Socioeconomic Impacts and Regional Drivers of Fire Management: The Case of Portugal

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Abstract Wildfires are uncontrolled and unwanted fires that usually occur in forested/rural areas and burn forests, agricultural areas, and wildlands. Land abandonment, with the consequent growth of the rural–urban interface, increases the exposure and vulnerability of fire-prone regions around the World. In the last two decades, Europe experienced a high number of wildfires causing large burnt areas mainly concentrated in the Mediterranean Basin. This high fire incidence seems to be the result of human activities including land use/land cover changes, but also of climate variability and change. In the present study, we analyse the current situation in Portugal, which is the European country with the highest total number of wildfires and the second-highest total burnt area. The spatial and temporal variability of the wildfires within the country is very heterogeneous, due to the human and biophysical drivers. In this regard, four main aspects are considered and discussed: (1) the spatial and temporal distribution of wildfires in mainland Portugal; (2) the main human and biophysical fire drivers; (3) socioeconomic impacts; and (4) the main strategies for fire risk mapping and management. The main results indicate high spatial heterogeneity of the fire incidence, with higher fire activity in the northern region than the southern region, mainly promoted by a higher irregular topography and significantly different types of climate and land use/land cover characteristics. We highlight how fire incidence is strongly dependent on many biophysical and human factors/drivers and the direct and indirect socioeconomic impacts of wildfires. Methodologies and indexes developed by Portuguese authorities to map fire risk and assess fire danger

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J. Rodrigo-Comino and L. Salvati (eds.), *Fire Hazards: Socio-economic and Regional issues*, https://doi.org/10.1007/978-3-031-50446-4_14

are described. The elements discussed in this chapter result from research and lessons learned in recent years on the fire regime in Portugal and Europe. These findings can contribute to improving forest, landscape, and fire management, in Mediterranean European countries which share similar characteristics.

Keywords Wildfire · Human drivers · Spatial patterns · Fire incidence · Biophysical drivers · Burnt area · Portugal

1 Introduction

Wildfires have been an essential component of Mediterranean ecosystems since 24 million years ago (San-Miguel-Ayanz et al., 2013). This area is highly prone to fires, mainly due to the vegetation heterogeneity and the favourable climate conditions characterized by wet and mild springs and hot and dry summers, increasingly affected in recent decades by heat waves and droughts that promote the thermal and hydric stress of the vegetation (Pereira et al., 2013). Human factors may also contribute to the extent of the fire incidence in the Mediterranean basin, such as the migration of rural populations to urban areas over the last 50 years (Bowman et al., 2011). Decreasing precipitation and increasing air temperature, combined with the above-mentioned factors, increase the fire risk in the Mediterranean region, especially during the summer months (San-Miguel-Ayanz et al., 2013).

In the last two decades, wildfires have affected more than 6.2 million people and were responsible for more than 2400 fatalities, and losses with an amount of 61 billion euros around the world (Wallemacq & House, 2018). Extreme wildfire events with catastrophic consequences have become more frequent in the recent period. For example, in Portugal, wildfires of 2017 burnt 1.2 million hectares of natural land, including 25% of Natura 2000, causing 127 human fatalities and losses of about 10 billion euros (San-Miguel-Ayanz et al., 2018). Despite its smaller land area in comparison with the other European Mediterranean countries, Portugal is the European country with the highest total number of wildfires and the second-highest total burnt area (San-Miguel-Ayanz et al., 2018). The growth of the rural–urban interface has increased the likelihood of fire ignition by humans (Tonini et al., 2018). In addition, the rural abandonment contributed to the decrease in forest fuel consumption and the subsequent biomass accumulation (Pereira et al., 2014). The combination of these factors with the climate and weather conditions makes Portugal a high-fire-risk area, especially in summer (San-Miguel-Ayanz et al., 2013). The variation in fire incidence is related to landscape characteristics that can act as biological, socioeconomic, and physical drivers (Parente et al., 2018c). Regardless of the fire cause (lighting, accidental, negligent, or intentional), wildfires may have significant impacts. Wildfire's impacts and characteristics highly depend on several human and biophysical drivers, such as (1) socioeconomic parameters (Oliveira et al., 2017; Parente et al., 2018c); (2) land and forest management practices (Parente et al., 2016); (3) topography (Fernandes et al., 2016b; Parente et al., 2018c); and (4) weather and climatic conditions (Parente et al., 2018a, 2018b, 2019). In this context, identifying the regions where those fire impacts and fire drivers have more influence is of greater importance for increasing the efficiency of fire management actions.

