
2. Silvopasture-based fire-smart (SPFS): applies livestock grazing and mechanical operations to reduce fuel load and continuity in potentially abandoned marginal agricultural land (e.g., conversion of abandoned marginal cropland to grazed grassland), shrublands around forest stands (e.g., conversion to grasslands with low fuel load), and agroforestry areas; and
3. Forest- and Silvopasture-based fire-smart (FFS + SPFS): combines FFS and SPFS treatments and vegetation type conversions targeting fuel hazard.

Each of the fire-smart management strategies was implemented by shifts in parameters of BFOLDS-FRM and/or Base Harvest extensions (Tables A1.6 and A1.7—Appendix A). The potential managed area resulting from each of the management strategies is shown in Table 2.

Table 1 Mean annual rate of cropland area converted (%/year) to seminatural and agroforestry classes observed in the study area (1995–2018) and simulated (2020–2050) in each fire management strategy (15 repetitions) to mimic farmland abandonment in the Base Harvest extension

Transition		Observed (1995–2018)	Simulated (2020–2050)
From	To		
Cropland	Grassland	0.5	0.2
Cropland	Shrubland		0.2
Cropland	Agroforestry	0.6	0.7

Climate change scenarios

We controlled uncertainty around future climate conditions by using four climate models to simulate the effects of two climate change scenarios for 2050: Representative Concentration Pathways (RCP) 4.5 and 8.5 (Pedersen et al. 2020). RCP 4.5 and RCP 8.5 represent intermediate and more extreme conditions compared to the reference period (1989–2005). Data for the climate scenarios were obtained from four climate models (CNRM, ICHEC,

Table 2 Potential mean managed area (%) per management operation in each fire-smart management strategy (15 repetitions) and climate scenario over the 30 years of simulation in BFOLDS-FRM and Base Harvest extensions

Fire management strategy	Climate scenario	Management operations					
		Fuel reduction (vegetation removal + prescribed burning)	Fuel structure modification (pruning)	Fuel type conversion	Fuel reduction (grazing)	Fuel reduction (mechanical)	Total
FFS	RCP 4.5	1.2	19.5	5.5	–	–	26.2
	RCP 8.5	1.2	19.9	5.5	–	–	26.7
SPFS	RCP 4.5	–	–	–	13.4	12.0	25.4
	RCP 8.5	–	–	–	13.4	12.0	25.4
FFS + SPFS	RCP 4.5	1.2	19.0	5.2	13.6	12.1	51.2
	RCP 8.5	1.2	19.4	5.2	13.7	12.1	51.7

FFS Forest-based fire-smart, *SPFS* Silvopasture-based fire-smart, *FFS + SPFS* Forest- and Silvopasture-based fire-smart strategy

IPSL, and MPI) generated within the EURO-CORDEX project (Jacob et al. 2020). This framework has been applied recently in studies encompassing our study area (Aparício et al. 2022; Iglesias et al. 2022; Campos et al. 2022). Climate data were used to feed the BFOLDS-FRM extension of LANDIS-II FLM. These datasets consist of data points in a 9 × 9 grid cell for daily mean values of temperature and wind speed and direction measured at 10-m height, daily minimum relative humidity and cumulative daily precipitation, which were used to compute the Canadian Forest Fire Weather Index (FWI) System codes required by the model (i.e., FFMC, DMC, and BUI) using the CFFDRS R package (Wang et al. 2017). Then, two supplementary software applications companion of BFOLDS-FRM (Ouellette et al. 2020; Perera et al. 2014) were used to create two spline weather surfaces based on the FWI codes (FFMC, DMC, and BUI), and the wind profile (wind direction and wind speed), in order to provide the model with the required weather inputs. Fire disturbance is the only process directly affected by climate conditions since the Age-Only Succession and Base Harvest extensions do not include climate variables in their models.

Assessment of future landscape dynamics and fire regulation capacity (FRC)

We assessed future (2020–2050) landscape dynamics and FRC by contrasting the fire-smart management strategies (FFS, SPFS, and FFS + SPFS) against the BAU strategy, assuming the latter as the baseline scenario.

For landscape dynamics, we computed landscape composition, i.e., the proportion of land cover and changes (2020–2050) for eight land cover classes (Table 3), as well as landscape diversity and configuration through landscape metrics (Table 4) by applying the 'landscapemetrics' R package (R Core Team 2020). All landscape metrics refer to the overall study area.

Table 3 Land cover classes in the Sabor River upper basin and correspondent dominant species, vegetation types, or land use class

Land cover	Dominant species, vegetation types, or land use
Deciduous broadleaved	*Quercus pyrenaica*
Coniferous	*Pinus pinaster*
Other coniferous	*Pseudotsuga menziensii*
Evergreen broadleaved	*Quercus rotundifolia*
Shrublands	*Erica* spp.
Grasslands	*Festuca elegans*
Agroforestry systems	*Castanea sativa*
Agricultural areas	Croplands

For FRC analysis, we assessed the capacity of the landscape to restrain potentially large, i.e., > 100 ha, the official fire size threshold in Portugal (ICNF 2019), and intense fires, i.e., the annual burned fraction at Very High (4000–10,000 kW/m) and Extreme (> 10,000 kW/m) fire intensity classes (Alexander and Lanoville 1989). We assumed a decrease in FRC whenever the number of large fires and/or the annual percentage of burned area at fire intensity > 4000 kW/m increase.

First, we computed fire size and the annual fraction of burned area per fire intensity class for each combination of climate scenario and fire management strategy based on LANDIS-II spatial outputs for the annual burned area and fire intensity. Then, we applied the *Mann–Kendall Trend Test* to test for the presence of monotonic trends in FRC indicators (2020–2050) and the *Wilcoxon signed-rank* test and respective effect size to compare FRC indicators between BAU and fire-smart management strategies under RCP 4.5 and 8.5 climate scenarios. All statistical analyses were performed in

Table 4 Diversity and configuration (aggregation and area/edge) landscape metrics computed for the Sabor River upper basin

Class	Metric	Level	Units	Range
Diversity	Shannon's Diversity Index (SHDI)	Landscape	None	SHDI ≥ 0
	Simpson's Diversity Index (SIDI)	Landscape	None	0 ≤ SIDI < 1
	Shannon's Evenness Index (SHEI)	Landscape	None	0 ≤ SHEI < 1
	Simpson's Evenness Index (SIEI)	Landscape	None	0 < SIEI ≤ 1
Aggregation	Landscape Shape Index (LSI)	Landscape	None	LSI ≥ 1
	Number of Patches (NP)	Landscape	None	NP ≥ 1
	Contagion Index (CONTAG)	Landscape	None	0 < CONTAG ≤ 100
Area/Edge	Largest Patch Index (LPI)	Landscape	%	0 < LPI ≤ 100
	Mean of patch area (AREA_MN)	Landscape	ha	AREA_MN > 0
	Edge Density (ED)	Landscape	m/ha	ED ≥ 0

RStudio by applying the 'rstatix' and 'Kendall' packages (R Core Team 2020).

Assessment of current and future fire regimes

We characterized contemporary (1989–2019) and simulated future fire regimes (2020–2050) by computing fire regime metrics describing temporal and spatial fire attributes (Krebs et al. 2010; Oddi 2018) namely, the annual burned fraction (i.e., area burned per unit time within a given area and during a certain period)—Eq. 1; the fire rotation period (i.e., time required for an area equivalent to the size of an area of interest to burn)—Eq. 2; the annual number of fires (i.e., number of occurrences of fire during a certain period)—Eq. 3:

$$ABF = \left(\frac{TBA}{A \times N}\right) \times 100 \tag{1}$$

$$FRP = \frac{A \times N}{TBA} \tag{2}$$

$$ANF = \frac{NF}{N} \tag{3}$$

where ABF is the annual burned fraction (%), FRP is the fire rotation period (years), ANF is the annual number of fires, TBA is the total burned area over the simulation period, A is the total burnable area, N is the number of years over the simulated period, and NF is the total number of fires over the simulated period.

To do this, we used data on burned area and number of fires observed in the study area in 1989–2019 retrieved from the Portuguese fire database (ICNF 2021) and projections for the same attributes for the 2020–2050 period obtained from the outputs of BFOLDS-FRM simulations. Based on these metrics, we assessed potential shifts between contemporary and future fire regimes driven by climate conditions, using the BAU fire management strategy as the baseline.

Then, we compared three fire-smart management strategies (FFS, SPFS, and FFS + SPFS) to the BAU strategy under the RCP 4.5 and 8.5 climate scenarios to assess the potential effect of fire management strategies on future fire regimes. We applied nonparametric statistical methods, namely the *Wilcoxon signed-rank* test and respective effect size, to compare fire regime metrics between past observed and future simulated data and between baseline and each combination of landscape/fire management and climate scenarios in the future.

Results

Landscape composition

Landscape composition changed between 2020 and 2050 for all fire management strategies and climate scenarios (Fig. 3). In the BAU strategy, seminatural areas still dominate the landscape in 2050 despite decreasing over time under both climate scenarios. Forests (coniferous and deciduous broadleaved) and agroforestry areas increased under both climate scenarios, while agriculture decreased (Fig. 3).

Likewise, in the fire-smart strategies, seminatural areas remained dominant in the landscape, followed by forests, agroforestry systems, and last, agricultural areas (Fig. 3). Yet, under the FFS strategy, seminatural areas (shrublands and grasslands) and other conifer forests decreased more than in the BAU strategy, while evergreen woodlands increased considerably. In the SPFS and FFS + SPFS strategies, the increase in grasslands balanced the loss of shrublands. Forest areas increased less than in the BAU strategy, although in the FFS + SPFS strategy evergreen woodlands increased substantially (Fig. 3).

