

Regional Issues of Fire Management: The Role of Extreme Weather, Climate and Vegetation Type



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Abstract It is of paramount importance to discuss and reflect on the influence that climate and land management have on fire regimes and, consequently, on the regional character of fire management. Our focus is on the Iberian Peninsula, although the results and conclusions presented here are common to many other regions of the world with a Mediterranean climate. The discussion is based on the concept of risk, starting with conjunctural risk factors, moving on to structural factors and including their interconnection. Conjunctural risk factors of weather and climate are discussed in the context of requirements for fire to occur, which include the existence of fuels, a state of dryness suitable for combustion and a source of ignition. The influence of climate and weather is discussed at different space–time scales and related to characteristics of vegetation and land management. The roles of atmospheric patterns, types of weather, extreme events, meteorological hazard indices in patterns of fire incidence, their grouping and definition of pyro-regions are presented. Within structural factors, human populations shape fire regimes by changing the ignition patterns, fighting wildfires, modifying landscapes (e.g., urbanization, deforestation and afforestation) and changing land management. Finally, the interconnection between these risk factors in the context of global changes, in particular

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climate change, and the challenges they pose to the regional landscape, forest and fire management are highlighted.

Keywords Fire management · Fire risk · Structural/conjunctural risk factors · Extreme fire weather · Climate · Land management · Vegetation type

1 Introduction

Wildfire risk mapping is a key determinant tool for fire management because is closely associated with socioeconomic impacts. Fire risk can be defined as the combination of fire hazard, which is the probability of a region being affected by a fire in a given period, which depends on the probability of occurrence and the susceptibility of the region; and potential damage, which depends on the region's vulnerability to fire and the economic value of the damage caused by the fire (Parente & Pereira, 2016).

The concept of fire risk can be divided into two components: one structural and the other conjunctural (Bergonse et al., 2021; Lourdes & Pessanha, 2009; Verde, 2010). The first has to do with essentially stationary variables or variables that vary in the long term, such as topography, land use/land cover (LULC), population or socioeconomic activities. The second depends on variables that vary in the short term, such as atmospheric conditions, in particular the occurrence of extreme events such as drought and heat waves (HW).

Weather monitoring (e.g., drought) and forecasting (e.g., HW in the short term and drought in the medium term) and, consequently, the assessment of meteorological fire danger/hazard are key components of fire management, namely for short-term fire weather risk mitigation, resource allocation and a better understanding of wildfire dynamics for active firefighting planning.

On the other hand, the type of vegetation plays a key role in the structural component of fire risk and, therefore, of fire management. For example, the wildfire risk map in Portugal includes LULC as one of the risk factors and the fire weather index (FWI) of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987), one of the most used fire hazard indices in the world, is based on the relationship between atmospheric conditions and vegetation (IPMA, 2020). The role of vegetation type is fundamental both before and after a fire, whereas (agro)forestry management activities (preventive silviculture and restoration) also play an equally fundamental role in the risk and management of fires.

All these aspects have an essentially regional character, as the spatial distribution of fires, vegetation type and atmospheric conditions are not uniform across the territory, but are characterized by great diversity and even clustering of events (Parente et al., 2016). This chapter aims to describe the role of climate, atmospheric conditions and vegetation in the danger and risk of fire and, consequently, in the management and socioeconomic impacts of fires. The focus will be on the Iberian Peninsula (IP) and Portugal in particular, as Portugal and Spain are the most affected countries in Europe both in terms of the number of wildfires (NW) and burned areas (BA). This

region is a case study characteristic of the Mediterranean basin and regions of the world with a temperate/Mediterranean type of climate with dry and hot summers. The Mediterranean basin is also a hot spot for studies of climate change impacts, adaptation and vulnerability (Paeth et al., 2017; Tuel & Eltahir, 2020).