Following this line of reasoning, the present chapter aims to briefly discuss and characterize for mainland of Portugal (hereafter, Portugal): (1) the spatial and temporal distribution of wildfires; (2) the main fire drivers, causes, and impacts; and (3) the main fire risk management characteristics.

2 Spatial and Temporal Distribution of Wildfires

Wildfires display a complex spatiotemporal pattern strongly related to forest landscape and neighbouring anthropogenic developments, such as urban and rural areas, and road and pathways networks. Fire occurrences tend to present clusters (Vega Orozco et al., 2012), where events are found closer in space and time than expected for a random distribution. Thus, cluster analyses can be applied to investigate these patterns and to disclose vulnerable areas and frame periods where wildfires are more likely to occur (Vega Orozco et al., 2012).

Portugal can be divided by the Tagus River into two regions of about the same size: (1) the northern region has a temperate type of climate with dry and warm summer (Peel et al., 2007), and is characterized by an irregular topography, flat along the western coast and mountainous towards the central and eastern side (with a pick of 1993 m), the predominance of forest and semi-natural areas, and a dense river network; (2) the southern region has dry and hot summers (Peel et al., 2007), and is characterized by lowlands dominated by agricultural areas, with the only exception of two patches of mixed and broad-leaved forest extending near the south coast at mid-altitude (with a pick of 1000 m). Not surprisingly, the northern region is much more affected by wildfires than the southern half (Parente et al., 2016; Tonini et al., 2018). Also, considering the fire dataset available by the *Instituto da Conservação da Natureza e Florestas* (ICNF, https://icnf.pt/), before the 1980s, the burnt area had never reached 10,000 ha for a single occurrence. Instead, from the 1990s to nowadays (2021, the year of the last available burnt area dataset), this threshold has been exceeded several times, especially with the catastrophic wildfire events in 2003, 2005, and 2017. Still, it must be underlined that the number of wildfires has been steadily decreasing since the early 2000s, and this tendency is followed up by its decrease with a Daily Severity Rating above five (Observatório Técnico Independente et al., 2020).

Investigating Land use/Land cover changes occurring in Portugal for two decades (1990–2012), Tonini et al. (2018) revealed an increase in the rural–urban interface more pronounced in the northwest sector and along the coast, where the transition from heterogeneous agricultural areas to urban fabric was particularly intense. This development was mainly due to urban growth and the intensification of the road network. Comparing the evolution of the rural–urban interface with the mapped burnt areas, these authors discovered that the first increased by more than two-thirds, while the latter decreased by about one-third; nevertheless, the burnt area within the rural–urban interface doubled, highlighting the importance of monitoring this interface area for adequate fire management and prevention. Even if not included in the mentioned study, the recent extreme fire season of 2017, which burnt an area of 539,920 ha of forests, shrubland, agricultural land, and artificial surfaces in one hundred and fifty municipalities in the north-central Portuguese regions (San-Miguel-Ayanz et al., 2021), is highly representative of the same undergoing process. In recent studies (Comissão Técnica Independente et al., 2018; Observatório Técnico Independente et al., 2020; San-Miguel-Ayanz et al., 2021), the list of significant factors that can potentially increase the frequency of these extreme events includes not only extreme climate conditions, but also fire causes (e.g. arsonist), fuel management, land use/land cover changes, increasing depopulation in rural areas, and increase in the rural–urban interface.

A deeper investigation of the spatiotemporal distribution of wildfires in Portugal revealed to be fundamental to detecting over-densities and trends in fire risk, allowing to address prevention and forecasting measures. Indeed, in a fire-prone country like Portugal, where thousands of events occur each year, extracting useful information from the original raw data (i.e. mapped ignition points or burnt areas and related attribute tables) is a demanding task. In this respect, statistical methods initially developed for stochastic point processes have been successfully employed in the past (Parente et al., 2016; Pereira et al., 2015). In a recent study, Tonini et al. (2017) combined different methods to detect wildfire overdensities: (1) Geographically Weighted Summary Statistics (GWSS) to explore how the average burnt area varies in space; (2) the Cross K-function to assess whether or not burnt areas of different sizes are independently distributed; and (3) the 3D-kernel density estimator (3D-KDE) to elaborate smoothed maps representing the continuous spatial density distribution of wildfires and their temporal evolution.