In the fire-smart strategies, landscape fragmentation and complexity also increased (Fig. 4). Yet, in the first decade, landscape aggregation levels decreased more

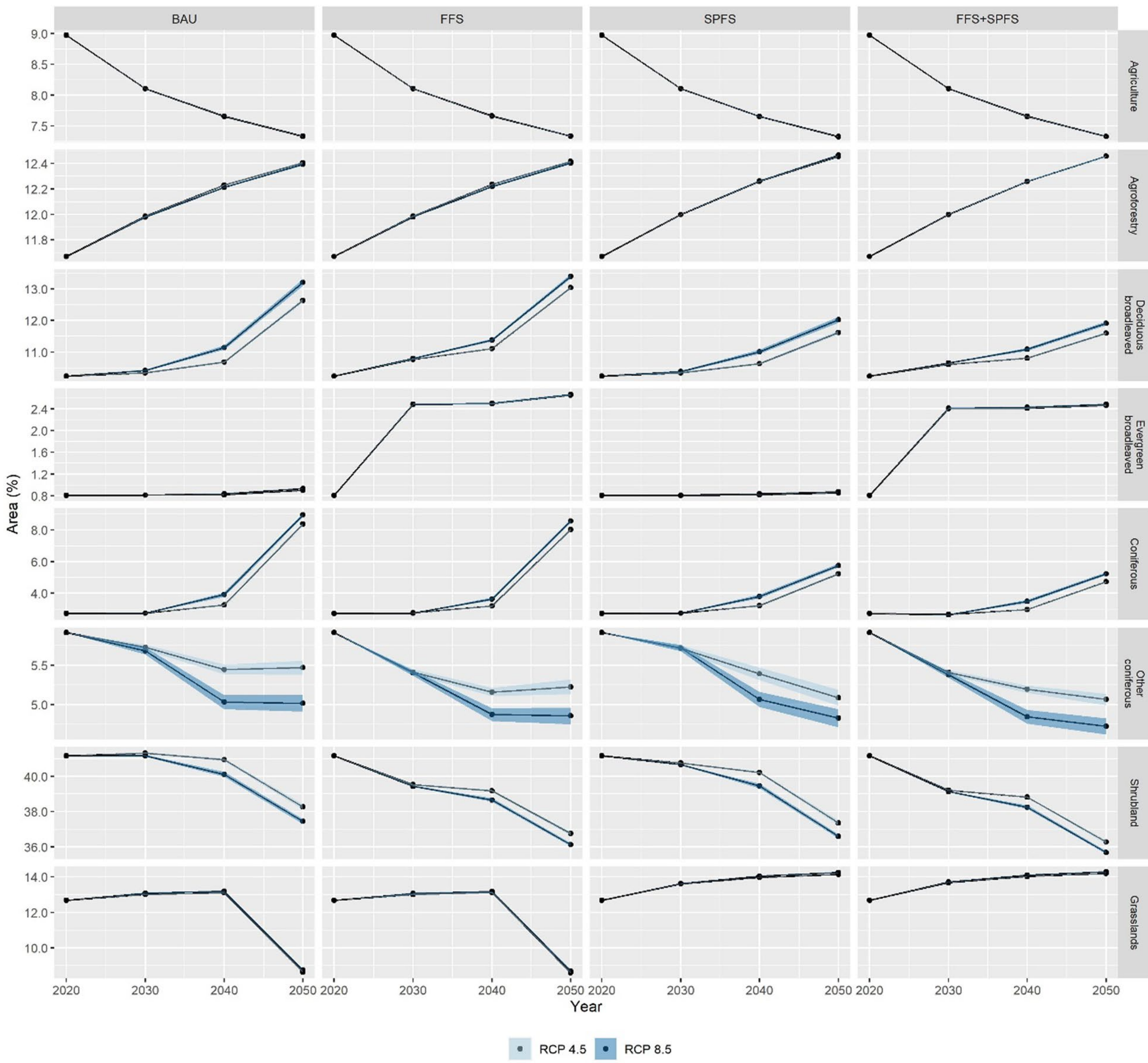

Fig. 3 Simulated land cover changes (%) between 2020 and 2050, for the major land cover classes per fire management strategy and under the RCP 4.5 and 8.5 climate scenarios. All values are averages of 15 runs per fire management strategy. Shaded areas indicate 95% confidence level intervals

markedly in the FFS and FFS+SPFS strategies than in the BAU strategy, but were less pronounced in the SPFS strategy. From 2030 on, landscape aggregation levels decreased sharply in the FFS strategy and slightly in FFS+SPFS and SPFS (Fig. 4).

Landscape configuration

Levels of landscape fragmentation and complexity increased in the BAU strategy (Fig. 4), as showed by landscape aggregation metrics, i.e., the increase in the number of patches (NP) and the landscape shape index (LSI) and the decrease in the contagion index (CONTAG), and by landscape spatial complexity metrics, i.e., the increase in edge density (ED) and decrease in the patch area (AREA_MN) and the lower dominance of the largest patch (LPI).

In the fire-smart strategies, landscape fragmentation and complexity also increased (Fig. 4). Yet, in the first decade, landscape aggregation levels decreased more markedly in the FFS and FFS + SPFS strategies than in the BAU strategy, but were less pronounced in the SPFS strategy. From 2030 on, decreased sharply in

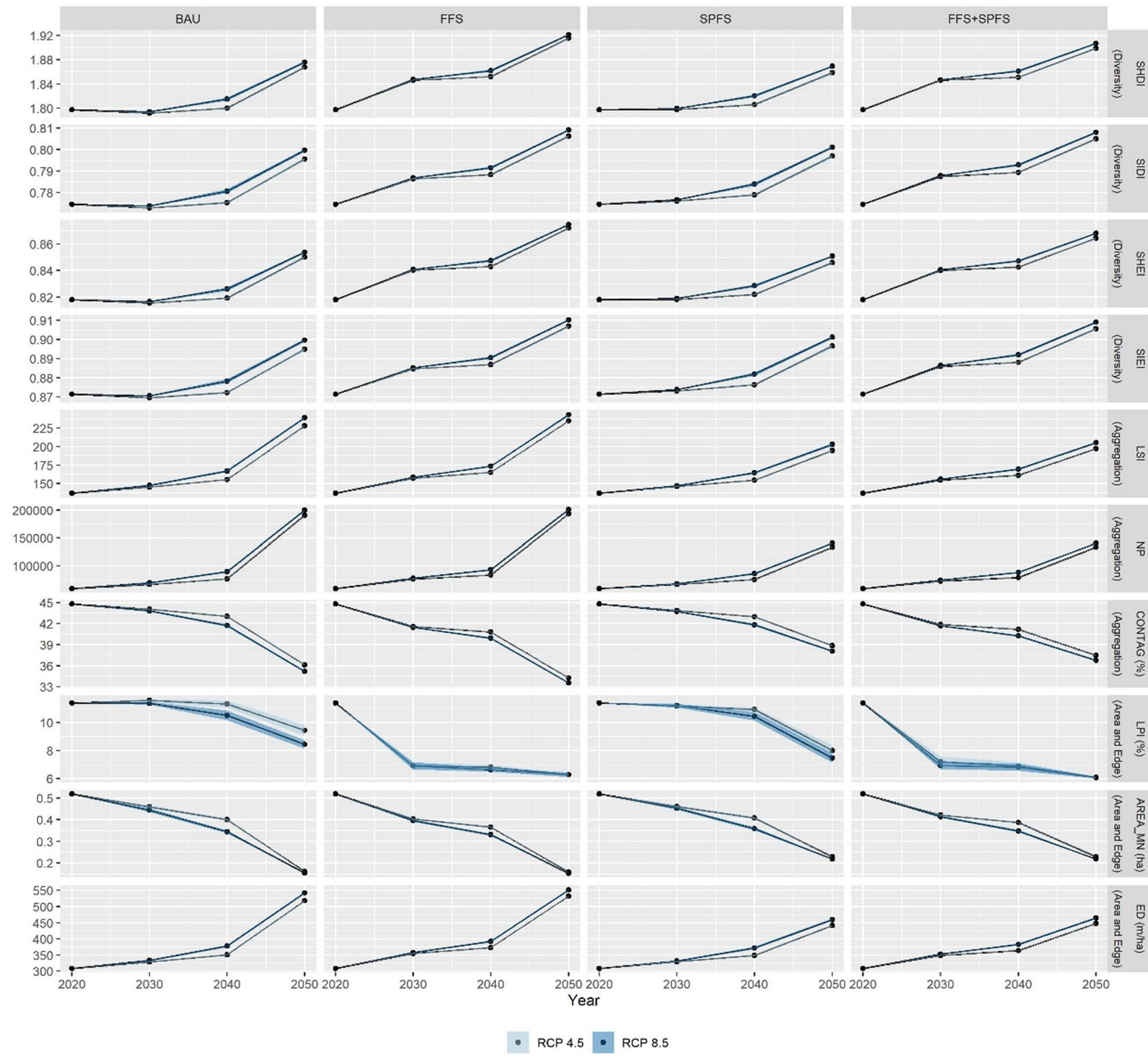

Fig. 4 Diversity, aggregation, and area/edge landscape metrics in the Sabor River upper basin between 2020 and 2050, for each combination of fire management strategy and climate scenario. *SHDI* Shannon's Diversity Index, *SIDI* Simpson's Diversity Index, *SHEI* Shannon's Evenness Index, *SIEI* Simpson's Evenness Index, *LSI* Landscape Shape Index, *NP* Number of Patches, *CONTAG* Contagion Index to describe changes in landscape spatial pattern, *LPI* Largest Patch Index, *AREA_MN* Mean of patch area, *ED* Edge Density. All values are averages of 15 runs per fire management strategy. Shaded areas indicate 95% confidence level intervals

the FFS strategy and slightly in FFS + SPFS and SPFS (Fig. 4). Also, the landscape became more spatially complex in the FFS and FFS + SPFS strategies than in the BAU strategy during the first decade, but less pronounced in the SPFS strategy (Fig. 4). Then, levels of landscape complexity became more pronounced in the FFS strategy than in the SPFS and FFS + SPFS strategies (Fig. 4).

