Dissertationes Forestales 369

Fires in Mediterranean forests: patterns of occurrence, transitions and impact

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Academic dissertation

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ABSTRACT

Wildfires are disturbances affecting forests significantly, especially in Mediterranean landscapes. Traditional forest management and planning attends to targets that might not align with fire prevention and adaptation strategies that promote forest resistance and resilience. This thesis presents tools to integrate fire prevention and adaptation into strategic forest planning given the increasing impacts caused by wildfires, aiming to reduce and prevent their negative effects on forest systems. The first study delves into the size-related differences of the drivers behind fire occurrence in Mediterranean landscapes, producing recommendations on what prevention strategies to adopt on areas with varying probabilities of being burnt by small, medium or large fire events. The second study focuses on mapping and assessing fire recurrence probability and investigates the factors influencing reburnt areas, analysing the role of post-fire vegetation and timing of the first fire. The last study examines post-fire mortality patterns in pure and mixed forest stands, focusing on different species combinations, their mixture levels and the role of fire-related traits and strategies on fire resistance of Spanish forests. The developed methodologies revolve around the integration of modelling and ecological approaches, while making use of spatial tools for fire risk assessment. A step-by-step approach to evaluate fire risk is presented throughout the studies, based on the calculation of burnt area probabilities and the posterior estimation of damage caused by fire in fire-prone forests. The chosen modelling variables and drivers of occurrence, recurrence and damage in the studies are instrumental for the consideration of fire risk in strategic forest planning. The produced models and findings provide the necessary assessments to establish guidelines for future fire prevention and adaptation strategies.

Keywords: fire risk, resistance, fire damage, fire prevention, forest management, strategic planning

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Joensuu, 22nd January 2025

Marina

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I-IV.

I Peris-Llopis M, González-Olabarria JR, Mola-Yudego B (2020) Size dependency of variables influencing fire occurrence in Mediterranean forests of Eastern Spain. European Journal of Forest Research 139: 525-537.
https://doi.org/10.1007/s10342-020-01265-9

II Peris-Llopis M, Vastaranta M, Saarinen N, González-Olabarria JR, García-Gonzalo J, Mola-Yudego B (2024) Post-fire vegetation dynamics and location as main drivers of fire recurrence in Mediterranean forests. Forest Ecology and Management 568:122126.
https://doi.org/10.1016/j.foreco.2024.122126

III Peris-Llopis, M, Mola-Yudego, B, Berninger, F, García-Gonzalo, J, González-Olabarria, JR (2024) Impact of species composition on fire-induced stand damage in Spanish forests. Scientific reports 14, article id 8594. https://doi.org/10.1038/s41598-024-59210-4

Author´s contributions

Marina Peris Llopis is responsible for the compilation and writing of this thesis. For all the articles, the author was responsible for conceptualization, data preparation and formal analyses, programming, drafting and writing the manuscripts. Co-authors participated in the planning and conceptualization of the studies, discussion of the results and critical review throughout the manuscripts.

TABLE OF CONTENTS

ABBREVIATIONS AND DEFINITIONS

Abbreviations

CLC	Corine Land Cover
MFE	Spanish Forest Map [Mapa Forestal de España]
NFI	National Forest Inventory

INTRODUCTION

Fire in forest ecosystems

Fire is an integral part of natural cycles in forests across the world that can cause both positive and negative impacts to forests (McLauchlan et al. 2020), from promoting biodiversity of pyrophilous species and biomass renewal to substantial CO_2 emissions and hindering the provision of ecosystem services among others (Bowman et al. 2009). The footprint of fire can be perceived in landscapes all around the world, evidenced by changes in fossil charcoal throughout geological eras and the more recent signs of the use of fire by humans, as in slash-and-burn agriculture (Bowman et al. 2009). Over time, forest species have adapted to fire, shaping their geographical distributions and presenting traits to withstand fire pressures (Bond and Keeley 2005; Archibald et al. 2018). Likewise, humans have learnt to coexist with fire, adopting strategies that range from preventive measures to suppression activities aimed to extinguish fire.

The concept of fire risk involves two key components: the probability of a fire event happening in an area (fire hazard) and the impact that it generates (Bachmann and Allgöwer 2001). These elements are essential to understand fire regimes, which describe the spatial and temporal patterns of fire and its impacts at the ecosystem or landscape level (Krebs et al. 2010; Sommers et al. 2011). This thesis explores various elements influencing fire risk and fire regimes. Fist, fire occurrence, defined as the number of fires occurring in a given area during a specific period of time (Finney 2005). For a fire to occur, an ignition or starting point (heat), a fuel to burn and the presence of oxygen are required (Wagtendonk 2018). Depending on these elements and the weather conditions, an ignition can become a fire, with the potential to gain momentum and burn large areas. Burning probability is a related concept that refers to the probability of an area to be burnt by a wildfire during a certain time period (Finney 2005; Miller and Ager 2013). Additionally, some areas experience fire recurrence, understood as the occurrence of consecutive fires in the same location during a specific period. Another component of fire risk is fire damage, which measures the impact generated by fire on a system. It is defined in this thesis as tree mortality due to fire, and it is often referred in the literature as fire severity, particularly when indicating biomass loss (Keeley 2009), although it can also refer to the impact on other ecosystem elements and being represented by several indicators.

Even though forest around the globe have evolved in the presence of fire, latest extreme fire events have raised concerns about shifting fire regimes and the contribution of humans to these changes, as well as the adaptation capacity of forest ecosystems (McWethy et al. 2013; Enright et al. 2014; Pausas and Keeley 2014). Research points at both directions, human role in exacerbating the fire issue but also its contribution to decreased burnt area (Rogers et al. 2020). Human activity influence fire risk in different ways. Land cover distribution and land use changes alter forested landscapes, leading to more fragmented or more homogeneous landscapes. These affect the continuity of forest fuels, and by extension, fire behaviour and impacts (Cochrane and Bowman 2021). Forest planning and management practices play a crucial role on these dynamics (Gauthier et al. 2014), whether by promoting biomass accumulation or through proactive measures to prevent fire impacts, such as fuel breaks or changes in species composition and distribution of fuels. Many of these measures also serve adaptation goals, promoting changes in forest systems to increase their future ability to cope with disturbances.

Current trends and drivers

Globally, fire is one of the most frequent disturbances impacting forests (Pattaca et al. 2022; Altman et al. 2024) although it is more prevalent in certain biomes. As forecasted, we are already witnessing a rise in burnt area worldwide, a trend heavily influenced by climate change (Seidl et al. 2011; Burton et al. 2024). In some areas, rather than the frequency or extent of forest fires, the primary concern is the increasing intensity of individual fire events (Cunningham et al. 2024), with a greater potential to cause extensive damages.

In the case of Spain, trends in total burnt area and number of wildfires show a decline as a result of suppression activities (Silva et al. 2018; Rodrigues et al. 2020), but there is an increasing occurrence of extreme events in terms of intensity (Moreira et al. 2020), and existing scenarios predict more hazardous fire-weather conditions in the future (Alcasena et al. 2019; Rodrigues et al. 2020). This trend has also been observed in other Mediterranean countries, where there is an increasing frequency of large fires (Royé et al. 2019). In addition to being a hotspot for fires, in many Mediterranean areas there is a high exposure to fire, derived from a vast wildland-urban interface (Salis et al. 2014; Oliveira et al. 2018), with potential negative consequences for human communities (Alcasena et al. 2019). The combination of several elements and their spatial coincidence in Mediterranean Spain makes it particularly interesting from a fire risk point of view, being representative of fire-prone conditions while including an elevated human exposure, as well as intensified fire risk partly derived from past fire management legacies and climate change effects (i.e. suppression bias, Kreider et al. 2024). Moreover, the area is severely affected by other disturbances such as droughts, which are also expected to increase in the future, generating potential feedbacks with unforeseen consequences in Mediterranean ecosystems (Ruffault et al. 2018).

Forest fires are influenced by different factors such as human activity, fuels, climate and topography, defining their occurrence, severity and distribution. Humans play a key role in the occurrence of fires by directly causing ignitions, modifying the existent landscapes, influencing fuel conditions, or by fighting active fires. In Mediterranean areas about 71% of the ignitions are anthropogenic (Ganteaume et al. 2013), and in the case of Spain their specific causes and motivations vary widely (Martínez et al. 2009; González-Olabarria et al. 2015). On the other hand, human activity can help reduce fire risk by increasing landscape heterogeneity which modifies fuel continuity and connectivity, and through fire suppression efforts (Bowman et al. 2011).

Climate is another element influencing fire risk, it shapes the distribution of species and forest types across the globe (Pais et al. 2023), affects how vegetation becomes different types of fuels, and controls inter-annual variability in burnt area (Abatzoglou et al. 2018). Locally, weather conditions such as wind speed and relative humidity influence fire behaviour, modulating the potential extent and damages caused by fire (Benson et al. 2008). Additionally, lightning can cause ignitions, that under the proper conditions can develop into fires and burn large areas. Recent studies link climate change to the lengthening of fire seasons and the expansion of fire-prone areas (Senande-Rivera et al. 2022), with climate scenarios indicating more favourable weather conditions for the occurrence of large fires in the Mediterranean Basin (Ruffault et al. 2020). Climate change effects in the long-term are deeply uncertain and research efforts have been made to account for uncertainty associated to fire risk and climate change, aiming to facilitate decision making in forest planning (Johnson et al. 2023) and prioritising robust decisions in a changing arena (Yousefpour and Hanewinkel 2016).