The results for GWSS (Fig. 1 on the right) indicate regions with (1) local mean burnt area above 500 ha localized in the central regions in Portugal (districts of Coimbra, Castelo Branco, Santarém, and Portalegre) and along the southern coast (Faro District); (2) local mean burnt area below 200 ha quite dispersed in the southern half of the country; (3) meagre and low local means predominant and concentrated in the region between Bragança and Vila Real (to the east), between Porto and Viana do Castelo (to the west) and around Lisbon (to the centre). Additionally, hot spots of the high local mean for the burnt area were identified due to a few events with a very large burnt area surrounded by several events with a small burnt area.

The cross K-function results revealed the propensity of medium wildfires (15 ha $\leq$ burnt area $<$ 100 ha) to aggregate around small wildfires (5 ha $\leq$ burnt area $<$ 15 ha), while large wildfires (burnt area $\geq$ 100 ha) aggregated at a larger spatiotemporal scale, indicating a return period longer and more complex than for small and medium wildfires. In more detail, the cluster behaviour of small and medium wildfires increased with the distance, with picks of cluster every 3 and 4 years, while large wildfires resulted in being randomly distributed within a distance lower than 3 km and clustered above, with two picks of cluster each 6 and 10 years.

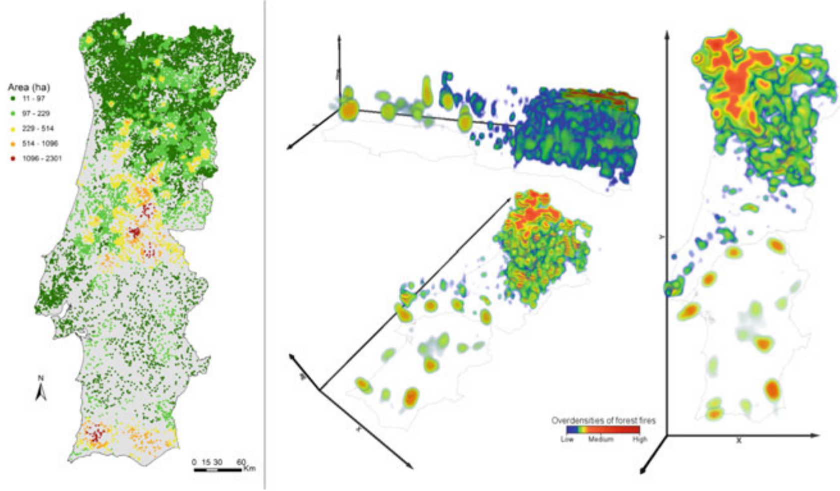

Fig. 1 3D-kernel density (on the left) and geographically weighted local means (on the right) of the burned area in Portugal for the period 1990–2013

The 3D-KDE results (Fig. 1 on the left) revealed the highest densities located in the northwestern area of Portugal, nearby the regions of Viana do Castelo, Braga, and Vila Real, and in the northern-central area, nearby the regions of Viseu, Guarda, and Castelo Branco. Lower spatial densities of wildfires were present in the southern coastal regions of Lisboa, Santarém, Leiria, and Coimbra. Paying attention to the wildfires' temporal evolution, the higher densities were registered between 1995 and 2004, while the lowest densities were disclosed in the two years, 1992 and 1993, characterized by a very low number of wildfires. The southern half of the country exhibited lower smoothed densities than the northern regions. In the central period (1998–2006), medium–high densities were spatially homogeneously distributed, with the highest values in the period 2000–2004. Finally, the volume rendering technique was employed to elaborate 3D maps representing the spatiotemporal evolution of these smoothed densities into a unique map, allowing one to visualize at glance regions and frame periods with more clusters of wildfires.

We conclude by mentioning that the wildfires' spatial and temporal distributions are two factors strongly correlated, meaning that events closer in space are also closer in time, with an increased risk for emerging megafires events.