Fire regulation capacity

The mean annual number of large fires and high-intensity burned areas showed a slight upward trend between 2020 and 2050 in all fire management strategies and under both climate scenarios (Fig. 5 and Appendix B—Table B1.1). Overall, the average number of large fires and areas burned at high intensity were substantially higher under RCP 8.5 for all fire management strategies

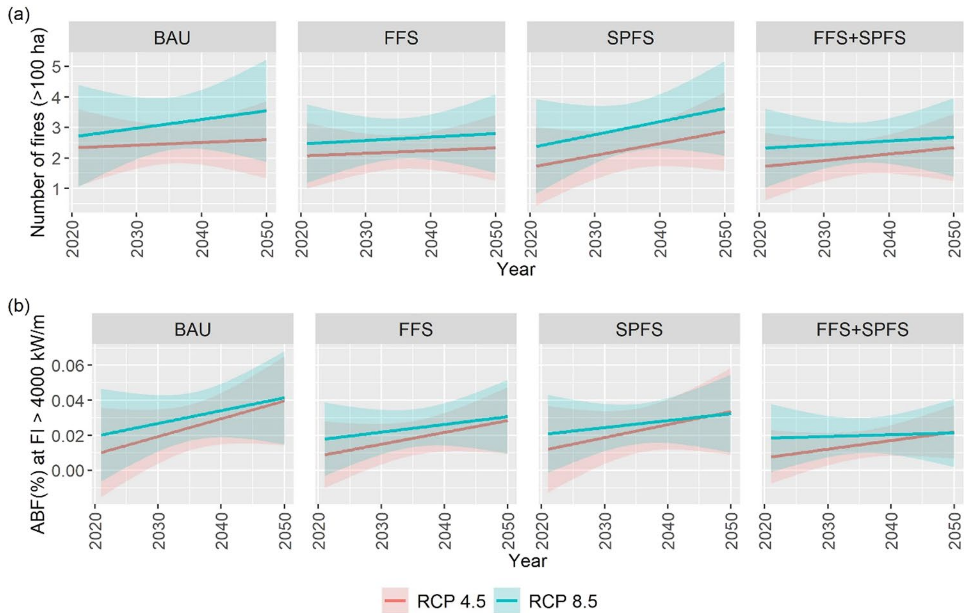

Fig. 5 Simulated **a** annual number of large fires (> 100 ha) and **b** annual burned fraction (ABF) at fire intensity (FI) > 4000 kW/m between 2020 and 2050, for each fire management strategy under RCP 4.5 and RCP 8.5. Solid lines indicate the mean and shaded areas indicate the 95% confidence level interval

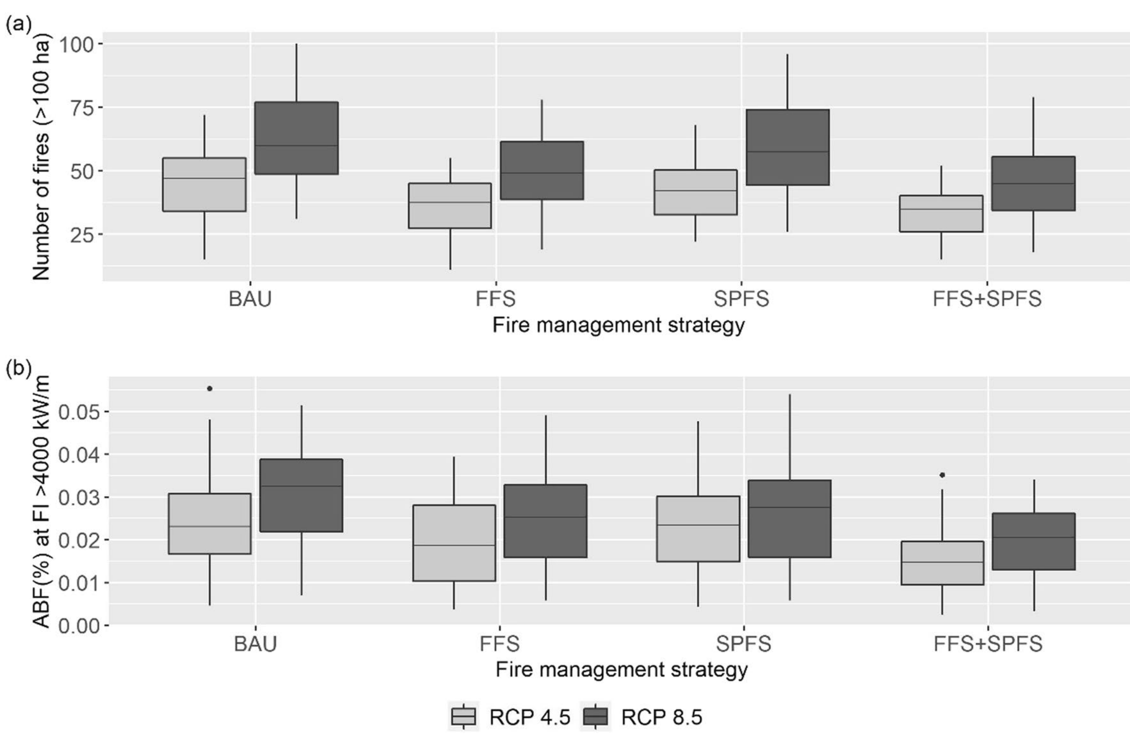

Fig. 6 Simulated **a** total number of large fires (> 100 ha) and **b** total annual burned fraction (ABF) at fire intensity (FI) > 4000 kW/m (2020–2050) for the two RCPs. Boxplots show median, quartiles, and outlier values

(Fig. 6 and Appendix B—Table B1.3). Yet, fire-smart strategies resulted in fewer large fires and high-intensity burned areas than the BAU strategy (Fig. 6 and Appendix B—Table B1.2), particularly in the FFS + SPFS strategy (Fig. 6 and Appendix B—Table B1.4).

Fire regimes

The annual percentage of burned landscape (ABF) under RCP 4.5 was slightly higher in the BAU strategy than in the historical period and substantially higher under RCP 8.5 (Fig. 7; Appendix B—Tables B1.5 and B1.6). ABF under RCP 4.5 was significantly lower in the FFS and FFS + SPFS management strategies than in the historical period but slightly higher in the SPFS strategy. Under RCP 8.5, ABF was moderately higher in the FFS + SPFS strategy than in the historical period but considerably higher in the SPFS and FFS strategies (Fig. 7; Appendix B—Tables B1.5 and B1.6). All fire-smart strategies showed a lower ABF than the BAU strategy, particularly the FFS + SPFS, whose differences were more pronounced in both climate scenarios (Fig. 7; Appendix B—Tables B1.6 and B1.7).

Under RCP 4.5, the fire rotation period (FRP) was slightly shorter in the BAU strategy than in the historical period and significantly shorter under RCP 8.5 (Fig. 7; Appendix B—Tables B1.5 and B1.6). FRP under RCP 4.5 was considerably higher in the FFS and FFS + SPFS management strategies than in the historical period but slightly lower in the SPFS strategy. Under RCP 8.5, FRP was slightly shorter in the FFS + SPFS strategy than in the historical period but substantially shorter in the SPFS and FFS strategies (Fig. 7; Appendix B—Tables B1.5 and B1.6). FRP was longer in all fire-smart strategies than in the BAU strategy, particularly the FFS + SPFS strategy, whose differences were more marked in both climate scenarios (Fig. 7; Appendix B—Tables B1.6 and B1.7).

The annual number of fires (ANF) was substantially lower in all fire management strategies than in the historical period under both climate scenarios (Fig. 7; Appendix B—Tables B1.5 and B1.6). ANF was similar in both BAU and SPFS strategies. In the FFS and FFS + SPFS strategies, ANF was lower than in BAU under both RCPs (Fig. 7; Appendix B—Tables B1.6 and B1.7).

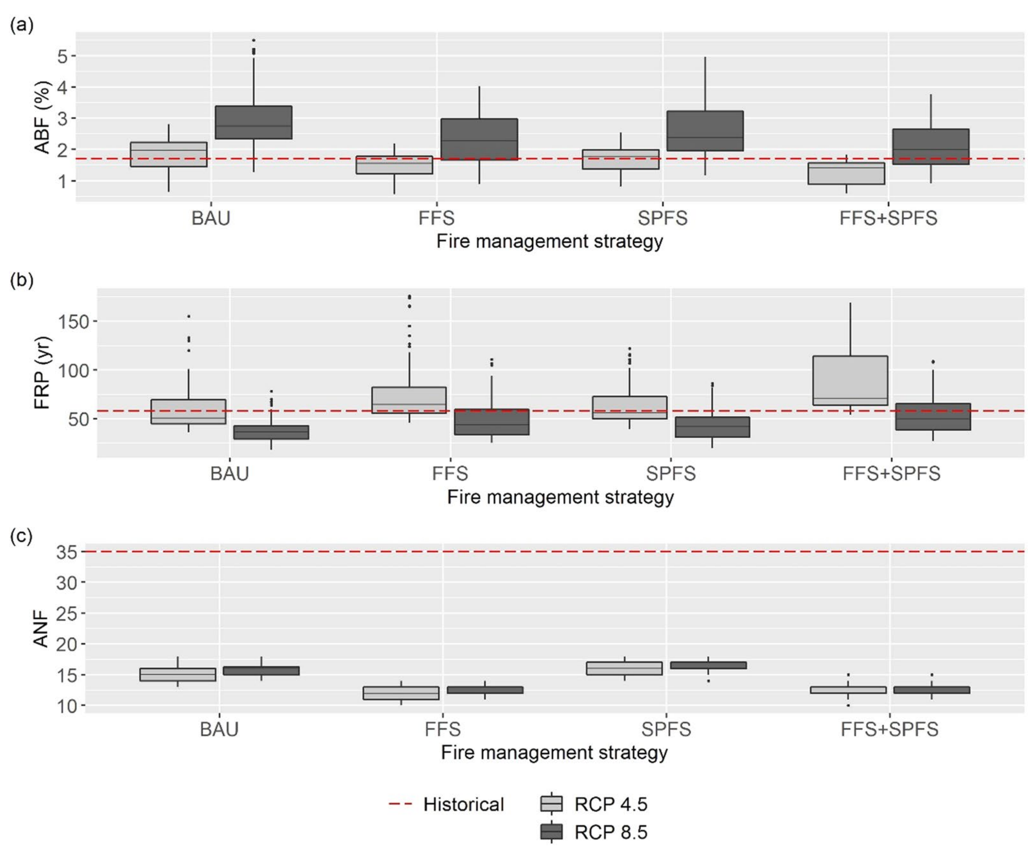

Fig. 7 Fire regime metrics for the historical period (1989–2019) and fire management strategies under RCP 4.5 and RCP 8.5 (2020–2050): **a** annual burned fraction (ABF), **b** fire rotation period (FRP), and **c** annual number of fires (ANF). Boxplots show median, quartiles, and outlier values