Topography can either facilitate or hinder fire spread and plays a role in the distribution of fire ignitions (Ganteaume et al. 2013; Calviño-Cancela et al. 2017) as well as variations in fuel moisture levels (Holden and Jolly 2011). It can also facilitate suppression efforts, with less rugged terrains being advantageous during fire extinction activities. Regarding present fuels or vegetation with the potential to burn, these will determine the type of fire and its extent. Species with varying flammability degrees, structural characteristics and traits strongly influence potential fire risk (Schwilk and Caprio 2011). Varying species composition and developmental stages generate different forest structures, modulating fire behaviour and resulting damage (González et al. 2007; Fernandes et al. 2010; Peris-Llopis et al. 2024a). Most of these factors can be modified applying long-term changes executed through strategic forest planning.

The importance and role of these drivers in modifying fire activity varies across biomes and time, with recent studies pointing to the on-going changes in fire regimes (Pausas and Fernández-Muñoz 2012; Wasserman and Mueller 2023) and their implications for fire prevention and mitigation strategies (Fernandes 2013). Furthermore, interactions between these elements are common and rapidly shifting as human communities and ecosystems readjust to changing conditions, influencing fire activity and fire regimes (Linn et al. 2007; Holsinger et al. 2016; Kreider et al. 2024).

Strategic planning and adaptation in the light of fire

The role of humans on exacerbating the fire issue is well-known, but humans also have the tools to prevent and mitigate the negative impacts generated by forest fires, starting with the reduction of ignitions. In this sense, research focusing on the occurrence of human-caused fires and ignitions acknowledges the need to tackle these events from the root (i.e. Martell et al 1978; Rodrigues et al. 2016; Costafreda-Aumedes et al. 2017), aiming to prevent that an ignition occurs and becomes a large fire. For this to happen, the presence of a fuel is needed, in our case a forest fuel. As mentioned previously, forest types, characteristics and their state directly determine fire risk. Forest management and planning plays an essential part in reducing fire risk, through the design of strategies and actions that integrate fire prevention and mitigation. More recently, strategies advocating for the adaptation of forests to disturbances are gaining terrain, concentrating on promoting forests and landscapes that can better adapt to fire (Schelhaas et al. 2010; Hessburg et al. 2021).

Traditional wildfire management has focused on fire suppression, which in the long-term has exacerbated the fire problem due to the accumulation of fuels that otherwise would have been regulated (Kreider et al. 2024). In the last decade, strategies that emphasize prevention have become prominent and there is plenty of research in this line (González-Olabarria and Pukkala 2011; Costa-Freitas et al. 2017). These provide a framework for estimating fire risk and incorporating it into a management problem with a clear objective. For instance, sustainable timber production in fire-prone areas, or reducing fire risk while maximizing other ecosystem services (as in Bagdon et al. 2016). Once fire risk has been mapped and different objectives acknowledged, elements related to preventing and suppressing the fire itself can be optimally allocated in the territory (e.g. González-Olabarria et al. 2017; Ramalho et al. 2021). Latest developments call also for frameworks to reduce fire risk involving adaptative measures that consider the feedback mechanisms between disturbances impacting forests and planned changes to prevent those fires and their consequences, as in the case of human activity resulting in forest and landscape modifications that feed future fire activity in different ways (Fernandes 2013). In this context, strategic planning could benefit from a broader spatial and ecological perspective on the development of tools for fire prevention and adaptation.

Identifying areas with higher probabilities of burning is the first step to analyse burnt area patterns and identify locations with larger needs for fire prevention and adaptation activities. In this sense, areas with different characteristics present varying probabilities of fire occurrence and different resources at risk. For example, certain areas might have a higher likelihood to have a large fire with potentially higher intensity, whereas other areas will have smaller fires that do not cause substantial damages. At the same time, factors driving the occurrence of these fires can differ based on the final area burnt. Fire prevention and adaptation actions can be targeted in different areas based on those differences (study **I**), focusing either on actions destined to the population and increasing their awareness towards fire risk, or on forest planning strategies aiming to reduce fire risk. In the last case, fires happening in forested systems with the potential to burn large areas and generate mass mortality events would be the aim of the designed or planned actions. Moreover, certain areas can be subject to consecutive fires, compromising vegetation´s ability to recover given short fire recurrence intervals. Understanding post-fire vegetation dynamics and their relationship with recurrence probability (study **II**) is essential in order to provide information to identify time windows and locations where to target fire prevention and adaptation activities. In this respect, forest planning strategies aiming to prevent these recurrent events benefit from knowledge on the fire-proneness and characteristics of vegetation covers before and after fires. Research in this line has linked fuel types and stand structural features to varying levels of fire recurrence (Fernandes et al. 2015) and reburnt severity (Yocom et al. 2022), mentioning both their negative effects on vegetation (Malkisnon et al. 2011) but also their potential in reducing severity of future fire events (Fernandes et al. 2015; Yocom et al. 2022).

Another key component of fire risk that can be approached from a forest planning perspective is fire damage. Fire damage depends on several factors, many of which can be influenced through forest management and planning (study **III**). For instance, less hazardous stand structures can be maintained by means of thinning and understory biomass control using different methods (Crecente-Campo et al. 2009; Vilà-Vilardell et al. 2023). Species composition derives on different forest structures, with diverse degrees of resistance to fire. Fire risk can be tackled by strategically promoting certain species or their mixtures in locations known to be severely affected by fire and collectively reducing tree mortality due to fire in the long-term (Peris-Llopis et al. 2024a). Mixtures of different species could also be used as buffer areas to prevent or slow down fire spread, modifying the local conditions and providing multiple benefits (Marshall et al. 2024), always based on specific studies about the suitability of those areas and their climatic profiles for the development of the selected mixtures.

In this thesis, variables representative of drivers and conditions modifying fire risk and its components are analysed. An important criterion for their selection is the fact that the factors considered through the variables can be influenced through forest management and planning, ultimately at the strategic level. The chosen variables are also used for modelling purposes, describing their influence on fire occurrence and damage. These models can be used with prevention purposes but also aiming to better prepare forests to adapt to fire disturbances. Such is the case of long-term changes in species composition or land covers with a lower likelihood of burning repeatedly, both aiming to boost forest adaptation capacity.

Models for fire prevention and adaptation

Models are essential tools to explain real-world phenomena, enabling to identify trends and relationships between the phenomenon of interest and the factors influencing it. Beyond isolating the effects of various drivers, models can quantify variation unexplained by the independent variables. In forestry, models are widely used, exemplified by the broad use of allometric equations to estimate forest growth or the reliance on fuel models by fire suppression professionals.

A vast selection of models exists, and the choice of the proper one to address a specific phenomenon depends on multiple considerations. The first aspect to consider is how the response variable is quantified, esteeming from the core definition of the problem and derived from the available data in the case of empirical models. One example could be fire damage, quantified as a percentage of damage (continuous response) or as a severity class (categorical response). The choice of model would vary accordingly, as would the assumptions about the response variable´s distribution. Another aspect to consider is the nature of the relationship between the response variable and predictors, particularly regarding the potential existence of hierarchies and their implications. For instance, models based on National Forest Inventory (NFI) data often involve hierarchical structures, where measurements are taken at various levels and are located within specific strata. Similarly, models must account for variation arising from multi-temporal data, acknowledging the varying nature of fires and their inter-annual variability.

Modelling efforts in fire research are focused on diverse aspects of the fire phenomenon and rely on different types of data. For example, flammability models based on laboratory experiments in which the ignition and burning times of different fuels are tested. At broader scales, fire-related models have traditionally focused on two areas: fire behaviour and fire ecology. Fire behaviour models, concentrated on elements surrounding the fire events while these are active, like fire spread models (examples in Silva et al. 2022). These are frequently developed to meet fire suppression objectives, functioning at an operational level (Duff and Tolhurst 2015), but also serving preventive purposes. Fire ecology models address vegetation dynamics and the ecological impacts generated by fires. Some models integrate these two areas, capturing interacting elements and feedbacks between fire behaviour and ecological responses and mechanisms (some examples in Keane et al. 2004; Ager et al. 2011; Ager et al. 2020). It is at this intersection that models with fire prevention and adaptation purposes are developed in this thesis, considering the impacts of fire on fuel dynamics and vice versa.

Models can be refined to reflect inherent aspects of the studied phenomenon. In this line, when working with unbalanced data, model weights can correct potential over or underrepresentation of certain observations. In this thesis, model weights are used to account for differences in burnt area, fire sizes, and variations in stocking density across NFI plots. Similarly, incorporating mixed effects in the models allows to account for varying degrees of clustering and grouping, which can introduce between and within groups variation that affects parameter estimates. This approach is particularly crucial in cases involving high levels of clustering, such as recurrent fire events.

In this thesis, models are developed to address fire occurrence, fire recurrence and fire damage, collectively aiming to explain key components of fire risk. By concatenating results from these models, fire risk in forests can be estimated. First, by locating fire-prone areas and the probability of burnt area. Second, by identifying areas subject to repeated fires and estimating recurrence probability and the impact of fire on associated land covers. Third, by providing a tool (a fire damage model) to estimate the impact generated by fire in burnt areas and assessing fire resistance of pure and mixed species forests. These models serve as instruments for promoting forest resilience under fire risk, supporting decision makers in the design and implementation of prevention and adaptation strategies. Estimations and guidelines arising from the models can help to identify and map priority areas for fire prevention activities as well as offering potential indicators and measures for future forest adaptation.

Aims of the thesis

The ultimate goal of this thesis is to understand spatiotemporal patterns linked to the occurrence of forest fires, burnt area and fire damage, along with the associated changes in forested landscapes. In the long-term, this information could be used to mitigate fire adverse impacts while enhancing forest adaptation capacity, with the aim to promote forests and landscapes resilient to fire disturbances. To this end, this thesis proposes models and estimates that add valuable knowledge that can help consider fire risk into strategic forest planning, as well as methods to assess some of the elements contributing to fire risk. These can support decision-making processes related to fire prevention and adaptation strategies.