2 The Role of Climate, Weather and Extreme Events

The climate and atmospheric conditions are decisive for the occurrence of a wildfire that requires the existence of fuels, an adequate state of dryness and an ignition source (Ventura & Vasconcelos, 2006; Whitlock et al., 2010). In summary, climate determines the existence, type and life cycle of the vegetation; weather determines the state of the fuels and influences all stages of the fire; and, both, explain the spatial–temporal patterns of fire incidence (NW and BA) that are observed at global and regional scales (Pereira et al., 2019).

Climatic elements, such as surface air temperature and precipitation, determine the water availability to plants and the spatial distribution of the world's vegetation, major biomes and ecoregions (Kelly & Goulden, 2008; Woodward & Williams, 1987; Woodward & Woodward, 1987). The role of climate is also revealed by the seasonality observed in the vegetative cycle and, consequently, in the incidence of fire (Accatino & De Michele, 2013; Alvarado et al., 2017; Giglio et al., 2015; Krawchuk et al., 2009; Le Page et al., 2008; Saha et al., 2019). For example, the Mediterranean climate type is characterized by a rainy and mild period, which promotes the development of vegetation, and a hot and dry period, which promotes the thermal and hydric stress of the vegetation, when wildfire weather danger is higher (Parente et al., 2016; Pereira et al., 2005; Trigo et al., 2016a). Thus, it is not surprising the high similarity between the patterns of climate type, terrestrial ecosystems and wildfire incidence, at global and regional scales (Oliveira et al., 2018; Parente et al., 2016) as well as the identification of regions with similar fire regime—pyroregions—and climate type (Archibald et al., 2013; Galizia et al., 2021; Krawchuk et al., 2009; Pereira et al., 2022; Sousa et al., 2015a; Trigo et al., 2016a).

If climate explains the large-scale patterns of the spatial–temporal distribution of vegetation and fire incidence, the climate variability and weather types explain the characteristics of the fire regime at local and regional spatial scales, and shorter temporal scales (Dwyer et al., 2000; Rodrigues et al., 2020; Trigo et al., 2016a; Turco et al., 2018). At typical wildfire time scales (hours to days), atmospheric conditions play an admittedly important role in all fire phases (Calheiros et al., 2022; Pereira et al., 2019). Lightning causes fires worldwide, especially in the boreal regions, and large summer wildfires when associated with dry storms or with little precipitation (He et al., 2022; Pérez-Invernón et al., 2021; Sullivan, 2017). Wind, humidity and air temperature are important drivers of fire propagation and behavior (Benson et al., 2008; Pastor et al., 2003), while precipitation and air humidity help fight and extinguish fires (Awad et al., 2020).

At longer temporal scales, climate variability and weather explain other characteristics of the fire regime such as the inter-annual variability of the fire incidence and the asymmetry of the fire size distribution (Andela et al., 2019; Cansler & McKenzie, 2014; Hantson et al., 2015). For example, several studies show that about 2/3 of the interannual variability of the burned area in IP pyroregions is explained by atmospheric conditions (Pereira et al., 2005; Sousa et al., 2015a; Trigo et al., 2016a). In each region, the fire size distribution tends to be highly skewed to the right, which means the existence of a high number of small wildfires and a few numbers of extreme wildfires that tend to be responsible for the majority of the total burnt area. In the case of Portugal, 10% of the largest wildfires account for 80% of the total burnt area (Pereira et al., 2005).

A power law can be fitted to the heavy-tail wildfire size distribution and help to illustrate and explain the rarity of large fires (Kanevski & Pereira, 2017; Malamud et al., 1998; Telesca & Pereira, 2010). This distribution reveals the existence of different classes of fires, for which the fire propagation is dominated by different atmospheric/climatic conditions: drought is responsible for the propagation of large fires, the relative humidity of the medium fires, and the wind governed the propagation of smaller fires. These results are consistent with the idea that fire propagation involves limits of scale, with small-scale drivers allowing fires to propagate after ignition, but limiting further spread only when large-scale drivers exist (Slocum et al., 2010).