Discussion

Trends in landscape dynamics

Our results suggest that the compound effect of farmland abandonment, fire management strategies, fire activity, and vegetation traits affected landscape dynamics in the Sabor River upper basin between 2020 and 2050.

Farmland abandonment, for example, modified landscape composition by fostering the increase of agroforestry systems and seminatural areas at the expense of croplands in all fire management strategies. Besides, different levels of landscape heterogeneity were observed depending on the management strategy. For example, in the BAU strategy, vegetation encroachment (e.g., seminatural areas) at the expense of croplands kept the landscape homogenous during the first decade of simulation. Likewise, in the SPFS strategy, management measures focused on fuel load reduction rather than fuel type conversion resulted in a less heterogeneous landscape. In contrast, fuel type conversion (e.g., other coniferous forests and shrublands converted into evergreen oak woodlands) in the FFS and FFS + SPFS strategies increased levels of landscape heterogeneity. Our results agree with the findings regarding the lasting effects of rural exodus in mountainous landscapes (Azevedo et al. 2011; Mantero et al. 2020; Lasanta et al. 2017) and the potential effects of fire management measures on landscape structure (Gillson et al. 2019; Lasanta et al. 2022).

Moreover, our results show an increasing trend in overall landscape heterogeneity and fragmentation for all fire management strategies from 2030 on. Fire activity intensification under increasing severity of fire weather conditions (particularly under RCP 8.5) and subsequent fire-vegetation feedback combined with the legacy of farmland abandonment and vegetation succession (conversion of seminatural into forest areas) can help explain this trend, particularly in the BAU and FFS strategies. Yet, the maintenance of grazed grasslands smoothed this effect in the SPFS and FFS + SPFS strategies. Our results are in line with findings reporting that, at intermediate levels, fire can alter ecosystem composition and spatial configuration, increasing heterogeneity (Turner 2010) or fragmentation (Driscoll et al. 2021).

In addition, the fire-adaptive traits of most of the modelled species help explain the relative stability in landscape composition in our simulations. These traits allow species to cope with changes in fire regimes, at least within a certain threshold (Clarke et al. 2013; Pausas and Keeley 2014; Ne'eman et al. 2012), and persist through time, resembling an auto-succession process commonly found in Mediterranean ecosystems (Trabaud 1992). For example, the high resprouting capacity (Calvo et al. 2003; de Rigo and Caudullo 2016; Conedera et al. 2016) and relatively moderate flammability (Aparício et al. 2022; Azevedo et al. 2013; Fernandes 2009) of many broadleaved species (e.g., *Quercus pyrenaica*, *Quercus rotundifolia* or *Castanea sativa*) enabled their recovery and persistence through time; serotiny and the relatively long seed dispersal range in fire-embracing pines, such as *Pinus pinaster*, enabled the colonization of burned areas and opportunistically replace other species (van Wilgen and Siegfried 1986; Fernandes and Rigolot 2007); the high resprouting ability of some *Erica* spp. enabled individuals to thrive in post-fire environments (Clarke et al. 2013), although in our study, the decreasing trend from 2030 on may reflect the potential loss of post-fire regeneration capacity due to ageing (Clarke et al. 2013; Ne'eman et al. 2012) and the opportunistic colonization from surrounding vegetation (e.g. grasslands or pines). However, not all the species/cover types modelled managed to thrive under the future fire regime. For example, other conifer forests showed a downward trend in the landscape. This agrees with other studies that reported high regeneration failure of the non-serotinous *Pseudotsuga menziesii* in highly fire-prone environments (Hansen et al. 2018; Vázquez et al. 2015; Tapias et al. 2004).

Trends in fire regulation capacity

Overall, our results anticipate that fire regulation capacity (FRC) will decrease over time in all fire management, particularly in the BAU strategy and under RCP 8.5. This trend reflects the effect of future climate conditions and the legacy of past landscape changes on fire activity in the study area. For example, the aggravation of climate conditions can increase the frequency of days with extreme fire danger (e.g., high temperature and low relative humidity), resulting in an increased likelihood of extreme fire events (Duane et al. 2021a; Aparício et al. 2022; Ruffault et al. 2020). Also, the loss of agricultural mosaic over the last decades and the increase of hazardous fuels in the landscape (e.g., shrublands and forest) resulted in a more homogeneous and flammable landscape, thus favouring the occurrence of large and intense fires (Azevedo et al. 2011; Sil et al. 2019b; Fernandes et al. 2016, 2014).

Nevertheless, our results indicate that fire-smart management strategies can mitigate the potential intensification of fire activity in the study area, particularly when combining forest- and silvopasture-oriented management, as shown in the FFS + SPFS strategy. For example, fuel type conversion and fuel treatments in forests and shrublands maintained or increased landscape heterogeneity levels and reduced the fire behaviour potential, which in turn helped restrain large fires and areas burned at very high fire intensity (Benali et al. 2021; Azevedo et al. 2013; Pais et al. 2020; Sil et al. 2019b). Also, fuel load reduction in grasslands and agroforestry systems helped decrease fire intensity (Bergmeier et al. 2021; Damianidis et al. 2021; Rouet-Leduc et al. 2021).

In addition, the size of the managed area can also help explain the higher effectiveness of the FFS + SPFS strategy (managed area ≈50%) than the other fire-smart strategies (managed area ≈25%). For example, management measures in the FFS + SPFS strategy helped avoid the critical percolation threshold (≈60%), commonly described as essential for disturbance processes, such as fire, to spread across the landscape (Duane et al. 2021b; Turner et al. 1989; Desmet 2018). On the contrary, in the FFS strategy, lack of fuel load management in grassland fuel types resulted in fast and moderate- to high-intensity fires during summer (Alexander and Cruz 2018; Cruz et al. 2022b), while in the SPFS strategy, fuel load reduction in grassland fuel types was insufficient to stop fires from spreading and reaching areas of unmanaged forests and shrublands. Yet, from 2040 onwards, the absence of management actions to control post-fire regeneration (i.e., outside the pre-defined management areas) led to fuel build-up, thus decreasing the fire regulation capacity.

Trends and drivers of fire regimes

Our results indicate that future fire activity will remain high in the Sabor River upper basin, leading to a change in the contemporary fire regime (1989–2019), as indicated by fire regime metrics. Still, the magnitude to which the current fire regime will change depends on whether ongoing climate change follows an intermediate (RCP 4.5) or high (RCP 8.5) emissions scenario and which fire management strategies are implemented over time.

In the BAU strategy, further intensification of the fire regime is expected due to the marked decrease in the landscape capacity to regulate large and intense fires, particularly under RCP 8.5. On the other hand, all fire-smart management strategies proved more effective than the BAU strategy in regulating fire regimes, particularly in the FFS + SPFS strategy. Yet, the effect of fuel management on fire regimes is likely to be reduced under severe burning conditions (Cruz et al. 2022a).

Overall, our results are in line with findings reported in other modelling studies in Euro-Mediterranean landscapes that suggest an overall increase in the burned area either due to land abandonment processes (Pais et al. 2020) or changes in climate conditions (Amatulli et al. 2013) and a reduction in the fire rotation period due to increasing fire activity influenced by changes in climate (Vázquez et al. 2015). Also, our results are in line with the decreasing trend in ANF observed at the national level (San-Miguel-Ayanz et al. 2022) and for the study area, where ANF has been decreasing on average at a rate of 23 fires/year between 2001–2019 (ICNF 2021).

Insights for management and planning

The lack of effectiveness in fire management policies in Euro-Mediterranean landscapes suggests the need to change the current fire suppression-oriented model to cope with current challenges posed by global change (Moreira et al. 2020). In this context, managing fuel hazard is crucial to attaining climate- and fire-resilient landscapes (Fernandes 2022; Regos 2022). This is particularly significant given the technological limitations of current fire suppression approaches under extreme weather conditions (Tedim et al. 2018; UNEP 2022; Carnicer et al. 2022).

Our results identified that ongoing land abandonment and fire management policies focused on fire suppression are relevant drivers of change in contemporary fire regimes, which are in line with studies elsewhere in the Mediterranean basin (Mantero et al. 2020; Fernandes et al. 2020). Also, our results agree with findings indicating that the combination of highly flammable landscapes with increased fire weather season length (Aparício et al. 2022; Jolly et al. 2015) and hot and dry summer conditions (Turco et al. 2017; Aparício et al. 2022) may shift fire regimes from a historically fuel-limited towards a climate-driven fire regime in the Mediterranean basin (Pausas and Fernández-Muñoz 2012; Fernandes et al. 2014). In this sense, our study highlights that integrating fire-smart strategies into landscape planning and management can improve fire resistance and resilience of fire-prone landscapes in the Euro-Mediterranean region under future global change conditions (Fernandes 2013; Moreira et al. 2020; Regos et al. 2023).