The specific objectives are:

1. To identify fire-prone areas and estimate probability of burnt area based on forest conditions, topography and human accessibility, categorized by fire size classes.
2. To assess fire recurrence probability, the role of post-fire vegetation, its time dependence and impacts.
3. To evaluate the influence of species composition, their fire-related strategies and mixture levels on stand´s resistance to fire damage.

The hypotheses are:

1. Fires of different sizes are influenced by fire occurrence and burnt area drivers in distinct ways. Therefore, prevention strategies should be tailored to the varying probabilities of having a small, medium or large fire in a given area. (Study **I**).
2. The probability of reburnt area depends on post-fire fuel types and recovery time or time since the previous fire. In the short term, fire recurrence reduces fuel complexity, leading to a decline in more structurally heterogeneous forest types. (Study **II**).
3. Mixtures of tree species do not always show higher resistance to fire; resistance depends on species, levels of mixture and species fire-related traits. (Study **III**).

MATERIALS AND METHODS

Study area

The forests studied in this thesis are located in Spain, with a particular focus on the Mediterranean area (Catalonia and *Comunitat Valenciana* regions, highlighted in **Fig. 1**), a hotspot for forest fires. Atlantic, Macaronesian and Alpine bioregions are also part of the studies, encompassing a diverse range of conditions and associated forest ecosystems. Approximately 55% of Spain is covered in forests, which continue to grow in both volume and number of trees (Ministerio para la Transición Ecológica y el Reto Demográfico 2021). The most common tree species in the country are *Pinus pinaster* and *Pinus sylvestris*, followed by *Pinus halepensis* (Ministerio para la Transición Ecológica y el Reto Demográfico 2021), the latter being the most affected conifer by forest fires in Spain (Ministerio de Agricultura, Pesca y Alimentación 2019). In general, forest management practices in Spain are strongly dependent on the region and forest types, with Atlantic forests in northern areas more focused on timber production and Mediterranean forests adopting more protective approaches (Vadell et al. 2022). Concerning fire risk management in Spain, although a national level body coordinates firefighting activities (particularly of large fires), firefighting and fire prevention competencies are allocated regionally (Ley de Montes 43/2003). Different regions have their own fire management bodies, with operational decisions being made mostly at the regional level.

The first study focuses on the *Comunitat Valenciana* (NUTS ES52), a region with a Mediterranean climate characterized by densely populated coastal areas. Forests cover 56% of the region, with *Pinus halepensis* as the predominant tree species. Shrublands account for almost half of the forest lands (Generalitat Valenciana). Commercial use of forests is not very extended, whereas the agricultural and touristic sectors are more dominant. The region is severely affected by forest disturbances such as droughts and fires, specially by the occurrence of large fires, leading the rankings of largest proportion of area burnt by large fires (>500 ha) in the country for several years (Ministerio de Agricultura, Alimentación y Medio Ambiente 2012; Ministerio de Agricultura, Pesca y Alimentación 2019).

Catalonia (NUTS ES51) is located in the Mediterranean area and features a diverse landscape that includes the Pyrenees Mountain range, with alpine forests at high elevations. Forests occupy about 63% of the territory, with *Pinus halepensis* and *Pinus sylvestris* being the most abundant species (Ministerio de Agricultura, Alimentación y Medio Ambiente 2017). Commercial use of forests is more extended in this region, co-existing with recreational and agricultural uses in certain areas. Over the past decade, Catalonia has been one of the regions with higher number of fires annually (Ministerio de Agricultura, Pesca y Alimentación 2019) and presents a large share of area burnt by large fires (Ministerio de Agricultura, Pesca y Alimentación 2019).

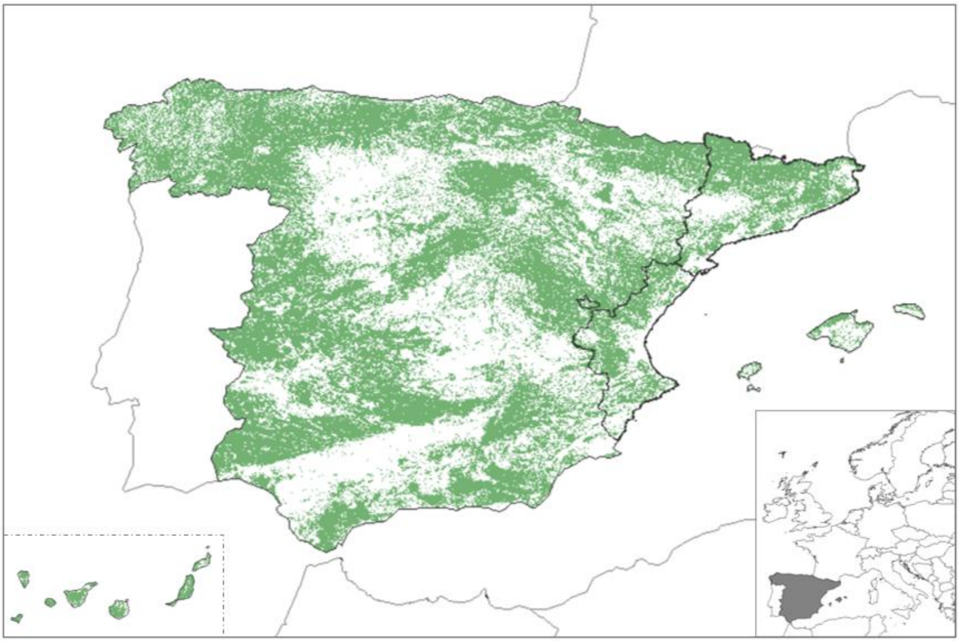

Figure 1. Location of the study areas and forest cover (in green): Spain, Catalonia and *Comunitat Valenciana*. Forest cover data from the Spanish Forest Map (MFE, 1997-2006).

Both regions share common features influencing fire risk, such as their Mediterranean climate and landscapes strongly influenced by rural abandonment (and related lack of forest management) and agricultural practices, as in the widespread use of fire for in-situ burning of agricultural residues. This has implications for the configuration of land covers in the landscapes as well as for the conditions, continuity and connectivity of potential fuels. Both regions have extensive wildland-urban interfaces, which contribute to the high number of evacuations during fire events (Ministerio de Agricultura, Pesca y Alimentación 2019) and evidence the exposure of these communities to fire. Furthermore, tourism is an important sector influencing their economies, increasing human pressure on the region's forests.

Data

The present thesis makes use of various datasets available for Spain and the considered regions, relying on their combination for the statistical and spatial analyses.

Fire perimeters and data about fire events in the *Comunitat Valenciana* (studies **I** and **II, Fig. 2**) were obtained from the fire reports and resulting maps prepared by the *Conselleria de Agricultura, Medio Ambiente, Cambio Climático y Desarrollo Rural* (Generalitat Valenciana 2018). Fire perimeters and burnt areas for Catalonia, used in study **II** (**Fig. 2**), were provided by *Generalitat de Catalunya* (2018).

Forest and land cover data were obtained from different sources. In study **I**, the Spanish Forest Map (MFE, with scale 1:50000) provided data on existent species and forest structures. In study **II**, Corine Land Cover maps distributed by the European Environment

Agency (Copernicus Land Monitoring Service) were used, including data for 1990, 2000, 2006, 2012 and 2018. In study **III**, both the forest related variables and fire damage observations were extracted from the second and third NFI (1986-1996 and 1997-2007, **Fig. 2**), available through *Ministerio de Agricultura, Alimentación y Medio Ambiente*. Last cycle of the NFI (2008-) was not publicly available for all the regions at the moment the study was completed. Spanish NFI conducts continuous measurements of permanent plots in 10-year cycles, with each field plot consisting of four circular concentric sub-plots with fixed areas. Data on fire-related traits of tree species was sourced from BROT database (Tavsanoglu and Pausas, 2018) and from Tapias et al. 2004.

Topographic variables used in studies **I** and **II** were derived from the Digital Terrain Models (DTM) for both regions, with a scale 1:200, provided by Instituto *Geográfico Nacional* (2009). Road density was calculated using the national road network, available through *Instituto Geográfico Nacional* (2007). Population density was derived from disaggregated Corine Land Cover 2000 maps (European Environment Agency; Gallego 2010).

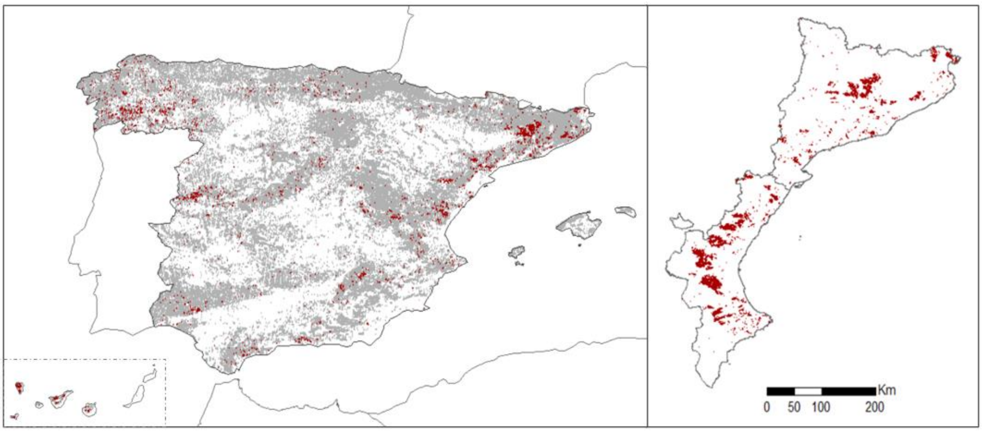

Figure 2. Left: National Forest Inventory plots in Spain (grey), plots with observed fire damage in red. Right: Forest fire perimeters and burnt areas in Catalonia and *Comunitat Valenciana* between 1993 and 2015.