3 Fire Drivers: Human and Biophysical Drivers

It is easier to understand the high spatial and temporal variability of the fire incidence (number of wildfires and burnt area) in Portugal by discussing the influence of the role of human and biophysical drivers on this variability. This variability presents a south-north gradient with much higher values in the North region and high differences at national and regional scales. Additionally, understanding the role of human and biophysical drivers on this variability is of fundamental importance to support forest and fire management as well as the implementation of legislation. It is worth a mention that fire characteristics (e.g. size, intensity, duration, and behaviour) and their consequences highly depend on several human and biophysical drivers, including socioeconomic factors (Nunes et al., 2016; Oliveira et al., 2017), landscape and forest management practices (Godinho et al., 2016; Parente et al., 2016), topography (Fernandes et al., 2016b), organization, shape, size, and characteristics of patches of different types of vegetation cover (Bond & Keane, 2017; Jan et al., 2018), and finally weather and climate conditions (Parente et al., 2018b, 2019; Russo et al., 2017).

At the national level, in Portugal, about 85.5% of the forest areas are privately owned (Bouillon et al., 2020). The combination of rural land abandonment within these areas and their split of land ownership creates a complex landscape mosaic of neglected shrublands and small- to large-scale forest plantations (Bouillon et al., 2020). Also, the rural–urban interface has increased by more than two-thirds between 1990 and 2012 (Tonini et al., 2018). So, the combination of such factors with the fact that most of the fire ignitions are human intentional (Parente et al., 2018c) makes it no surprise that several studies have identified as the most critical drivers of fire incidence the population density and topography/landscape characteristics (Catry et al., 2007; Nunes et al., 2016). Additionally, Fernandes et al. (2016a) have shown that wildfires larger than 500 ha were increasingly controlled by fuel-related variables, such as fuel composition, fuel connectivity, and pyrodiversity. Also, they have found that climate-weather variables only have an importance of 15% as bottom-up variables on the influence of fire size. On the other hand, extreme weather conditions (e.g. drought and heat waves), in combination with high fuel load drive extremely large wildfires (burnt area $\geq$ 2500 ha). Nevertheless, it is important to highlight the following points (Parente et al., 2018c): (1) fire occurrence (total number of wildfires) increases with population density; (2) fire incidence decreases with the distance to the nearest road; (3) fire ignition is higher at a lower altitude, and in the artificial surfaces, pastures, and heterogeneous agricultural areas; (4) total amount of burnt area increase with altitude and is higher in agricultural areas, forests (mainly *Eucalyptus globulus* and *Pinus pinaster*), and semi-natural areas; (5) slope has the lowest influence on fire occurrence but has the strongest influence in the total amount of burnt area; and, (6) fire extent is essentially driven by fire weather conditions and ignition density (Davim et al., 2022). Finally, the extent of a large wildfire is mainly a function of human and biophysical drivers that land-use planning, forest, and fuel management can partially address (Fernandes et al., 2016a).

4 Fire Causes and Fire Socioeconomic Impacts

In the last decades, EU Member States have experienced critical fire events that have resulted in the loss of human lives and significant economic and environmental losses (San-Miguel-Ayanz et al., 2021), and Portugal is no exception. Portugal has been marked by substantial landscape transformation related to land cover/land use changes and rural depopulation, especially in its interior (Medeiros et al., 2022; Poeta Fernandes, 2019). Those depopulated areas have experienced a dramatic increase in biomass amount and continuity, contributing to the rise of new fire regimes (Pausas & Fernández-Muñoz, 2012), with even more frequent catastrophic wildfires events (San-Miguel-Ayanz et al., 2018). There is no significant cause–effect relationship between the atmospheric conditions favourable for fire occurrence and fire occurrence, in the sense that ignitions in Portugal are essentially due to human activity (Amraoui et al., 2013). Additionally, human ignition is the primary cause of wildfires nowadays, accounting for about 99% of total ignitions with known causes (Parente et al., 2018c). Nevertheless, the Portuguese *Instituto da Conservação da Natureza e das Florestas* (ICNF, www.icnf.pt) categorize fire causes in a three-level hierarchical structure, and each level identifies several major categories. The first level identifies six major categories of fire cause, namely: (1) use of fire; (2) accidental; (3) structural; (4) incendiarism; (5) natural, and (6) unidentified. The second level discriminates the causes of the previous one, identifying them in groups and discriminating against specific activities. Finally, the third level divides activities into subgroups and discriminates specific behaviours and attitudes leading to a total of 70 different fire causes. For the sake of simplicity, four major categories may cluster all this information, namely: (1) negligent wildfires that comprise the use of fire and/or accidental fire; (2) intentional wildfires that include structural fire and/or incendiarism; (3) natural wildfires; and (4) unidentified wildfires. Considering the temporal distribution of such categories between 2001 and 2014, they exhibit two different trends: the number of unidentified wildfires decreases with time, and the number of negligent and intentional wildfires increases (Parente et al., 2018c).