Fire-smart management strategies tested in our study helped to maintain or improve landscape diversity in terms of composition, structure, and spatial organization of fuels. For example, under the current fire management model focused on fire suppression (BAU), the high landscape fuel hazard driven by seminatural vegetation encroachment in former cropland kept the landscape homogenous (e.g., diversity indices decreased, and landscape fragmentation and complexity were maintained constant during the first decade). Thus, under more severe weather conditions, larger fires and more areas in the landscape were enabled where fire intensity exceeds suppression capacity. In turn, fire-smart management focused on modifying fuel composition and structure in the landscape increased landscape heterogeneity (e.g., increase in diversity indices and landscape fragmentation and complexity). This helped prevent large and intense fires more than the BAU strategy in both climate scenarios, thereby mitigating fire regime intensification caused by land abandonment and climate change, particularly when combining forest- and silvopasture-based measures (FFS + SPFS).

Moreover, our results indicated that most species modelled in the Sabor River upper basin are highly resilient to potential changes in current fire patterns. Fire-adapted forest species such as serotinous conifers (*Pinus pinaster*) or broadleaved forests (*Quercus pyrenaica, Quercus rotundifolia*) increased over time. Although broadleaved forests tend to be less flammable than conifers (Azevedo et al. 2013; Fernandes 2009), thereby more suitable for future afforestation actions, managing fuel in both forest types is crucial to mitigate potentially catastrophic fires promoted by more severe fire weather (Oliveira et al. 2023). On the other hand, it is expected that some vegetation types may fade away (e.g., *Pseudotsuga menziesii*). In such cases, forest areas may hold scenic and recreational values and act as carbon sinks, and thus maintaining these areas could be important to providing cultural and regulating ecosystem services in the study area (Fonseca et al. 2019; Spiecker et al. 2019). In addition, the low fire-proneness and moderate fire resistance of short-needles conifers such as *Pseudotsuga menziesii* can reduce severe wildfires compared to *Pinus pinaster* stands (Fernandes et al. 2010). Still, as a non-native species, caution is needed to avoid dense and continuous plantations that can incur negative impacts (Spiecker et al. 2019; Thomas et al. 2022). Moreover, other vegetation types may decrease their area of dominance in the landscape (e.g., shrublands). In such cases, their replacement with sclerophyllous native species (e.g. *Quercus rotundifolia*), can increase landscape heterogeneity levels, disrupt fuel continuity and decrease fire spread potential. Still, post-fire emergency measures in steeper terrain may be necessary to avoid soil erosion and maintain ecological processes and the supply of ecosystem services (Girona-García et al. 2023; Lucas-Borja et al. 2022).

In this sense, the future planning, design, and management of fire-prone mountainous areas similar to the Sabor River upper basin must: (1) foster the expansion of low-flammability species in the landscape (e.g., holm oak) to break spatial continuity of more flammable vegetation types, particularly in steeper terrain; (2) restore natural pastures and promote pastoral practices to decrease fuel hazard; (3) combine mechanized operations and prescribed burning to modify fuel load and structure in more flammable vegetation types; (4) monitor and manage post-fire regeneration to avoid increased future wildfire risk; and (5) identify and restore more vulnerable areas affected by fire to mitigate harmful impacts of fire and maintain ecological processes and the supply of ecosystem services.

In addition, implementing effective fire management strategies requires (1) acknowledging stakeholders' perceptions of wildfires and land management (Lecina-Diaz et al. 2023a; Varela et al. 2018), (2) assessing economic costs and benefits of fire and land management strategies (Elia et al. 2016; Lecina-Diaz et al. 2023b; Verkerk et al. 2018), and (3) incorporating scientific and social knowledge into fire management policy instruments for planning and management fire-prone landscapes under global change (Iglesias et al. 2022; UNEP 2022).

Modelling limitations

Our study showed that LANDIS-II FLM is useful for simulating the feedback between climate-fire-vegetation under farmland abandonment and fire management strategies. We acknowledge, however, modelling limitations whose future incorporation would improve the accuracy of our predictions. For example, directly addressing the effects of climate on vegetation is relevant to simulate landscape dynamics in the future (Williams et al. 2023), particularly on post-fire resprouters dynamics of some oak and shrub species (Batllori et al. 2019; Baudena et al. 2020) and chestnut species (Freitas et al. 2021) in Mediterranean landscapes.

Also, better integration of fire-adapting traits in LANDIS-II FLM would improve simulations of post-fire regeneration of modelled species, for example, include variability in the degree of serotiny among individuals in *Pinus pinaster* stands (Tapias et al. 2004; Hernández-Serrano et al. 2013), or fire resistance, for example, bark thickness protects *Pseudotsuga menziesii* from most surface fires (Uchytil 1991; Fernandes et al. 2010), thus requiring a different threshold for stand-replacement fire compared to other species (e.g., shrublands).

Furthermore, we acknowledge that more recent climate scenarios are available [e.g. CMIP6 climate projections; Copernicus Climate Change Service (2021)] and their incorporation in the simulation framework may improve future model applications. However, although CMIP6 scenarios may present advantages over previous ones (Wyser et al. 2020), uncertainties on future projection still exist (Cos et al. 2022) and further testing is needed to ensure the suitability of data projections in simulating fire weather conditions that many fire modelling systems require as input (Gallo et al. 2023).

Conclusions

In this study, we modelled future landscape dynamics and the capacity to regulate potential large and intense fires and their impacts on contemporary and future fire regimes in the Sabor River upper basin under different fire management strategies in the context of climate change and long-term farmland abandonment. Climate-fire-vegetation interactions, combined with changes driven by farmland abandonment and fire management strategies, played an important role in landscape dynamics (composition and configuration). Also, the combined effect of landscape and climate change may alter contemporary fire regimes due to decreased fire regulation capacity over time.

Fire-smart strategies performed better than BAU in averting the current fire regime intensification. In this sense, combining forest and silvopasture-based measures (FFS + SPFS) is the most promising strategy for taming the effects of climate and farmland abandonment on fire activity in the Sabor River upper basin. Therefore, fire management policies implemented in the Sabor River upper basin, as well as in areas with similar settings, must incorporate fire-smart strategies to buffer the effects of climate and landscape change on fire regimes in fire-prone Mediterranean mountains.

Abbreviations

ABF	Annual burned fraction
ANF	Annual number of fires
BAU	Business-as-usual
FFS	Forest-based fire-smart
FFS + SPFS	Forest- and silvopasture-based fire-smart
FRC	Fire regulation capacity
FRP	Fire rotation period
RCP	Representative concentration pathways
SPFS	Silvopasture-based fire-smart
TBA	Total burned area

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-024-00535-3.

Supplementary Material 1.

Supplementary Material 2.

Acknowledgements
ÂS acknowledges the Portuguese Foundation for Science and Technology (FCT) for the support received through the Ph.D. Grant SFRH/BD/132838/2017, funded by the Ministry of Science, Technology and Higher Education and the European Social Fund—Operational Program Human Capital within the 2014–2020 EU Strategic Framework. The authors acknowledge the FirESmart project (FirESmart—Nature-based solutions for preventive fire management and sustained supply of ecosystem services: PCIF/MOG/0083/2017) for making climate data available to perform all the simulations. The authors wish to thank Prof. José Rufino, from the CeDRI/SusTEC research centre, for his assistance in using the resources of the CeDRI computational cluster to perform all the simulations.

Author contributions
ÂS: Conceptualization, data curation, investigation, methodology, formal analysis, writing—original draft, writing—review & editing. JCA: conceptualization, methodology, writing—original draft, writing—review & editing. PMF: conceptualization, methodology, writing—original draft, writing—review & editing. JPH: conceptualization, methodology, writing—original draft, writing—review & editing.

Funding
ÂS received support from the Portuguese Foundation for Science and Technology (FCT) through Ph.D. Grant SFRH/BD/132838/2017, funded by the Ministry of Science, Technology and Higher Education, and by the European Social Fund—Operational Program Human Capital within the 2014–2020 EU Strategic Framework. This research was supported by Portuguese national funds through FCT—Foundation for Science and Technology, I.P., under the SeverusPT project (PCIF/RPG/0170/2019). ÂS and JPH were supported by the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101060415, for the project "SELINA—Science for evidence-based and sustainable decisions about natural capital". JCA was supported by national funds through FCT/MCTES (PIDDAC): CIMO, UIDB/00690/2020 (https://doi.org/10.54499/UIDB/00690/2020) and UIDP/00690/2020 (https://doi.org/10.54499/UIDP/00690/2020); and SusTEC, LA/P/0007/2020 (https://doi.org/10.54499/LA/P/0007/2020). PMF was supported by Portuguese funds through FCT- Portuguese Foundation for Science and Technology, project UIDB/04033/2020 (https://doi.org/10.54499/UIDB/04033/2020). BIOPOLIS receives institucional funding from the European Union's Horizon 2020 Research and Innovation Programme under the Grant Agreement Number 857251.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that, they have no conflict of Interest.

Author details
[1]CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Campus de Vairão, Universidade do Porto, 4485-661 Vairão, Portugal. [2]BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Campus de Vairão, 4485-661 Vairão, Portugal. [3]Departamento de Biologia, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, S/N, Edifício FC4, 4169-007 Porto, Portugal. [4]CITAB-Centro de Investigação e de Tecnologias Agro-Ambientais e Biológicas, Universidade de Trás-os-Montes e Alto Douro, 5001-801 Vila Real, Portugal. [5]CIMO-Centro de Investigação de Montanha, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal. [6]SusTEC-Laboratório Associado Para a Sustentabilidade e Tecnologia em Regiões de Montanha, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal.