Methods

Modelling fire occurrence

Forest fires occurring in the *Comunitat Valenciana* between 1993 and 2015 were analysed and classified into three size classes: small (5-50 ha), medium (50-500 ha) and large fires (>500 ha). Variables representing drivers of fire occurrence, such as vegetation, topography, and accessibility, were extracted from various data sources and categorized across the entire region using a raster cell size of 200 m. Additionally, variables related to the fire events, such as temperature and humidity (extracted from the fire dataset), were analysed, and differences between size classes compared using Tukey tests.

Forest and land cover data were processed and grouped into classes to represent potential fuels, using the forest structural types, developmental stage and species data from the MFE50. Altitude-Elevation (masl), slope (%) and aspect were grouped into classes to simplify subsequent computational analyses (the resulting classes for these and other variables are listed in Table 1 of study **I**). Population density (hab*km^{-2}) and road density (km*km^{-2}) were used as indicators of human accessibility to the forests and were also classified based on their data distributions. These variables were then combined to create strata with similar characteristics concerning drivers of fire occurrence and burnt area (**Fig. 3**).

Raster cells were assigned values 0 or 1 indicating the absence or presence of fire. The proportion of burnt area for each size class, or number of burnt cells per strata, was calculated and used as the response variable in four Weighted Generalized Linear Models (WGLM), producing a general model for all fires and one model per size class. WGLM permit to fit non-linear relationships between predictors and the response variable. These models are particularly useful when the response variable does not follow a normal distribution, directly applying transformation functions to accommodate the distribution family.

Binomial or quasibinomial distributions of the response were assumed in each model, and a logit link function was applied to the dependent variable. The number of burnt cells per stratum was included as weights in the models to account for differences in fire frequency across size classes. The models explained burnt area per size class based on potential fuels (species and structure, both categorical variables), topography (altitude, slope and aspect), and human accessibility (road and population densities).

A pseudo-R^2 was calculated to assess the goodness of fit of the models (see Equation 2 in study **I**). Road density and slope were transformed for a better fit. Non-significant variables and factor levels were iteratively tested and removed from the models.

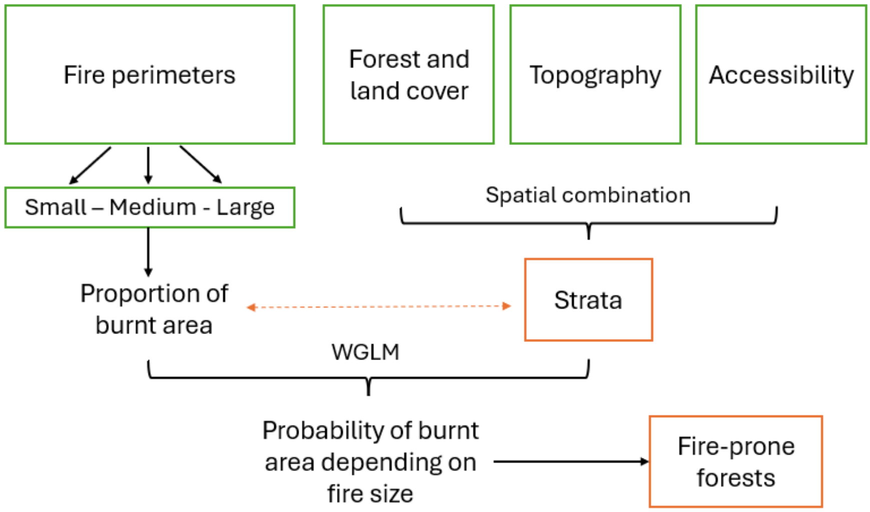

Figure 3. Methodology followed to generate strata and build the fire occurrence models. WGLM: Weighted Generalized Linear Model.

Modelling fire recurrence

In study **II**, a recurrence index was developed by overlapping fire data by year, resulting in a raster map (cell size of 50 m) that identifies areas burnt up to five times between 1993 and 2015 in both Catalonia and the *Comunitat Valenciana*. Following a similar methodological approach to study **I**, strata with homogeneous characteristics were created for the burnt areas and locations with different recurrence indexes were characterized based on the variables considered to be driving fire recurrence. These variables were: post-fire vegetation, altitude (masl), slope (degrees), aspect, road density (km*km^{-2}) and population density (hab*km^{-2}). Differences in topography and accessibility variables by recurrence index were tested using Wilcoxon tests.

CLC forest classes were used to depict vegetation development stages in reburnt areas. The classes, listed in descending order of structural complexity, included tree covered forest (whether coniferous, broadleaved, or mixed), transitional shrubs, sclerophyllous vegetation, moors and heathland and natural grasslands. Other CLC classes, such as sparsely vegetated areas and agricultural lands, were part of the description of post-fire successions but not used for modelling efforts. The use of multiple CLC datasets enabled an accurate description of the vegetation present in the burnt areas and their changes through time, permitting to capture vegetation dynamics and the representation of secondary forest successions. These changes provide an initial assessment of the impact of repeated fires on land covers. Additionally, variables representing topography and human accessibility were included and grouped in classes to generate strata (variables and classes are listed in Table 1 of study **II**).

A mixed effects model was built to explain the proportion of reburnt area in forests burning once and twice (*y* in **Eq. 1**), using the following predictor variables: post-fire vegetation type (fuel), slope, altitude, road density and population density. The year of the first fire occurrence in each location was considered as a random effect (μ_{First} in **Eq. 1**), aiming to account for the reduced chances of burning as the study period progresses. The number of cells per stratum was included as weights in the model.

$$\text{logit}(y) = \beta_1 Slope + \beta_2 Altitude + \beta_3 Roads + \beta_4 Fuel + \beta_5 Population + \mu_{First} \quad (1)$$

Fire damage and species mixtures

More than 80.000 plots from the third NFI were analysed in study **III** and those with observed fire damage and comparable to the second NFI were selected for further analyses, totalling 2782 plots. Mortality was examined on a tree-by-tree basis, comparing trees dead due to fire in the third NFI that were alive in the second NFI. Fire damage was calculated as the proportion of dead trees due to fire in the burnt plots (y in **Eq. 2**).

A WGLM was developed to explain fire damage based on stand structural characteristics and site conditions (**Eq. 2**). The response was assumed to follow a quasibinomial distribution and the logit transformation was applied. The variables included in the model were stand basal area (G, m^2 ha^{-1}), a proxy for stand density calculated as the ratio of stand basal area to quadratic mean diameter (G/Dq), and slope (5 classes), all extracted or calculated using the original NFI data from the burnt plots.

$$\text{logit}(y) = \beta_0 + \beta_1 G + \beta_{2\text{-}5} Slope + \beta_6 G/Dq + \varepsilon \quad (2)$$

Other potential modelling variables were tested but excluded due to their low significance or lack of consistency across regions. The number of trees per plot was included as weights in the model. Potential correlations among variables were assessed using variance inflation factors (VIF) and diagnostic plots.

The most common mixtures of two species in the burnt plots were identified and classified based on mixture levels, determined by the proportion of stand basal area contributed by each species. Three levels were considered: 25-75%, 50-50% and 75-25%. Fire-related traits of these species were examined, namely resprouting capacity, post-fire seedling emergence, serotiny, cone persistence, self-pruning capacity and bark thickness. Different combinations of these traits were assigned to one of the following fire strategies: fire resistant, fire resilient and fire avoider species (traits and resulting species classification are displayed on Table 2 of study **III**). Fire resistant species which present characteristics enabling them to avoid surface fires by protecting their sensitive tissues and increasing the distance between the lower branches and the understory (these species exhibit self-pruning capacity and thick barks). Fire resilient species are those that rely on their resprouting capacity or post-fire seedling emergence to persist after fire. Fire avoider species are those found in environments with minimal fire occurrence.

Observed damage, model predictions and model residuals were compared for each of the species' mixtures considered. Studying the patterns in differential mortality (model residuals) within the mixtures helps to separate the mortality explained by stand structural features (model predictions) from that unexplained by structure, which was associated with species mixture identity and mixture levels (**Fig. 4**). Mean damage in pure plots of each species in the mixtures served as baselines for comparing changes across the three mixture levels considered. Fire damage among combinations of fire-related strategies was compared by applying post-hoc significance tests to the corresponding observed damage, model predictions and residuals.

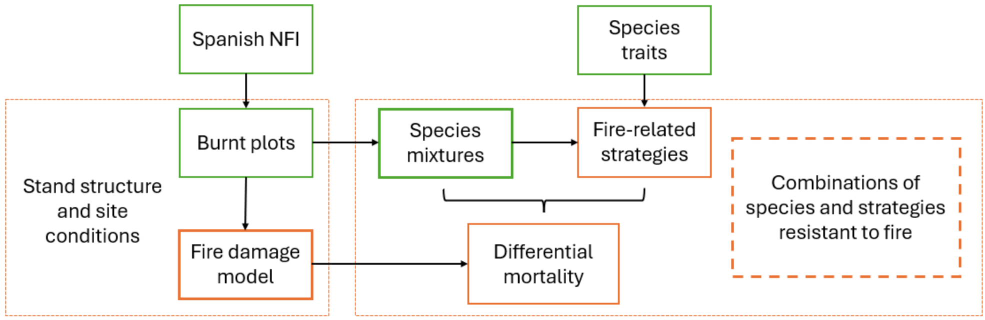

Figure 4. Methodology followed to build the fire damage model and identify fire resistance of common species mixtures in Spanish burnt forests.