For regional hazard assessment and fire management support, the influence of atmospheric conditions on fires has been studied and objectively quantified in several ways, including hazard indices and meteorological fire risk (e.g., San-Miguel-Ayanz et al., 2003); fire propagation and behavior models (e.g., Pastor et al., 2003); burnt area models (Pereira et al., 2013; Sousa et al., 2015b; Trigo et al., 2016b); identification of atmospheric patterns and weather types associated with high fire incidence (Amraoui et al., 2015; Rodrigues et al., 2020); assessment of the role of extreme meteorological (e.g., HW, storms) and climatic (e.g., drought) events.

HW and droughts are the main climatic drivers of fire incidence and, in particular, extreme fires (Pereira et al., 2005). For this reason, the HW characteristics (frequency, duration, seasonality and intensity) and their influence on extreme wildfires (wildfires with BA $\geq$ 5000 ha) in mainland Portugal were evaluated for recent past and future climate conditions (Parente et al., 2018). About 130 HW were identified in 1981–2010, between May and October, but concentrated in July and August. HW characteristics show great interannual variability, clearly associated with the temporal and spatial distribution of extreme wildfires: 97% of the total number of extreme wildfires were active during an HW, 90% of the total days of extreme wildfires were also HW days; 82% of the extreme wildfires had duration contained in the duration of an HW; and 83% of extreme wildfires occurred during and in the area affected by HW. Results also show that HW should increase in number, duration and amplitude, most significantly for RCP 8.5, and the end of the twenty-first century. The results of this study should support the definition of climate change adaptation strategies for fire hazard and risk management.

Other unsuspected extreme weather events can promote extreme wildfires. On October 15, 2017, after an exceptionally hot and dry season, with unusually intense droughts and heat waves, the fire weather was extreme and fuel moisture very low when the tropical storm (former hurricane) Ophelia passed along the west coast of Portugal, promoting strong south winds over the mainland, advected hot and dry North African air, increased the rate of fire spread and growth and gave rise to several mega fire events (Augusto et al., 2020; Castellnou et al., 2018; Sánchez-Benítez et al., 2018; Turco et al., 2019).

Recently, a study characterized the drought regime in the climatic conditions of the recent past (1981–2017) using various drought indices (Standardized Precipitation Index SPI, Standardized Precipitation Evapotranspiration Index, SPEI, Reconnaissance Drought Index, RDI and Vegetation Condition Index, VCI) and evaluated the influence of drought on the occurrence of extreme wildfires (Parente et al., 2019). Results reveal that: all extreme wildfires occurred during the drought evaluated with SPI or SPEI; more than 95% of the number of extreme wildfires and 97% of the burned area occurred during the drought evaluated with one of these indices; and 85% and 87% of extreme wildfires occurred in drought-affected areas evaluated with SPI or SPEI, respectively. The relationship between drought and fire incidence is statistically significant for 3-month SPI, 3-month and 6-month SPEI, and particularly strong for moderate and severe drought. It is not clear which is the best index, but drought is decisive for the occurrence of large wildfires.

The evaluation of fire weather danger and risk is useful to support firefighters and fire management stakeholders in several activities. The Canadian Forest FWI System (Van Wagner, 1987) evaluates the severity of fire weather conditions and comprises: three indices to numerically rate the fuel moisture in three relevant forest fuel layers, including the Drought Code (DC), which assesses the effect of drought on forest fuels; and four relative indices of fire behavior, including the Fire Weather Index (FWI) and the Daily Severity Rating (DSR) (Wotton, 2009). The DSR rates the difficulty of controlling fires because it reflects more accurately the expected effort required for fire suppression (Pereira et al., 2013; Wotton, 2009). The FWI System rates the relative fire potential just based on weather data (Stocks et al., 1989), namely daily values registered at noon of four meteorological variables, namely air temperature, relative humidity, wind speed and daily accumulated precipitation. The FWI System was developed for Canada, but for a common standardized forest type and is globally and regionally computed and extensively used to rate the fire weather danger, especially in the Mediterranean basin (Bedia et al., 2012; Flannigan et al., 2016; Guenni et al., 2022; Pereira et al., 2013; Silva et al., 2019a, 2019b; Vitolo et al., 2019).