Received: 14 March 2024 Accepted: 9 July 2024
Published online: 01 August 2024

References

Aguiar C, Rodrigues O, Azevedo J, Domingos T (2009) Montanha. In: Pereira HM (ed) Ecossistemas e bem-estar humano: avaliação para Portugal do Millennium Ecosystem Assessment. Lisboa, Escolar Editora, pp 295–339

Alexander ME, Cruz MG (2018) Fireline Intensity. In: Manzello SL (ed) Encyclopedia of wildfires and wildland-urban interface (WUI) Fires. Springer International Publishing, Cham, pp 1–8. https://doi.org/10.1007/978-3-319-51727-8_52-1

Alexander ME, Lanoville RA (1989) Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. Northern Forestry Centre & Territorial Forest Fire Centre—Poster (with text). Forestry Canada: Northern Forestry Center, & Government of the Northwest Territories—Department of Renewable Resources: Territorial Forest Fire Centre, Edmonton (Alberta) & Fort Smith (Northwest Territories), Canada

Ali E, Cramer W, Carnicer J et al (2022) Cross-chapter paper 4: Mediterranean region. In: Pörtner H-O, Roberts DC, Tignor M et al (eds) Climate change 2022: impacts, adaptation and vulnerability, contribution of working Group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 2233–2272. https://doi.org/10.1017/9781009325844.021

Amatulli G, Camia A, San-Miguel-Ayanz J (2013) Estimating future burned areas under changing climate in the EU-Mediterranean countries. Sci Total Environ 450–451:209–222. https://doi.org/10.1016/j.scitotenv.2013.02.014

Aparício BA, Santos JA, Freitas TR, Sá ACL, Pereira JMC, Fernandes PM (2022) Unravelling the effect of climate change on fire danger and

fire behaviour in the Transboundary Biosphere Reserve of Meseta Ibérica (Portugal-Spain). Clim Change 173:5. https://doi.org/10.1007/s10584-022-03399-8
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(1):34–51. https://doi.org/10.1007/s10021-019-00385-7
Argles APK, Moore JR, Cox PM (2022) Dynamic global vegetation models: searching for the balance between demographic process representation and computational tractability. PLOS Climate 1(9):e0000068. https://doi.org/10.1371/journal.pclm.0000068
Azevedo JC, Moreira C, Castro JP, Loureiro C (2011) Agriculture abandonment, land use change and fire hazard in mountain landscapes in northeastern Portugal. In: Li C, Lafortezza R, Chen J (eds) Landscape ecology in forest management and conservation: challenges and solutions for global change. Springer, New York, pp 329–351
Azevedo J, Aguiar C, Possacos A et al (2013) The role of holm oak edges in the control of disturbance and conservation of plant diversity in fire-prone landscapes. For Ecol Manage 297:37–48. https://doi.org/10.1016/j.foreco.2013.02.007
Batllori E, De Cáceres M, Brotons L, Ackerly DD, Moritz MA, Lloret F (2019) Compound fire-drought regimes promote ecosystem transitions in Mediterranean ecosystems. J Ecol 107(3):1187–1198. https://doi.org/10.1111/1365-2745.13115
Baudena M, Santana VM, Baeza MJ et al (2020) Increased aridity drives post-fire recovery of Mediterranean forests towards open shrublands. New Phytol 225(4):1500–1515. https://doi.org/10.1111/nph.16252
Benali A, Sá ACL, Pinho J, Fernandes PM, Pereira JMC (2021) Understanding the impact of different landscape-level fuel management strategies on wildfire hazard in central Portugal. Forests 12(5):522
Bergmeier E, Capelo J, Di Pietro R et al (2021) 'Back to the Future'—Oak wood-pasture for wildfire prevention in the Mediterranean. Plant Sociol 58(2):41–48. https://doi.org/10.3897/pls2021582/04
European Environment Agency (EEA) (2016) Biogeographical regions, Europe 2016, version 1. https://www.eea.europa.eu/en/datahub/datahubitem-view/11db8d14-f167-4cd5-9205-95638dfd9618. Accessed 2023
Calvo L, Santalla S, Marcos E, Valbuena L, Tárrega R, Luis E (2003) Regeneration after wildfire in communities dominated by *Pinus pinaster*, an obligate seeder, and in others dominated by *Quercus pyrenaica*, a typical resprouter. For Ecol Manage 184(1):209–223. https://doi.org/10.1016/S0378-1127(03)00207-X
Campos JC, Rodrigues S, Sil Â et al (2022) Climate regulation ecosystem services and biodiversity conservation are enhanced differently by climate- and fire-smart landscape management. Environ Res Lett 17(5):054014. https://doi.org/10.1088/1748-9326/ac64b5
Carmo M, Moreira F, Casimiro P, Vaz P (2011) Land use and topography influences on wildfire occurrence in northern Portugal. Landsc Urban Plan 100(1):169–176. https://doi.org/10.1016/j.landurbplan.2010.11.017
Carnicer J, Alegria A, Giannakopoulos C et al (2022) Global warming is shifting the relationships between fire weather and realized fire-induced CO_2 emissions in Europe. Sci Rep 12:10365. https://doi.org/10.1038/s41598-022-14480-8
Castro Rego F, Morgan P, Fernandes P, Hoffman C (2021) Fire regimes, landscape dynamics, and landscape management. Fire Science: from Chemistry to Landscape Management. Springer International Publishing, Cham, pp 421–507. https://doi.org/10.1007/978-3-030-69815-7_12
Clarke PJ, Lawes MJ, Midgley JJ et al (2013) Resprouting as a key functional trait: how buds, protection and resources drive persistence after fire. New Phytol 197(1):19–35. https://doi.org/10.1111/nph.12001
Conedera M, Tinner W, Krebs P, Rigo DD, Caudullo G (2016) *Castanea sativa* in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz J, Rigo DD, Caudullo G, Durrant TH, Mauri A (eds) European atlas of forest tree species. Publication Office of the European Union, Luxembourg, p 202
Copernicus Climate Change Service, Climate Data Store (2021) CMIP6 climate projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.c866074c
Cos J, Doblas-Reyes F, Jury M, Marcos R, Bretonnière PA, Samsó M (2022) The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. Earth Syst Dynam 13(1):321–340. https://doi.org/10.5194/esd-13-321-2022
Cruz MG, Alexander ME, Fernandes PM (2022a) Evidence for lack of a fuel effect on forest and shrubland fire rates of spread under elevated fire danger conditions: implications for modelling and management. Int J Wildland Fire 31(5):471–479. https://doi.org/10.1071/WF21171
Cruz MG, Alexander ME, Kilinc M (2022b) Wildfire rates of spread in grasslands under critical burning conditions. Fire 5(2):55
Damianidis C, Santiago-Freijanes JJ, den Herder M et al (2021) Agroforestry as a sustainable land use option to reduce wildfires risk in European Mediterranean areas. Agrofor Syst 95(5):919–929. https://doi.org/10.1007/s10457-020-00482-w
Dax T, Schroll K, Machold I, Derszniak-Noirjean M, Schuh B, Gaupp-Berghausen M (2021) Land abandonment in mountain areas of the EU: an inevitable side effect of farming modernization and neglected threat to sustainable land use. Land 10(6):591
de Rigo D, Caudullo G (2016) *Quercus ilex* in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz J, Rigo DD, Caudullo G, Durrant TH, Mauri A (eds) European Atlas of Forest Tree Species. Publications Office of the European Union, Luxembourg, p 202
Depietri Y, Orenstein DE (2019) Fire-regulating services and disservices with an application to the Haifa-Carmel region in Israel. Front Environ Sci 7:107. https://doi.org/10.3389/fenvs.2019.00107
Depietri Y, Orenstein DE (2020) Managing fire risk at the wildland-urban interface requires reconciliation of tradeoffs between regulating and cultural ecosystem services. Ecosyst Serv 44:101108. https://doi.org/10.1016/j.ecoser.2020.101108
Desmet PG (2018) Using landscape fragmentation thresholds to determine ecological process targets in systematic conservation plans. Biol Conserv 221:257–260. https://doi.org/10.1016/j.biocon.2018.03.025
DGT (2019) Carta de Uso e Ocupação do Solo (COS) de Portugal Continental. Direção Geral do Território, Lisboa
DGT (2020) Carta de Ocupação do Solo Conjuntural—2020. Direção Geral do Território. https://geo2.dgterritorio.gov.pt/cosc/COSc2020.zip. Accessed 01 Dec 2021
Driscoll DA, Armenteras D, Bennett AF et al (2021) How fire interacts with habitat loss and fragmentation. Biol Rev 96(3):976–998. https://doi.org/10.1111/brv.12687
Duane A, Castellnou M, Brotons L (2021a) Towards a comprehensive look at global drivers of novel extreme wildfire events. Clim Change 165(3):43. https://doi.org/10.1007/s10584-021-03066-4
Duane A, Miranda MD, Brotons L (2021b) Forest connectivity percolation thresholds for fire spread under different weather conditions. For Ecol Manage 498:119558. https://doi.org/10.1016/j.foreco.2021.119558
Dupuy J-l, Fargeon H, Martin-StPaul N et al (2020) Climate change impact on future wildfire danger and activity in southern Europe: a review. Ann For Sci 77:35. https://doi.org/10.1007/s13595-020-00933-5
Elia M, Lovreglio R, Ranieri NA, Sanesi G, Lafortezza R (2016) Cost-effectiveness of fuel removals in mediterranean wildland-urban interfaces threatened by wildfires. Forests 7(7):149
EU (2021a) EU biodiversity strategy for 2030: bringing nature back into our lives. Publications Office of the European Union. https://doi.org/10.2779/677548
EU (2021b) New EU Forest Strategy for 2030—communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. European Commission, Brussels
Faivre N, Xanthopoulos F, Moreno J, Calzada V, Xanthopoulos G (2018) Forest fires—sparking firesmart policies in the EU. https://doi.org/10.2777/181450
Fernandes PM (2009) Combining forest structure data and fuel modelling to classify fire hazard in Portugal. Ann For Sci 66(4):415–415. https://doi.org/10.1051/forest/2009013
Fernandes PM (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 PM (2020) Sustainable Fire Management. In: Leal Filho W, Azul AM, Brandli L, Lange Salvia A, Wall T (eds) Life on land. Springer International Publishing, Cham, pp 1–11. https://doi.org/10.1007/978-3-319-71065-5_119-1
Fernandes PM (2022) Make Europe's forests climate-smart and fire-smart. Nature 609:32. https://doi.org/10.1038/d41586-022-02318-2