RESULTS

Size-dependent drivers of fire occurrence

Between 1993 and 2015 forest fires in the *Comunitat Valenciana* burnt a total of 285024 ha of forest, with 10722 fire events. The classification of these events into size classes, their characterization and posterior modelling allowed to identify differences in the drivers of occurrence of fires belonging to different size classes as well as the general trends across all fire events. There were evident differences on the distribution of forest fires according to size in the *Comunitat Valenciana*. Numerous small fires (5-50 ha) were scattered through the study area, while a fewer number of large events (>500 ha) was concentrated in transitional zones and accounted for most of the total burnt area.

The characterization of burnt areas according to their size revealed notable differences in their causes, predominant vegetation structures, weather conditions, and topography. For instance, variations in mean maximum temperature across size classes were statistically significant. The causes of fires followed a similar pattern for small and medium fires, in both cases approximately 10% were attributed to lightning, while 83% and 86%, respectively, were linked to human activity. In contrast, a lower proportion of large fires had an anthropogenic origin (77%), and similar results were obtained when comparing burnt area proportions.

Results for the four WGLM built, one per each fire size class and a general model, revealed changes in the significance, direction and magnitude of the variables driving fire occurrence (see **Fig. 5**). Potential fuels, described through the forest structural types (such as pasture, bushes, young trees, etc), and dominant species (pines, oaks, mixture of both, or other species) were significant in most cases (regression coefficients listed in table 3 of study **I**). Concerning species, pine dominance did not influence the occurrence of small fires, but it did relate positively to the occurrence of large fires and all fires (general model). Mixtures of oaks and pines were positively linked to the occurrence of large fires. The influence of fuel types varied depending on the size classes. For instance, pasture increased the likelihood of small fires but was not significant in explaining the occurrence of fires of other sizes. The presence of bushes combined with small trees increased the probability of burnt area in all cases. More developed forests, with medium and mature trees, were negatively related to small and large fires, with a more pronounced effect for large fires.

Topography was included in the models through altitude, slope and aspect variables. In all models, altitude consistently reduced the probability of burnt area. Among aspect classes, East-facing orientations were the only significant ones explaining proportion of burnt area and were positively associated with medium and large fires. Steeper slopes reduced the likelihood of large fires. Overall, the effect of topography on the occurrence of small fires was limited.

Human accessibility to forests was modelled using road and population densities. Both variables were negatively related to the proportion of burnt area in all models, indicating that areas with higher accessibility by humans have lower probabilities of burning. Nevertheless, the marginal effects (**Fig. 5**) showed a differing relationship in the case of road density for each developed model. In this sense, a larger proportion of area was burnt by large fires (and according to the general model for all fires) at low road densities, whereas at medium road densities there is a peak in area burnt by medium and small fires.

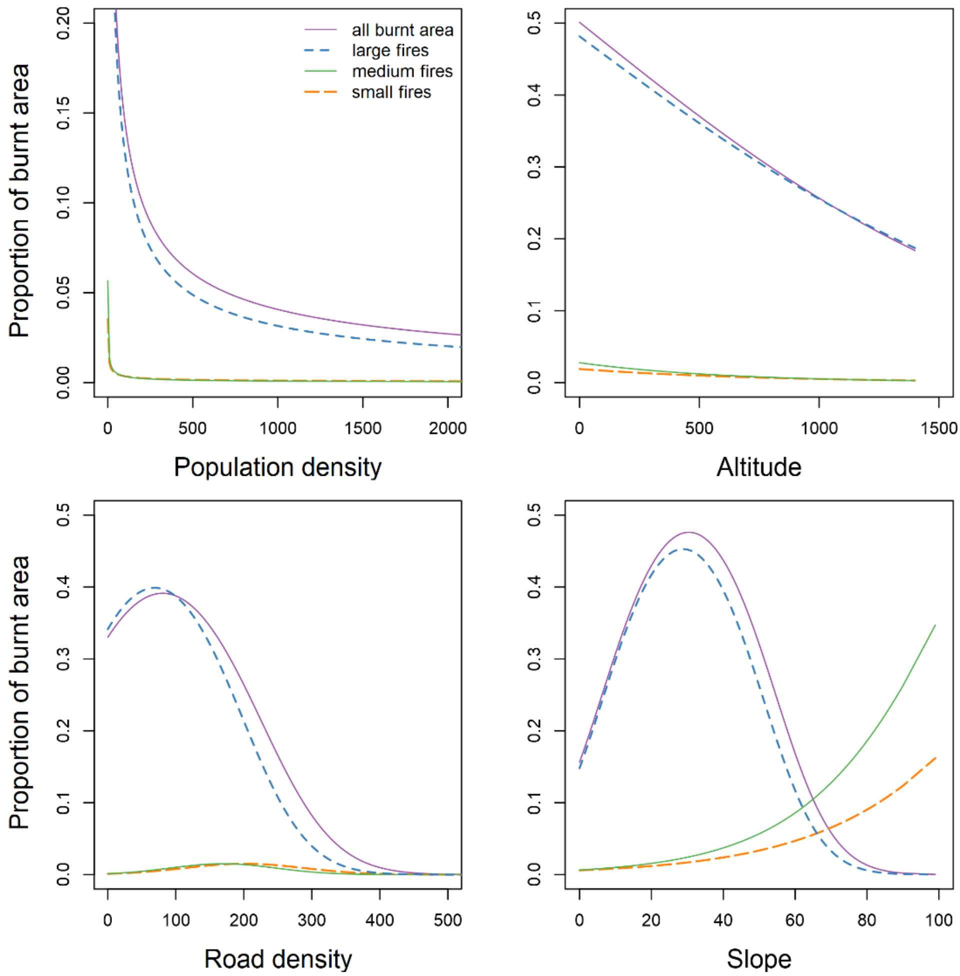

Figure 5. Marginal effects of the modelling variables on the proportion of burnt area according to the models by size class. Adapted from Peris-Llopis et al. 2020.

Pseudo-R^2 varied for the developed models. The model explaining the proportion of burnt area by small fires had a pseudo-R^2 of 0.14, medium fires model of 0.22, large fires model equal to 0.55, and the general model explained about 57% of the variance in the response variable. These results are in line with the regression coefficients and share of total burnt area by size class. Notably, the regression coefficients for the general model, which included all fires, followed the same tendency than in the large fires model, with comparable magnitudes and directions of the relationships for the variables considered. Modelling results point to distinct fire typologies, small fires barely dependent on topography or present species and more developed forests, whereas large fires are predominantly driven by fuels and more strongly influenced by topography.

Fire recurrence in Eastern Spain

About 8% of the total burnt area was reburnt in Eastern Spain between 1993 and 2015, with some locations experiencing up to five fires during that period. Spatial and temporal fire recurrence patterns, based on 12895 fire events, were analysed and linked to site-specific conditions, considering factors such as topography, post-fire vegetation and accessibility, but also time since the previous fire. Reburnt areas presented significantly different characteristics in terms of topography and human accessibility. Wilcoxon comparison tests indicated that areas burnt more than three times were located at significantly lower altitudes, flatter slopes and higher road densities. First and second fires predominantly affected forests and vegetation areas, whereas locations with more than three and four fires were characterised by several land covers and uses (i.e. in agricultural lands and salt marshes).

The study of secondary successions in the burnt areas revealed substantial transformations in land covers following repeated fires, with large areas of tree covered forests being replaced by shrublands. Forested covers such as coniferous, broad-leaved and mixed forests presented a lower stability to change, with abrupt decreases in their cover after fire compared to shrub formations (illustrated in **Fig. 6,** most common land cover transitions for all reburnt areas are presented in Fig. 2 in study **II**). After the second fire, other land covers, like agricultural lands, grasslands and sparse vegetation became more abundant, indicating a shift in the landscape composition after successive fire disturbances.

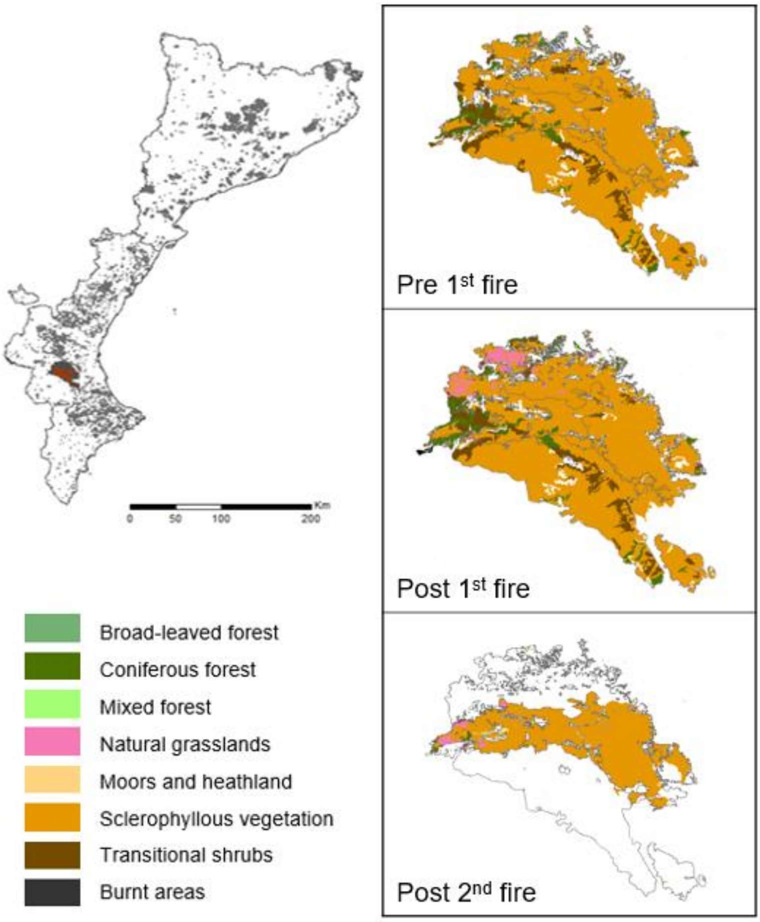

Figure 6. Land cover transitions in one of the reburnt areas in Eastern Spain (marked in red on the left map).