In Portugal, most wildfires are small (burnt areas below 100 ha), as a fire extinction/exclusion policy prevails in the country (San-Miguel-Ayanz et al., 2013). However, some of these events escape to the initial fire attack and the subsequent firefighting operations, mainly of the times due to the lack of a proper number of firefighters, which might be the consequence of the tremendous amount of fire ignitions at the same time (Comissão Técnica Independente et al., 2018). Consequently, these wildfires may become large and impact a diverse range of economic, social, and environmental assets and values (Stephenson et al., 2013). Measuring these latter impacts is not easy due to the difficulty in obtaining measurable data that allow establishing scales of social, economic, or even emotional and family impacts (Viegas et al., 2017). Nonetheless, we can point to several direct socioeconomic impacts: (1) loss of human life, registering more than 110 fatalities, between civilians and firefighters, in the last 25 years in Portugal (Tedim et al., 2020); (2) short- or/and medium-term health issues due to smoke inhalation/intoxication, burns, wounds, and also mental health problems in civilians and firefighters; (3) buildings loss, such as houses and agroforestry assets (Tedim et al., 2018, 2020); (4) large expenditures on fire management, e.g. the joint budget of Greece, France, Italy, Portugal, and Spain is €2500 million each year, more focused on fire detection and suppression (Doerr & Santín, 2016).

An example of such extreme events was the unprecedented 2017 fire season, from which can be highlighted the wildfires from 17th June. Here, 64 people (between 5 and 88 years old) lost their lives, more than 200 injured people, and 458 structures were destroyed (San-Miguel-Ayanz et al., 2021; Tedim et al., 2018). Beyond the impacts described above, wildfires may also have several indirect socioeconomic impacts such as (1) reduction of tourism; (2) decrease of landscape and home values; (3) changes in soil physical and chemical properties (Jiménez-Morillo et al., 2016); (4) soil erosion (Parente et al., 2022); (5) pollution of water bodies (Basso et al., 2021; Pereira et al., 2016), which may change water quality and quantity, limit the consumption of water by humans even its disruption, and provoke the death of aquatic animals; and (6) increase of air pollution, which may contribute to premature deaths (Johnston et al., 2016).

5 Fire Risk Mapping, Modelling, and Management

Fire risk assessment on ecological, social, and economic systems is a fundamental tool for fire management and the development of cost-effective mitigation strategies. Fire risk can be evaluated using quantitative or qualitative indicators allowing the evaluation of the probability of an area being ignited by natural or artificial means in a certain period, eventually providing information on the expected positive or negative impacts in that area (Parente & Pereira, 2016). Fire risk is divided into two major components according to explanatory variables of control fire characteristics, namely: (1) a dynamic component related to variables that significantly change in time, such as weather and soil moisture conditions; (2) a structural component associated with static variables, which barely change in time, such as vegetation composition or topography.

In Portugal, the *Instituto Português do Mar e da Atmosfera* is a public institute integrated into the indirect administration of the Portuguese State that computes and publishes the Conjunctural and Meteorological Index (RCM) of rural fire danger (IPMA, 2020), which is used by firefighters and civil protection and fire management authorities. The Conjunctural and Meteorological Index is calculated daily and results from the combination of two indices: (i) the Fire Weather Index (FWI), which is updated once a day, and (ii) the rural fire hazard index, which includes a decadal structural component and an annual conjunctural component, that considers the burnt areas of the last three years, both under the responsibility of the *Instituto da Conservação da Natureza e Florestas* (ICNF, https://icnf.pt/). The integration of the two indices is performed by applying a risk weighting matrix at the pixel level of 1 km spatial resolution, and the agglutination by administrative unit (municipality and district) is carried out by weighting the highest risk values, considering the threshold of 20% of the most serious classes (IPMA, 2020).