A cluster analysis carried out on the normalized burnt area revealed the existence of four pyroregions in the IP (Fig. 1), namely in the N—North, NW—Northwest, SW—Southwest and E—East (Sousa et al., 2015a; Trigo et al., 2016a). The four pyroregions differ in the intra-annual variability of the normalized burnt area, namely by the existence and dimension of peaks and month of occurrence of maximum values (Fig. 2). A recent study repeated the analysis for a longer period and, despite

confirming the existence of the four pyroregions, revealed differences in the administrative regions that constitute them (Calheiros et al., 2020). The authors calculated the Number of Extreme Days (NED), defined as the days with DSR and DC above the 95th percentile, and found a relationship between the intra-annual variability of the NED and the normalized burnt area, with high and statistically significant correlation, in each pyroregion and capable of explaining the changes in pyroregions. Recent changes in the intra-annual variability of the normalized burnt area were observed in some border provinces of the pyroregions, associated with the NED and confirmed that large values of BA are strongly linked to extreme weather conditions.

This robust link was used to project the future pyroregions of the Iberian Peninsula, using simulated data from a wide ensemble of climate models for two scenarios (RCP4.5 and RCP8.5) to estimate future FWI indices (namely DSR and DC) and NED (Calheiros et al., 2021). Results revealed a significant increase of the NED, especially in the south and central Iberia, for the end of the century and the RCP8.5 scenario, mostly due to significant increases in the DC, associated with the substantial

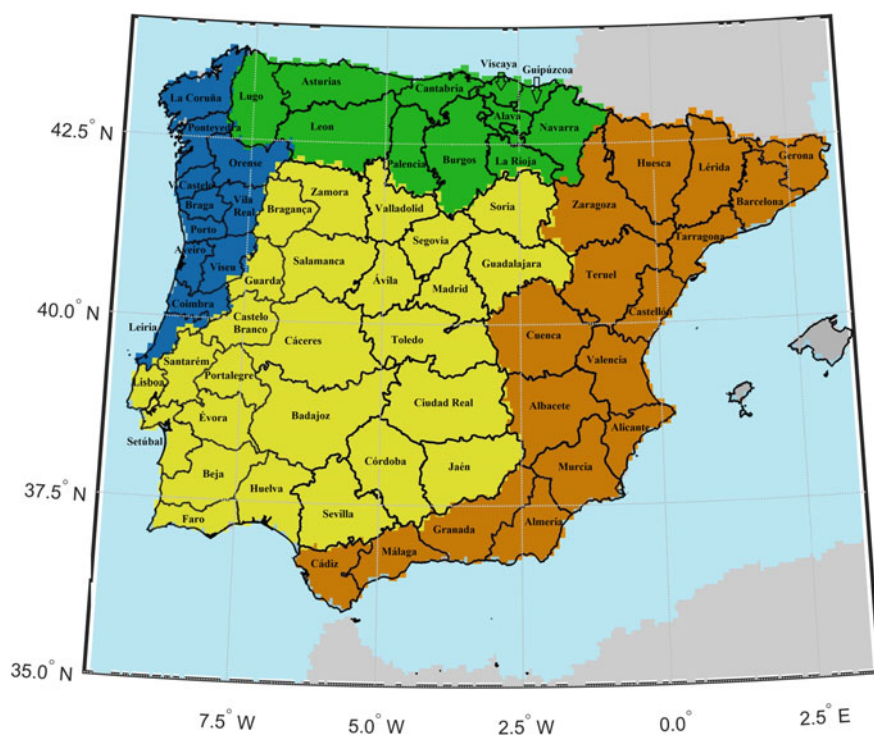
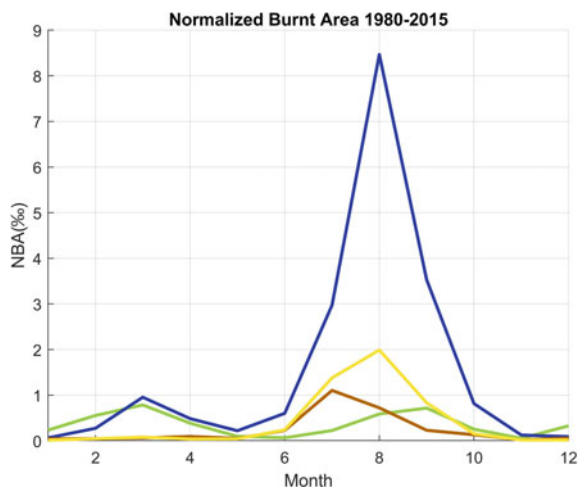