Post-fire vegetation played a significant role in determining the proportion of reburnt area. Tree covered forests exhibited lower probabilities of recurrence compared to shrub formations, particularly mixed forests of coniferous and broad-leaved species. The regression coefficients for shrub formations seem to follow the assumed stages of development, with the more developed transitional shrubs having a stronger influence on the likelihood of reburning than sclerophyllous vegetation and moors and heathland, although significant in all the cases (**Fig. 7**). Model predictions (displayed in Fig. 3 in study **II**) and regression coefficients for the topography variables indicated that lower altitudes (200-600 masl) were positively related to probability of reburning, whereas as altitude increased the probability reduced rapidly. Inversely, flatter slopes were negatively related to reburnt area and as slopes become steeper, the probability of reburning increased. In terms of accessibility, population and road densities were negatively related to probability of reburnt area, with modelling results showcasing higher predicted probabilities in less accessible areas.

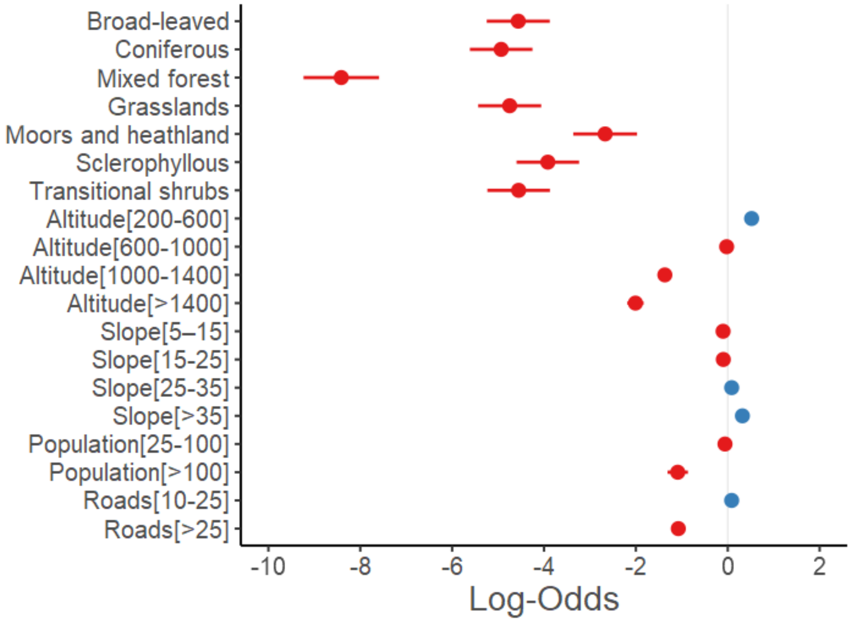

Figure 7. Regression coefficients of the fire recurrence model.

Fire recurrence is time-dependent, meaning that the between years variation, accounted for in the model using the year of the first fire as a random effect, was significant. In this way, the probability of having a second fire was higher when the first fire happened before year 2000 (with a few exceptions) or during 2004, 2006 and 2008. The remaining years were negatively related to recurrence probability, with this trend becoming more pronounced towards the end of the study period (see Fig. 4 in study **II**).

Tree mortality and damage in Spanish forests

In Spain, 2782 NFI plots were burnt in between the second and third NFI. Fire damage, defined as the proportion of dead trees due to fire in the plots, ranged from 0.1 to 0.99, with a mean value of 0.27, signifying that on average 27% of the trees in the burnt plots died (**Table 1**). The distribution of fire damage in the territory was uneven, with concentrations of burnt plots with higher fire damage mostly in areas in the North-West of Spain and along the Mediterranean coast in Eastern Spain. Fire damage presented a bimodal distribution, with more values towards the extremes, whether barely damaged or totally burnt stands.

Variables representing stand structure (G, and G/Dq) and site conditions (slope) in the burnt plots were analysed and pure and mixed plots characterised. Overall, burnt plots tended to have small stand basal areas and low densities, and were located in steep slopes (half of them with more than 20% inclination).

Table 1. Descriptive statistics of the variables in the fire damage model.

Variable	Range	Mean	SD
Fire damage	0.1-0.99	0.27	0.39
G	0.39-95.67	10.11	9.39
G/Dq	0.01-3.67	0.47	0.45

The model results indicate a negative effect of stand basal area on the proportion of dead trees, and the positive influence of stand density and slope on fire damage (**Fig. 8**). Denser stands (high values of G/Dq) at steep slopes presented higher fire damage than less dense plots located in flat areas. Slopes ranging from 3-12% and from 20-35% had similar regression coefficients, showing a statistically significant influence on stand fire damage in both cases (p-value < 0.05). There were no strong correlations between the included variables (VIF < 5) and McFadden and Nagelkerke pseudo-R^2 were equal to 0.13 and 0.21 respectively.

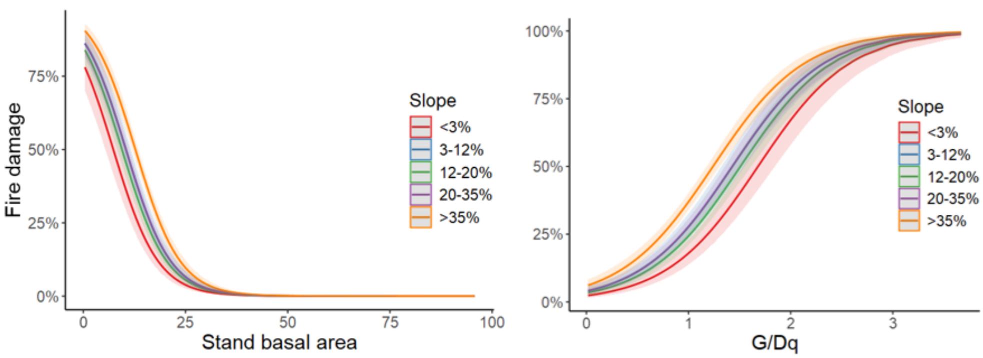

Figure 8. Marginal effects of stand basal area and stand basal area divided by quadratic mean diameter (G/Dq) on the proportion of dead trees at different slope intervals according to the fire damage model.

Fire strategies and resistance of species mixtures

The most abundant species in the burnt plots were *P. halepensis* and *P. pinaster* among the pines, and *Q. ilex* among the oaks. The most common mixtures in the burnt plots were those composed of pine and oak species, but also combinations of only pines (**Fig. 9**).

Analyses of tree mortality and stand damage by species and mixtures indicated a higher fire related damage in pure plots of pine species, specifically *Pinus halepensis* and *Pinus nigra* plots were the most damaged. Among the oak species considered, *Quercus faginea* and *Quercus ilex* presented the highest fire damage in pure plots and *Quercus robur* the lowest. In mixed plots of pines and oaks, on average a larger part of the fire-related mortality was sustained by the oak species (Fig. 1d in study **III**). In the selected mixtures fire damage varied with different mixture levels (**Fig. 10**). In three out of the 6 mixtures analysed, the mean observed damage was maximum when species were combined at a 50% level, surpassing the damage in pure plots of either species. It is the case of the mixtures: *P. halepensis* - *P. nigra*, *P. nigra* - *Q. faginea* and *P. nigra* - *P. sylvestris*. Other mixture levels also presented elevated fire damage (i.e. *P. halepensis* - *Q. ilex* at 25-75%). The residuals or difference between the observed and predicted values were linked to each combination of species and their mixture levels. Residuals were assumed to indicate the mixture effect on fire damage, which is the variance that is not explained by stand structure and site conditions as considered in the model. In the pure plots, observed and predicted damage were similar for many species, indicating a proper identification of the stand structure influence on fire damage by the considered modelling variables. In mixed plots, this difference becomes larger, representing the effect of mixing species and unexplained variation on resulting fire damage.

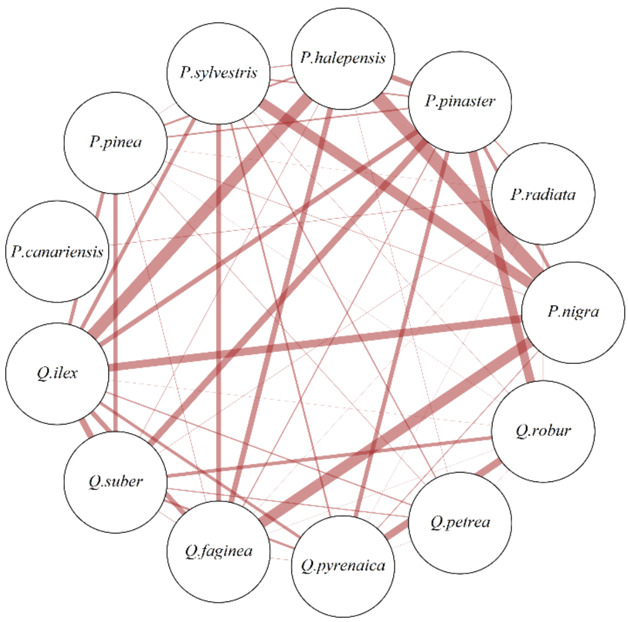

Figure 9. Most common mixtures in the burnt NFI plots in Spain. Line width represents number of co-occurrences. Adapted from Peris-Llopis et al. 2024a.