Fernandes PM, Rigolot E (2007) The fire ecology and management of maritime pine (*Pinus pinaster* Ait.). For Ecol Manag 241(1):1–13. https://doi.org/10.1016/j.foreco.2007.01.010

Fernandes PM, Luz A, Loureiro C (2010) Changes in wildfire severity from maritime pine woodland to contiguous forest types in the mountains of northwestern Portugal. For Ecol Manage 260(5):883–892. https://doi.org/10.1016/j.foreco.2010.06.008

Fernandes PM, Loureiro C, Guiomar N, Pezzatti GB, Manso FT, Lopes L (2014) The dynamics and drivers of fuel and fire in the Portuguese public forest. J Environ Manage 146:373–382. https://doi.org/10.1016/j.jenvman.2014.07.049

Fernandes PM, Monteiro-Henriques T, Guiomar N, Loureiro C, Barros AMG (2016) Bottom-up variables govern large-fire size in Portugal. Ecosystems 19(8):1362–1375. https://doi.org/10.1007/s10021-016-0010-2

Fernandes PM, Delogu GM, Leone V, Ascoli D (2020) Wildfire policies contribution to foster extreme wildfires. In: Tedim F, Leone V, McGee TK (eds) Extreme wildfire events and disasters. Elsevier, pp 187–200. https://doi.org/10.1016/B978-0-12-815721-3.00010-2

Finney MA (2006) An overview of flammap fire modeling. In: Andrews PL, Butler BW (eds) Fuels management: how to measure success. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO

Fonseca F, de Figueiredo T, Vilela Â et al (2019) Impact of tree species replacement on carbon stocks in a Mediterranean mountain area, NE Portugal. For Ecol Manage 439:181–188. https://doi.org/10.1016/j.foreco.2019.03.002

Freitas TR, Santos JA, Silva AP, Fraga H (2021) Influence of climate change on chestnut trees: a review. Plants 10:1463. https://doi.org/10.3390/plants10071463

Gallo C, Eden JM, Dieppois B et al (2023) Evaluation of CMIP6 model performances in simulating fire weather spatiotemporal variability on global and regional scales. Geosci Model Dev 16(10):3103–3122. https://doi.org/10.5194/gmd-16-3103-2023

Gillson L, Whitlock C, Humphrey G (2019) Resilience and fire management in the Anthropocene. Ecol Soc 24:14. https://doi.org/10.5751/ES-11022-240314

Girona-García A, Cretella C, Fernández C, Robichaud PR, Vieira DCS, Keizer JJ (2023) How much does it cost to mitigate soil erosion after wildfires? J Environ Manage 334:117478. https://doi.org/10.1016/j.jenvman.2023.117478

Guenni Bd, Cardoso M, Goldammer J, Hurtt G, Mata J (2005) Regulation of natural hazards: floods and fires. In: Hassan R, Scholes R, Ash N (eds) Ecosystems and human well-being: current state and trends. Island Press, Washington DC, pp 441–454

Gustafson E, Shifley S, Mladenoff D, Nimerfro K, He H (2000) Spatial simulation of forest succession and timber harvesting using LANDIS. Can J Forest Res 30:32–43. https://doi.org/10.1139/cjfr-30-1-32

Hansen WD, Braziunas KH, Rammer W, Seidl R, Turner MG (2018) It takes a few to tango: changing climate and fire regimes can cause regeneration failure of two subalpine conifers. Ecology 99(4):966–977. https://doi.org/10.1002/ecy.2181

Henne PD, Elkin C, Franke J et al (2015) Reviving extinct Mediterranean forest communities may improve ecosystem potential in a warmer future. Front Ecol Environ 13(7):356–362. https://doi.org/10.1890/150027

Hernández-Serrano A, Verdú M, González-Martínez SC, Pausas JG (2013) Fire structures pine serotiny at different scales. Am J Bot 100(12):2349–2356. https://doi.org/10.3732/ajb.1300182

Hirsch K, Kafka V, Tymstra C et al (2001) Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. For Chron 77(2):357–363. https://doi.org/10.5558/tfc77357-2

ICNF (2019) Annual report of forest fires in Portuguese mainland for 2019 (provisional report). Instituto da Conservação da Natureza e das Florestas. https://www.icnf.pt/api/file/doc/2b6e067a535002a2. Accessed 11 Apr 2019

ICNF (2021) Portuguese Fire Database. Instituto da Conservação da Natureza e das Florestas. https://www.icnf.pt/florestas/gfr/gfrgestaoinformacao/estatisticas. Accessed 04 Nov 2021

Iglesias MC, Hermoso V, Campos JC et al (2022) Climate- and fire-smart landscape scenarios call for redesigning protection regimes to achieve multiple management goals. J Environ Manage 322:116045. https://doi.org/10.1016/j.jenvman.2022.116045

INE (2021) Censos 2021. Instituto Nacional de Estatística. https://censos.ine.pt. Accessed 01 Oct 2022

Jacob D, Teichmann C, Sobolowski S et al (2020) Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. Reg Environ Change 20(2):51. https://doi.org/10.1007/s10113-020-01606-9

Jolly WM, Cochrane MA, Freeborn PH et al (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. Nat Commun 6:7537. https://doi.org/10.1038/ncomms8537

Keane RE, Loehman RA, Holsinger LM (2019) Selecting a landscape model for natural resource management applications. Curr Landsc Ecol Rep 4:31–40. https://doi.org/10.1007/s40823-019-00036-6

Krebs P, Pezzatti GB, Mazzoleni S, Talbot LM, Conedera M (2010) Fire regime: history and definition of a key concept in disturbance ecology. Theory Biosci 129:53–69. https://doi.org/10.1007/s12064-010-0082-z

Lasanta T, Arnáez J, Pascual N, Ruiz-Flaño P, Errea MP, 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

Lasanta T, Cortijos-López M, Errea MP, Khorchani M, Nadal-Romero E (2022) An environmental management experience to control wildfires in the mid-mountain mediterranean area: shrub clearing to generate mosaic landscapes. Land Use Policy 118:106147. https://doi.org/10.1016/j.landusepol.2022.106147

Lecina-Diaz J, Campos JC, Pais S et al (2023a) Stakeholder perceptions of wildfire management strategies as nature-based solutions in two Iberian biosphere reserves. Ecol Soc 28:39. https://doi.org/10.5751/ES-13907-280139

Lecina-Diaz J, Chas-Amil M-L, Aquilué N et al (2023b) Incorporating fire-smartness into agricultural policies reduces suppression costs and ecosystem services damages from wildfires. J Environ Manage 337:117707. https://doi.org/10.1016/j.jenvman.2023.117707

Lucas-Borja ME, Jing X, Van Stan JT et al (2022) Changes in soil functionality eight years after fire and post-fire hillslope stabilisation in Mediterranean forest ecosystems. Geoderma 409:115603. https://doi.org/10.1016/j.geoderma.2021.115603

Mairota P, Leronni V, Xi W, Mladenoff DJ, Nagendra H (2014) Using spatial simulations of habitat modification for adaptive management of protected areas: Mediterranean grassland modification by woody plant encroachment. Environ Conserv 41(2):144–156. https://doi.org/10.1017/S037689291300043X

Mantero G, Morresi D, Marzano R, Motta R, Mladenoff DJ, Garbarino M (2020) The influence of land abandonment on forest disturbance regimes: a global review. Landsc Ecol 35(12):2723–2744. https://doi.org/10.1007/s10980-020-01147-w

Meier S, Elliott RJR, Strobl E (2023) The regional economic impact of wildfires: evidence from Southern Europe. J Environ Econ Manag 118:102787. https://doi.org/10.1016/j.jeem.2023.102787

Millington JDA, Wainwright J, Perry GLW, Romero-Calcerrada R, Malamud BD (2009) Modelling Mediterranean landscape succession-disturbance dynamics: a landscape fire-succession model. Environ Model Softw 24(10):1196–1208. https://doi.org/10.1016/j.envsoft.2009.03.013

Moreira F, Ascoli D, Safford H et al (2020) Wildfire management in Mediterranean-type regions: paradigm change needed. Environ Res Lett 15:011001. https://doi.org/10.1088/1748-9326/ab541e

Moreira F, Leal M, Bergonse R et al (2023) Recent trends in fire regimes and associated territorial features in a fire-prone Mediterranean region. Fire 6(2):60

Moritz M, Batllori E, Bradstock R et al (2014) Learning to coexist with wildfire. Nature 515:58–66. https://doi.org/10.1038/nature13946

Mouillot F, Rambal S, Joffre R (2002) Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. Glob Change Biol 8(5):423–437. https://doi.org/10.1046/j.1365-2486.2002.00494.x