Fig. 1 The pyroregions identified in the Iberian Peninsula in the period 1980–2015 (NW in blue, N in green, SW in yellow and E in brown), the administrative regions are part of them (right panel) and the monthly averages of the normalized burnt area, computed for each month and the administrative region as the quotient between the monthly burnt area and the area of the administrative region (in per mileage) for the period (right panel)

Fig. 2 Normalized burn area from 1980 to 2015 per month



decrease in precipitation and increase in air temperature. Changes in NED intra-annual pattern should drive the pyroregions' future configuration and it is related to changes in future climate types (Beck et al., 2018). Pyroregions will move northward: The N pyroregion can be confined to the Cantabrian Mountains; the NW may include several provinces of the current N pyroregion; the SW will comprise most of the current provinces of the NW; and, E is expected to maintain its current boundaries, but changes in vegetation could lead to a new pyroregion in the extreme southeast (Calheiros et al., 2021).

3 The Role of Land Management

Besides climate, contemporary fire regimes are also impacted by human activities. Human populations modify fire regimes by suppressing natural ignitions or increasing human-caused ignitions, by increasing or decreasing the fuel loads (e.g., agriculture abandonment or prescribed fire), or by modifying the landscapes (e.g., urbanization, deforestation and afforestation). In Portugal, as in most Mediterranean countries, the land cover is largely the result of anthropogenic activities. Currently, the area of the country covered by forests is about 36% (ICNF, 2019), compared to less than 10% at the end of the XIX century (Mather & Perreira, 2006), and eucalypt and maritime pine plantations account for 48% of the forest area (ICNF, 2019). Cork and holm oak woodlands cover 34%, and the rest of the forest area comprises stone pine (6%), other oaks (3%), chestnut (1%) and other forest species (7%). An important area of the country is also covered by shrub formations and pastures (31%), and agriculture (23%).

On average, from 1996 to 2021, 41% of the annual burned area in Portugal occurred in forests, and 53% in shrublands and pastures (data from ICNF, the

Portuguese Forest Services). Analyzing the fire–vegetation relationship, namely the fire incidence by vegetation type is complex due to the firefighting activities, which modify this relationship given the decision of protecting a specific area with a specific land cover or vegetation type. Silva et al. (2019a), analyzing the long-term spatiotemporal trends of burnt area in the Iberian Peninsula, observed increasing trends of burnt area in northwestern Portugal (Braga, Porto, Aveiro districts) and decreasing trends in Galicia, Spain, with the first region showing a decrease in the area of forest and the second an increase of this area, revealing how firefighting and forest management shape the fire–vegetation relationship. The spatial pattern of the land cover types in a region may also have an impact on the fire incidence by land cover. In areas of the rural–urban interface (which is the case of northwestern Portugal), characterized by a mixture of different land cover types (urban areas, agricultural fields and forest areas), it is expected to have a different fire–vegetation relationship compared to regions largely dominated by forests or shrublands.