The Fire Weather Index is the fire intensity index of the Canadian Wildland Fire Information System (Van Wagner, 1987) used worldwide at regional and global scales to assess the fire hazard (McElhinny et al., 2020; Vitolo et al., 2020). It comprises six sub-indices (three fuel moisture codes and three fire behaviour indices) calculated with observed and predicted values at 12 UTC (Coordinated Universal Time) of air temperature, relative air humidity, wind intensity, and accumulated precipitation in the last 24 h (Pereira et al., 2020). The Fire Weather Index is then classified into five classes (1-minimum to 5-maximum), and the annual conjunctural hazard is into five classes (0-zero hazard, which essentially corresponds to urban areas and water plans, to 5 maximum hazards) (IPMA, 2020).

The fire structural hazard map is based on the fact that the spatial distribution of fire incidence (namely of the burned area) is not uniform (Parente et al., 2016; Pereira et al., 2015; Tonini et al., 2017) and that the propensity of the fire depends on and can be modelled based exclusively on spatial data, namely slope, altitude, and land use and occupation (IGOT & pahl_consulting, 2020; Pereira et al., 2014). Verde and Zêzere (2010) further details this fire susceptibility modelling and fire hazard mapping that form the basis of the structural fire risk mapped for mainland Portugal by Parente and Pereira (2016). In this study, the adopted concept of fire risk includes two components: (i) the fire hazard, defined as the probability of an area being affected by a fire during a specific period, comprising the susceptibility of that area and the probability of occurrence; and (ii) the potential damage, which accounts for the vulnerability of an area to the fire and the economic value of the damage caused. In a recent study, the statistically-based approach developed by Verde and Zêzere (2010) has been compared with a stochastic approach (Leuenberger et al., 2018), opening the way for further implementation of Machine Learning based approaches for fire susceptibility mapping (Tonini et al., 2020; Trucchia et al., 2022).

Other relevant approaches to evaluate fire risk include coupling fire behaviour modelling and stand characteristics (Botequim et al., 2017) or with a social-ecological approach (Tedim et al., 2016). Like other fire hazard and fire risk assessments, the Conjunctural and Meteorological Index integrates dynamic and structural variables observed in loco or remotely using geographic information system technologies (Caetano et al., 2004; Chuvieco et al., 2010). The fire structural hazard map was developed solely based on altitude, slope, land use, and occupation. However, the explanatory and predictive value of a much broader set of population, biophysical, and socioeconomic spatial variables has been demonstrated (Oliveira & Zêzere, 2020; Oliveira et al., 2012; Parente et al., 2018c) which has already led to a reassessment of fire susceptibility and hazard for mainland Portugal (Oliveira et al., 2021).

6 Conclusion

This chapter was devoted to the characterization of socioeconomic impacts and regional drivers using the example of Portugal. To this end, we have presented and discussed: (1) the use of several simple statistical methods to characterize wildfires' spatial and temporal patterns at the national scale; (2) the main fire drivers, causes, and impacts; and (3) the main indices used and for fire risk assessment and management in the country.

We can conclude that: (1) statistical methods developed for spatial and temporal stochastic point processes allow to highlight of local fire over-densities and mapping them; (2) despite the methodology used, the distribution of wildfires is very heterogeneous in Portugal; and (3) the fire incidence patterns and the ignition dates are strongly dependent on many human and biophysical drivers strongly. Characterizing the socioeconomic impacts of wildfires remain a challenge, especially in light of the current climate changes that increase the fire risk, especially the occurrence of megafire events in fire-prone countries such as Portugal. Finally, we discussed the fire risk mapping in Portugal resulting from the combination between the fire weather danger index and the fire hazard index. The resulting maps can be used to implement and support educational activities, awareness-raising initiatives, and prevention campaigns, as well as to support planning for better allocation of monitoring systems and firefighting.

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