Ne'eman G, Lev-Yadun S, Arianoutsou M (2012) Fire-related traits in Mediterranean basin plants. Israel J Ecol Evol 58(2–3):177–194. https://doi.org/10.1560/IJEE.58.2-3.177

Oddi FJ (2018) Fire regime. In: Manzello SL (ed) Encyclopedia of wildfires and wildland-urban interface (WUI) fires. Springer International Publishing, Cham, pp 1–12. https://doi.org/10.1007/978-3-319-51727-8_73-1

Oliveira S, Gonçalves A, Zêzere JL (2021) Reassessing wildfire susceptibility and hazard for mainland Portugal. Sci Total Environ 762:143121. https://doi.org/10.1016/j.scitotenv.2020.143121
Oliveira AS, Silva JS, Guiomar N et al (2023) The effect of broadleaf forests in wildfire mitigation in the WUI—a simulation study. Int J Disaster Risk Reduct 93:103788. https://doi.org/10.1016/j.ijdrr.2023.103788
Omi PN (2015) Theory and practice of wildland fuels management. Curr For Rep 1(2):100–117. https://doi.org/10.1007/s40725-015-0013-9
Ouellette MR, Perera A, Boychuc D (2020) BFOLDS fire regime module v2.1: user guide for LANDIS-II extension. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, ON
Pais S, Aquilué N, Campos J et al (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
Pais S, Aquilué N, Brotons L, Honrado JP, Fernandes PM, Regos A (2023) The REMAINS R-package: paving the way for fire-landscape modeling and management. Environ Model Softw 168:105801. https://doi.org/10.1016/j.envsoft.2023.105801
Pausas JG (2022) Pyrogeography across the western Palaearctic: a diversity of fire regimes. Glob Ecol Biogeogr 31(10):1923–1932. https://doi.org/10.1111/geb.13569
Pausas JG, Fernández-Muñoz S (2012) Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Clim Change 110(1):215–226. https://doi.org/10.1007/s10584-011-0060-6
Pausas JG, Keeley JE (2014) Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. New Phytol 204(1):55–65. https://doi.org/10.1111/nph.12921
Pedersen JST, van Vuuren DP, Aparício BA, Swart R, Gupta J, Santos FD (2020) Variability in historical emissions trends suggests a need for a wide range of global scenarios and regional analyses. Commun Earth Environ 1(1):41. https://doi.org/10.1038/s43247-020-00045-y
Pereira JMC, Silva PC, Melo I, Oom D, Baldassarre G, Pereira MG (2022) Cartografia de Regimes de Fogo à Escala da Freguesia (1980–2017) Vila Real, Portugal
Perera A, Ouellette MR, Boychuk D (2014) BFOLDS fire regime module v2.0: user guide for LANDIS-II extension. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, ON
Perpiña Castillo C, Jacobs-Crisioni C, Diogo V, Lavalle C (2021) Modelling agricultural land abandonment in a fine spatial resolution multi-level land-use model: an application for the EU. Environ Model Softw 136:104946. https://doi.org/10.1016/j.envsoft.2020.104946
Pettorelli N, Schulte to Bühne H, Tulloch A et al (2018) Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward. Remote Sens Ecol Conserv 4(2):71–93. https://doi.org/10.1002/rse2.59
R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
Regos A (2022) Nature-based solutions in an era of mega-fires. Nature 607:499. https://doi.org/10.1038/d41586-022-01955-x
Regos A, Pais S, Campos JC, Lecina-Diaz J (2023) Nature-based solutions to wildfires in rural landscapes of Southern Europe: let's be fire-smart! Int J Wildland Fire 32(6):942–950. https://doi.org/10.1071/WF22094
Rouet-Leduc J, Pe'er G, Moreira F et al (2021) Effects of large herbivores on fire regimes and wildfire mitigation. J Appl Ecol 58(12):2690–2702. https://doi.org/10.1111/1365-2664.13972
Ruffault J, Curt T, Moron V et al (2020) Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. Sci Rep 10:13790. https://doi.org/10.1038/s41598-020-70069-z
San-Miguel-Ayanz J, Durrant T, Boca R et al (2022) Forest fires in Europe, Middle East and North Africa 2021. Luxembourg. https://doi.org/10.2760/34094
Scheller RM, Domingo JB (2019) Landis-II Age-Only Succession v.5 - User guide. Available at: https://github.com/LANDIS-II-Foundation/Extension-Age-Only-Succession-Archived. Accessed 30 Mar 2021
Scheller RM, Domingo JB, Sturtevant BR et al (2007) Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecol Model 201(3–4):409–419. https://doi.org/10.1016/j.ecolmodel.2006.10.009
Scheller RM, Sturtevant BR, Gustafson EJ et al (2019) Base Harvest extension v5 - User guide. Available at: https://github.com/LANDIS-II-Foundation/Extension-Base-Harvest. Accessed 29 Apr 2021
Sil Â, Azevedo JC, Fernandes PM, Regos A, Vaz AS, Honrado JP (2019a) (Wild) fire is not an ecosystem service. Front Ecol Environ 17(8):429–430. https://doi.org/10.1002/fee.2106
Sil Â, Fernandes PM, Rodrigues AP et al (2019b) Farmland abandonment decreases the fire regulation capacity and the fire protection ecosystem service in mountain landscapes. Ecosyst Serv 36:100908. https://doi.org/10.1016/j.ecoser.2019.100908
Sil Â, Azevedo JC, Fernandes PM, Alonso J, Honrado JP (2022) Fine-tuning the BFOLDS Fire Regime Module to support the assessment of fire-related functions and services in a changing Mediterranean mountain landscape. Environ Model Softw 155:105464. https://doi.org/10.1016/j.envsoft.2022.105464
Spiecker H, Lindner M, Schuler J (2019) Douglas-fir—an option for Europe. EFI What Science Can Tell Us vol 9
Suárez-Muñoz M, Mina M, Salazar PC, Navarro-Cerrillo RM, Quero JL, Bonet-García FJ (2021) A step-by-step guide to initialize and calibrate landscape models: a case study in the Mediterranean mountains. Front Ecol Evol 9:653393. https://doi.org/10.3389/fevo.2021.653393
Tapias R, Climent J, Pardos JA, Gil L (2004) Life histories of Mediterranean pines. Plant Ecol 171(1):53–68. https://doi.org/10.1023/B:VEGE.0000029383.72609.f0
Tedim F, Leone V, Amraoui M et al (2018) Defining extreme wildfire events: difficulties, challenges, and impacts. Fire 1(1):9
Thomas FM, Rzepecki A, Werner W (2022) Non-native Douglas fir (*Pseudotsuga menziesii*) in Central Europe: ecology, performance and nature conservation. For Ecol Manage 506:119956. https://doi.org/10.1016/j.foreco.2021.119956
Trabaud L (1992) Community dynamics after fire disturbance: short-term change and long-term stability. Ekistics 59:287–292
Turco M, Bedia J, Di Liberto F et al (2016) Decreasing fires in Mediterranean Europe. PLoS ONE 11(3):e0150663. https://doi.org/10.1371/journal.pone.0150663
Turco M, von Hardenberg J, AghaKouchak A, Llasat MC, Provenzale A, Trigo RM (2017) On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. Sci Rep 7:81. https://doi.org/10.1038/s41598-017-00116-9
Turco M, Jerez S, Augusto S et al (2019) Climate drivers of the 2017 devastating fires in Portugal. Sci Rep 9:13886. https://doi.org/10.1038/s41598-019-50281-2
Turner MG (2010) Disturbance and landscape dynamics in a changing world. Ecology 91(10):2833–2849. https://doi.org/10.1890/10-0097.1
Turner M, Gardner R, Dale V, O'Neill R (1989) Predicting the spread of disturbance across heterogeneous landscapes. Oikos 55:121–129. https://doi.org/10.2307/3565881
Uchytil RJ (1991) *Pseudotsuga menziesii* var. *menziesii*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Accessed 2 Aug 2021
UNEP (2022) Spreading like wildfire—the rising threat of extraordinary landscape fires. A UNEP Rapid Response Assessment. Nairobi
van Wilgen BW, Siegfried WR (1986) Seed dispersal properties of three pine species as a determinant of invasive potential. S Afr J Bot 52(6):546–548. https://doi.org/10.1016/S0254-6299(16)31489-2
Varela E, Górriz Mifsud E, Ruiz-Mirazo J, López-i-Gelats F (2018) Payment for targeted grazing: integrating local shepherds into wildfire prevention. Forests 9:464. https://doi.org/10.3390/f9080464
Vázquez A, Climent JM, Casais L, Quintana JR (2015) Current and future estimates for the fire frequency and the fire rotation period in the main woodland types of peninsular Spain: a case-study approach. Forest Syst 24(2):e031. https://doi.org/10.5424/fs/2015242-06454
Verkerk PJ, Martinez de Arano I, Palahí M (2018) The bio-economy as an opportunity to tackle wildfires in Mediterranean forest ecosystems. Forest Policy Econ 86:1–3. https://doi.org/10.1016/j.forpol.2017.10.016
Wang X, Wotton BM, Cantin AS et al (2017) cffdrs: an R package for the Canadian forest fire danger rating system. Ecol Process 6:5. https://doi.org/10.1186/s13717-017-0070-z
Williams NG, Lucash MS, Ouellette MR et al (2023) Simulating dynamic fire regime and vegetation change in a warming Siberia. Fire Ecol 19:33. https://doi.org/10.1186/s42408-023-00188-1
WWF (2019) The Mediterranean burns: WWF's Mediterrenean proposal for the prevention of rural fires. WWF, Madrid

Wyser K, van Noije T, Yang S, von Hardenberg J, O'Donnell D, Döscher R (2020) On the increased climate sensitivity in the EC-Earth model from CMIP5 to CMIP6. Geosci Model Dev 13(8):3465–3474. https://doi.org/10.5194/gmd-13-3465-2020

Publisher's Note