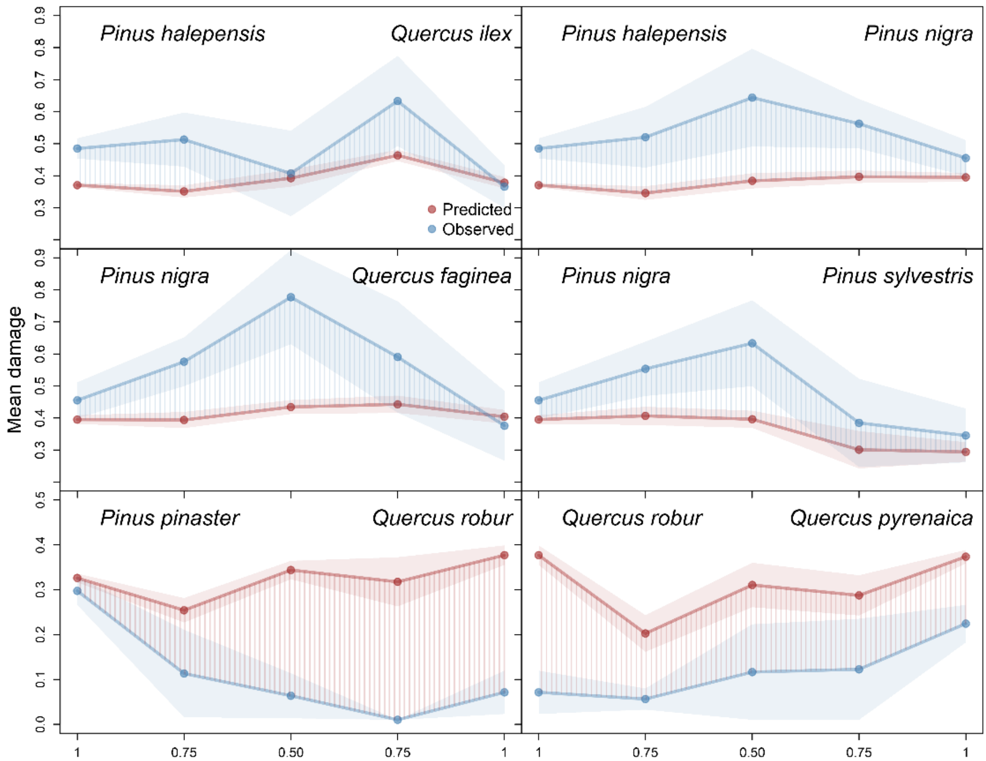

Figure 10. Mean fire damage (proportion of dead trees) as a function of species combinations and mixture levels in the most common mixtures in the burnt NFI plots in Spain. Vertical lines represent the gap between observed and predicted damage, indicating the direction of the residuals and over or underestimation of observed damage by the structure model (positive residuals or underestimation in blue, and negative residuals or overestimation of damage in red). Shaded areas represent standard errors of the means. Adapted from Peris-Llopis et al. 2024a.

Species were categorised into fire-related strategies based on several traits. *P. halepensis, P. pinaster* and oak species, were considered as fire resilient species, while *P. sylvestris* and *P. nigra* were considered as fire resistant species. Plots with fire resistant species mixed (*P. nigra - P. sylvestris*) were more damaged on average than those with fire resilient species combined (**Fig. 11**). There were significant differences in the distribution of observed damage, model predictions and residuals based on the combinations of fire-related species. Plots with fire resistant and fire resilient species mixed (*P. halepensis - P. nigra* and *P. nigra - Q. faginea*) had the highest observed damage of all potential combinations and were significantly different than mixtures of resilient species (p-value<0.001). Mixtures of resilient species were also significantly different than mixtures of resistant species (p-value<0.001). According to the residual's distribution, in plots with combinations of resilient species fire damage was overestimated by the model, with higher predicted damage than the observed. On the contrary, positive residuals indicate that fire damage was underestimated in plots with combinations of resistant species and resistant with resilient species.

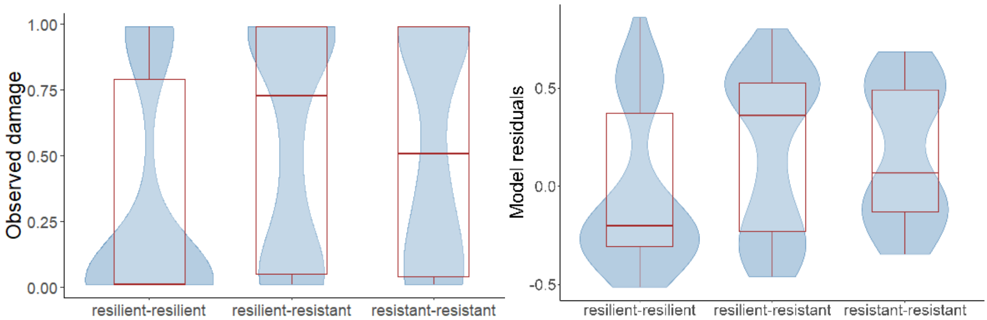

Figure 11. Distribution of observed fire damage (proportion of dead trees) and model residuals depending on the combination of fire-related strategies. Adapted from Peris-Llopis et al. 2024a.

DISCUSSION

The aim of this thesis was to provide methods and estimates to better understand patterns in fire occurrence, its impacts, and how these interact and modify forested landscapes. The findings presented in this thesis offer valuable information at different levels and scales, supporting the integration of these aspects into strategic forest planning to promote forest resilience and adaptation capacity. In this regard, it is important to consider the context in which forest fires occur and to recognize their role in natural cycles, serving as a regulatory element involved in processes such as biomass renewal and geochemical cycles. Intermediate disturbances play a vital role on maintaining forest ecosystems equilibrium, generating gaps for new vegetation to grow and initiating secondary successions. However, the increasing frequency of large, high-intensity fire events causing substantial damages, combined with the direct and indirect effects of climate change and their associated uncertainties, raises concerns about the resilience and adaptative capacity of forests worldwide (Jetté et al. 2024; Lindner et al. 2010).

Preventing and adapting to fire risk through strategic forest planning

Latest events and research efforts have proven the need to advance strategies focused on fire prevention and adaptation to tackle the fire issue in vulnerable areas. Results of this thesis and related studies emphasize the importance of targeted fire prevention strategies and approaches that prioritize forest adaptation capacity. In study **I**, differences among fire sizes and factors driving their occurrence emerged. Drivers of fire occurrence differed based on the final burnt area. Topography, present fuels and accessibility influenced in different ways the probability of having a small, medium or a large fire in Eastern Spain. For example, areas easily accessible for humans had a higher probability of being burnt by a small fire than more isolated areas, which presented more large fires. In this case, several factors are interconnected, as less accessible areas in the region have a larger forest cover and less opportunities for fire detection and fast suppression. In this sense, forested covers, particularly those composed by shrubs and small trees had higher probabilities of burning due to medium size fires, whereas the presence of more mature forests with medium and mature trees quickly reduced the probabilities of fire. Due to these disparities, the allocation of fire prevention efforts must change depending on the likelihood of having small, medium or large fires in an area. In some areas, activities targeted to raise awareness among the population should be emphasized, for instance through law reinforcement and education (Syphard and Keeley 2015). These areas are of little interest for forest planning activities, but in occasions raised awareness can translate into rapid reactions to spotting a fire and a lowered number of human-caused ignitions, which can become large fires given the proper conditions. Strategies in areas with more opportunities of being burnt by large fires should be focused on fuel treatments aiming at preventing fuel build-up and reducing its vertical and horizontal continuity and connectivity. Treatments and activities such as fuel breaks (Low et al. 2023), prescribed burnings (Fernández-Guisuraga and Fernandes 2024), combinations of both (Hood et al. 2024), and shifts towards species composition with proven resistance to fire (Peris-Llopis et al. 2024a) can promote forests health and adaptation to changing fire regimes.

All these focused on reducing fuel load and conditions that would, otherwise, exacerbate fire spread and severity. On this thought and given that fires are necessary disturbances maintaining natural cycles in forests (Stockdale et al. 2016; Cochrane and Bowman 2021), study **I** provided the instruments to identify in which areas to emphasize prevention and suppression efforts and which areas could be candidates to support natural fire cycles and safeguard the persistence of natural ecosystem dynamics.

As the effects of climate change become increasingly evident, more extreme disturbances are expected and being reported, often overlapping in extensively impacted landscapes (Kleinman et al. 2019; Altman et al. 2024). Within this context, fire recurrence has been observed in many Mediterranean areas (Barbati et al. 2015; Meneses et al. 2018; Peris-Llopis et al. 2024b) with potential impacts on ecosystem services (Moghli et al. 2022). Fire recurrence has implications for the existent land covers and their configuration in the landscape, promoting land cover changes due to repeated fire disturbances. Land cover changes modify landscape fuel patterns and fire hazard (Moreira et al. 2011). In study **II**, patterns of fire recurrence and land cover changes in Eastern Spain were analysed, and the role and significance of critical factors in the probability of reburning was evaluated. Similar to the findings from the fire occurrence study, reburning probability was determined by factors such as post-fire vegetation or present fuels, accessibility and topography. Land cover transitions in areas affected by repeated fires indicated a reduction in fuel complexity, shifting from developed tree-covered forests to shrubs associations and sparse vegetation after several fires, a pattern observed in other Mediterranean areas (i.e. Tessler et al. 2014). Consistent with existing research (Schaffhauser et al. 2012), establishment of shrubs after fire heightened the likelihood of reburning at a larger extent than other forest covers. Understanding land cover transitions in reburnt areas can inform decisions on what landscape configurations and fuel types to prioritize to buffer fire risk. It provides information on forest successions and the potentially disrupting role of fire, and coupled with data on time between fires it determines the locations and time windows to adapt these systems. Time interval between fires modulated recurrence probability, with the timing of the first fire influencing it at different extents. Coincidentally, the years with the largest probabilities of reburning were among those with reported severe drought periods in the studied regions (Romero Fresneda et al. 2020). These results stress the significance of studying interacting disturbances and their potential compound effects, such as the fire-drought combination (Batllori et al. 2019; Cardil et al. 2019). The identification of time windows and forest types in which to apply treatments is essential to prevent the degradation of certain vegetation associations and avoid the homogenization of forest covers throughout Mediterranean landscapes, particularly in areas with overlapping disturbances and changing regimes. Optimal timing of fire prevention treatments can also provide other benefits, as in the reduction of future suppression costs while maximizing forest values (Heines et al. 2018; Pacheco and Claro 2018). Nevertheless, in some cases it might be advisable to determine the need for fire prevention treatments in certain areas. For example, Braziunas et al. 2023 observed a delay in forest recovery after repeated fires at short fire intervals, in line with the findings in study **II**, but pointed at the role of the reduced canopy fuels due to these fires on lowering the likelihood of crown fires in the future (30 years or longer).