A fire frequency analysis in Portugal, based on burnt area maps derived from Landsat imagery for the period 1975–2005, revealed that a large portion of central and north Portugal had a fire return interval of fewer than 25 years (see Oliveira et al., 2012, for details on the imagery used and on the frequency analysis). In the regions covered predominantly by forests, there were not many fires but they were large, whereas in regions dominated by shrublands, the fire regime was characterized by more frequent but smaller fires (Oliveira et al., 2012). The size of wildfires is a very important factor in the fire–vegetation relationship, with large fires being less selective in terms of land cover (Barros & Pereira, 2014; Nunes et al., 2005). Nunes et al. (2005), using 506 fires that occurred in Portugal, investigated if fires select given land cover types for burning by comparing the proportions of land cover types present in burned areas and their respective surroundings. Results showed that fires are selective, with small fires exhibiting stronger land cover preferences than large fires, and that there is a marked preference for shrublands followed by forests, while agriculture is avoided. Following a different methodological approach, Barros and Pereira (2014) obtained similar results. The ranking of land cover types according to fire proneness, from less to most fire-prone was as follows: annual crops, evergreen oak woodlands, eucalypt plantations, pine stands and shrublands. All land cover types exhibited reductions in fire preference as fire size increased. Other studies obtained similar rankings (Moreira et al., 2001, 2009; Silva et al., 2009). The lower selectivity of eucalypts compared to pine may be explained in part by their economic value and active management, and suppression effectiveness, which contributes to mitigating the effect of severe weather conditions (Barros & Pereira, 2014).

Population and land cover determine much of the complex fire patterns in Portugal (Costa et al., 2011; Nunes et al., 2016). Nunes et al. (2016) analyzed the drivers of forest fires in Portugal at the municipal level. Concerning land cover, they found that uncultivated land was a factor that contributed to an increase in the burnt area. Uncultivated land, resulting from agricultural abandonment, more than doubled in the last five decades, and it is covered largely by vegetation that is very prone to fire. An analysis of the land cover changes in Portugal in the last 100 years concluded that from 1907 to 1990, the area covered by forests and woodlands increased, a process

called forest transition (Mather & Perreira, 2006) and that after 1990, there was a substantial conversion of forest areas to shrublands (Oliveira et al., 2017).

(Calheiros et al., 2022) assessed the relationships between vegetation/land use, fire weather and burnt area at high resolution (municipalities) for Portugal with recent data (2001–2019). ERA5-Land reanalysis dataset was used to compute the FWI indices, and the percentiles of the DSR (DSRp) were assessed with the large wildfires (BA > 100 ha). In detail, each wildfire was associated with the highest DSR recorded during the wildfire duration in the municipality or municipalities. This analysis revealed that the days with DSR above the DSRp between 85 and 95 were responsible for more than 80% of the total BA in mainland Portugal. Nevertheless, this threshold presents significant spatial diversity at the municipal scale. A cluster analysis revealed the clusters with different thresholds that explains 80% or 90% of BA. Further investigation showed that distinct vegetation and/or land use justifies this spatial variability. Indeed, it was demonstrated that the clusters located in coastal regions are predominantly covered with forest and have a large BA with the most extreme meteorological conditions, or very high DSR percentiles. On the contrary, clusters placed in the eastern parts of the country have the largest amount of shrublands, and the BA occurred more frequently with less extreme meteorological conditions or lower DSR percentiles. These results should be used in firefighting and regional fire management (Calheiros et al., 2022).