Fire disturbances have a lasting impact on forest dynamics, shaping them in the long-term. While forest management plans are usually designed to meet middle term objectives, fire prevention and adaptation strategies must align with the broader temporal scale of the dynamics addressed. Study **III** provided the necessary assessments to be considered for the design and application of this kind of strategies, emphasizing long-term changes in species composition, an approach previously hinted for the prevention and reduction of fire damage (Terrier et al. 2012; Jactel et al. 2017) but seldomly studied in detail. Forest adaptation capacity can be boosted by the choice of species composition that better withstands disturbances. In study **III**, the resistance to fire damage of commonly burnt species and mixtures in Spanish forests was explored. Additionally, fire-related traits of the species, with the potential to modify fire behaviour and severity (Schwilk and Ackerly 2001; Fernandes et al. 2008), were analysed. In this way, combinations of species and their fire resistant and fire resilient strategies exhibited higher fire damage than pure plots of either species in most of the studied mixtures. The inclusion of fire-related strategies in the study allowed to consider effects difficult to approach directly with the available data, as well as accounting for the species adaptations to thrive in fire-prone systems. Combinations of different fire-related strategies at maximum mixture levels presented the highest damage on average. These findings point to the more complex structures found in mixed stands and the existence of fuel ladders that facilitate the spread of fire through the vertical forest structure, causing more mortality. The identification of mixtures of species and traits that better withstand fire damage is the first step for the recommendation of the optimal allocation of species and mixtures to reduce fire impacts and improve coping capacity of Spanish forests. Nevertheless, the specific mechanisms behind these effects need to be studied in detail, on a mixture-by-mixture basis and considering other fire-related traits (such as flammability) and their role on boosting fire resistance. In the long-term and through research efforts, changes in species composition can contribute to reduced fire risk while considering other ecosystem services and planning objectives. Not only can the findings on resistant mixtures be used for prevention and adaptation purposes but also modelling results on influence of stand structural features on resulting fire damage. In this sense, understanding what types of forest structures exacerbate or diminish fire spread and damage gives us the hints on what elements to target through strategic forest planning. Treatments focused on reducing stand density, increasing canopy base height and managing surface and ladder fuels are known to reduce fire hazard (Agee and Skinner 2005), and can be adapted to specific species compositions.

Modelling fire risk

In this thesis, modelling approaches to incorporate fire risk into strategic forest planning are presented. These approaches rely on extensive data sources available in the study areas and the use of empirical models to estimate several elements contributing to fire risk in Spanish landscapes. An ecological perspective is introduced to these approaches, aiming to fill gaps in the existing knowledge and emphasize actions to promote forest adaptation at several levels.

Many factors might influence modelling results, starting with data types and sources, and their varying scales and levels of detail. In the studies part of this thesis, these elements are carefully considered, choosing the appropriate level of detail in each case and ensuring a proper alignment of the maps used. Furthermore, the developed models make use of different scales, transforming tree data to stand level data and also working at the landscape level, permitting to consider multi-scale processes and expanding the usability of the findings and methodologies from the regional to the national level. Likewise, data sources and their temporal scales were selected to accurately depict dynamics related to the phenomenon of interest, as in the case of the CLC maps used in study **II**, which provide a more frequent and refined representation of fuel dynamics and their changes under repeated fires. Variables of interest were defined according to existent literature and otherwise described in each study, indicating the calculation process and related details. When needed, variables from the original data were combined and reclassified. For example, new fuel classes were created in study **I** by combining various variables from the MFE, aiming to account for development stages and structural features of the present vegetation. These transformations also facilitated subsequent computing processes. In this sense, the combination of variables to create strata in studies **I** and **II** is a result itself, generating units with similar characteristics regarding fire-related drivers. These strata can be used when allocating prevention and suppression efforts, delineating and mapping homogeneous areas for forest planning and prevention activities.

In this thesis empirical models that can be used to assess fire risk in different areas were developed. First, a fire occurrence model to understand what drives the proportion of burnt area by fires with different sizes was built. Second, a fire recurrence model considering the influence of forest covers and several drivers on the probability of reburning. Then, a fire damage model for forest stands all over Spain was developed. Risk can be calculated by multiplying probability of occurrence by the impact generated by those fires, namely fire damage. Modelling results in this thesis were in line with those previously developed for other Mediterranean areas and neighbouring countries (i.e. González et al. 2006; González et al. 2007; Botequim et al. 2017), although introducing novel elements and providing a more ecological perspective to the estimation of fire risk and related drivers. For instance, by employing residuals as indicators of unexplained variance due to changes in environmental factors, with just a few studies exploring this approach (Dobbertin 2005; Díaz-Yáñez et al. 2020) and considering specific mixture levels, or by developing different models classified according to final burnt area. Analogously, the use of weights has been seldom exploited when assessing fire risk, integrated in this thesis through the development of Weighted Generalised Linear Models (studies **I** and **III**). These models are the basis to estimate probability of burnt area and fire damage, being appropriate to fit non-linear relationships through the application of a link function, and therefore accommodating different types of response variables (such as binomial and quasibinomial). In the case of mixed models (study **II**), weights can also be used, but the cornerstone of these models is the possibility to include random effects and account for variance due to data structures and hierarchies (as it is the case of fire recurrence and multi-temporal data). The inclusion of the timing of the first fire as a random effect unveiled its significant influence on the probability of reburning, expanding the scope of this and future studies.

Overall, the use of models allows to extract trends and relationships present in the data, accurately describing the phenomenon of interest and producing useful instruments for planning experts and future research. New approaches were introduced in each study, such as the development of models by size class and comparison of regression coefficients (study **I**), consideration of fire timing in reburnt areas (study **II**), or the use of a model to isolate measurable effects of stand structural features on fire damage from those related to species combinations (study **III**). All these aiming to identify areas and elements to target in order to prevent fire risk and promote fire resilient forests.

Future directions

While conducting this research, the potential existence of interactions among various disturbances affecting forests in the study area was identified. Given the forecasted increase of more extreme weather events and disturbances, diving into their drivers and linkages would be the initial step to understand how these interact and develop dual strategies to tackle their negative impacts on forests. This approach would enable to consider prevention and adaptation to disturbances globally rather than looking into individual disturbances, aiming to promote or generate forests and landscapes with the ability to adapt to interacting challenges. Forest planning strategies could focus on minimizing the impacts from several disturbances, while resulting in lowered management costs as well as expanding the positive impact to other sectors. At a more ambitious level, the development of approaches to explicitly model these interactions would be the logical following step. There are already some studies in this line (i.e. Grünig et al. 2022), but further research at broader spatial scales is essential in order to accurately define linkages between simultaneous or coinciding disturbances. Achieving this would require the existence of more periodic data available and exhaustive monitoring efforts. Moreover, once these interactions are defined, studies on effective treatments are necessary to integrate their prevention and management for the development of guidelines for decision-making. For example, in the case of recurring fires (fire interacting with fire) under drought conditions, results from this thesis could be coupled with data on fire severity to examine the combined effects of these three interacting disturbances and their potential use as treatments to control biomass accumulation as well as restoring natural fire regimes (as hinted by Stevens-Rumann and Morgan 2016).

On another line, the present research could be further expanded by developing fire spread models, producing more detailed information on how fire propagates in a given landscape. These results would complement current findings, and for example, help assess the role of species mixtures in reducing not only fire damage but also its extent. Additionally, during the modelling phase of study **III**, regional differences were observed in the relationship between stand structural variables and fire damage. Fire research and prevention and adaptation strategies could benefit from a reconciliation between national and regional level models, delving deeper into their differences and similarities. Determining the spatial scale threshold at which model coefficients differ could contribute to ongoing efforts on the development of more standardised fuel models. However, it is essential to account for other factors and interactions that might influence these differences, such as the transition from fuel-driven to climate-driven fires in many areas (Abatzoglou et al. 2021; Ellis et al. 2021). Such shifts may necessitate re-evaluating and re-adapting these models to ensure they remain relevant and effective under changing conditions.

Finally, once all the necessary models are developed, management alternatives need to be tested across different scenarios, aiming to find those best suited to achieve the planning (and adaptation) objectives. In this context, interactions between disturbances and climate change effects call for flexible approaches to address the choice of planning alternatives, permitting to consider the fact that not all information is available at the moment and decision makers might reconsider their objectives and preferred choices as conditions evolve. Robust decision making (RDM) offers a valuable framework when discussing about changing disturbance regimes and their associated uncertainty, prioritizing robust decisions instead of optimal ones (Lempert 2019). Integrating disturbances interacting in Mediterranean areas, such as fire, drought and erosion, into the RDM framework, could yield valuable insights for future planning and adaptation strategies.

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