Sá et al. (2018) modeled fire incidence with vegetation, precipitation and anthropogenic drivers, finding that urban and agricultural areas control fire absence, while forests and especially shrublands area are the main drivers of fire incidence. They also found the need to discriminate between irrigated and rainfed agriculture when studying fire–agriculture relationships. Eucalypt plantations are often viewed as highly flammable due to the nature and structure of the fuel complex, but the burnt area of this species did not increase over time (1980–2017) even with an increase in the area of eucalypt (Fernandes et al., 2019). This study also found that large-scale conversion of maritime pine to eucalypt stands implied lower fuel accumulation. Fernandes and Guedes (2011) analyzed each type of forest in Portugal the fire risk, how species respond to fire, and identified preventive silvicultural treatments. For eucalypts, fire danger (defined as the ease of ignition and fire propagation and its difficulty of extinction) is reduced in 39% of situations and it is extreme in 42% of cases. Tall eucalyptus (especially if open) is less vulnerable to fire; low and closed formations occupy the opposite extreme. Selection by fire is proportional to its availability in the landscape. For pines, fire danger is high and extreme in 60% and 23% of cases, respectively. The low maritime pine forest is very vulnerable to fire. Maritime pine tends to burn in a higher proportion than its availability in the landscape, especially in large fires, and its probability of burning is maximum.

Population density and distribution can also influence the fire regime through its contribution to ignitions. In the work by Calheiros et al. (2020) described earlier, an analysis of fire occurrence, burnt area and weather conditions (FWI) for the IP between 1980 and 2015 revealed clustering into four pyroregions with distinct fire regimes. One interesting result of this analysis is how different frequencies of ignitions influence these regimes. The Northwestern Iberia pyroregion has a large number

of ignitions, and hence, a large number of small fires which can evolve into large fires when weather conditions are extreme. Therefore, the climate is a determinant of the occurrence of large fires. In other pyroregions in the Southwestern and Eastern parts of the Peninsula, extreme weather conditions are more common but ignitions are less frequent, thus making climate relatively less important. Ignitions have been related to population density by Catry et al. (2009), and the northwestern part of Iberia has a relatively higher population density due to more dispersed settlement patterns than elsewhere in the peninsula.

Land management also affects the socioeconomic impacts of fires. The most obvious impact is through the exposure of population and property to fire impacts, potentially resulting in damage or fatalities (San-Miguel-Ayanz et al., 2020); areas with larger population densities and/or longer rural/urban interfaces are more exposed to impacts. But there are less obvious secondary impacts, of which the potential impacts on water resources are an example.

Water supplies are often collected from fire-prone watersheds (Robinne et al., 2021) since agricultural watersheds present higher rates of water contamination. But fires can have significant impacts on water quality, as discussed by Nunes et al. (2018) and Robinne et al. (2021). The ash created by fires can be mobilized to the stream networks, leading to excessive turbidity and increasing the concentration of nutrients, heavy metals or organic compounds; these problems can overwhelm the capacity of existing water treatment systems, and there are many cases of water supply limitations as a consequence of fires, often for several years afterward. In this case, the exposure problem might be reversed, as areas with lower population density might be more affected since they are preferential sources of water supply, and since water supply systems for smaller communities tend to have smaller water treatment capacities and therefore be less resilient to disruptions.

4 Conclusions

This chapter showed how climate combines with land management patterns to affect the regional impacts of fires, therefore presenting unique challenges to regional fire and forest managers. Climate drives the occurrence of fires by promoting the growth of vegetation, and thereby the creation of fuel; and a dry period which promotes fire occurrence and spread. The spatial distribution of population and vegetation is important in determining sources of ignition, ease of fire spread (especially for less intense fires), and difficulty of fire suppression. They also determine the potential socioeconomic impacts on populations and natural resources. In Mediterranean landscapes, and particularly in Portugal, vegetation distribution is mostly derived from human decisions, and therefore, land management plays a crucial role in fire risk.

While not much can be done about climate and extreme weather patterns, land management can be used to mitigate fire risk. This can include special attention to the distribution of forest and agriculture areas, promoting land-use patterns which limit fire spread; or differentiated prevention measures according to the distribution

of population and natural resources (e.g., water supplies). Since these factors have a strong spatial variability, the best level of planning to address them is the regional level, where best practices and solutions can be adapted to existing and projected conditions.

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