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The influence of climate, population density, tree species and land cover on fire pattern in mainland Portugal

Luís Fareleira Gomes

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Department of
Physical Geography and Ecosystem Science
Centre for Geographical Information Systems
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Luís Fareleira Gomes (2022).

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Supervisor:

Dr. Veiko Lehsten

Department of Physical Geography and Ecosystem Sciences

Lund University

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Finally, I dedicate this to António (Xurupicos), and hope that this work can contribute for a better tomorrow for him.

Abstract

Forest fires in mainland Portugal are becoming more extreme, resulting in increasingly larger burnt areas and tragic human fatalities, as was shown by the 2017 fires. Research shows that there are many natural factors contributing to such fire vulnerability conditions, such as climate, fuel continuity, forest structure, tree species types, amongst others, that are intertwined with anthropic factors than can intensity the fire vulnerability.

This study focusses on the investigation of how some of these factors (namely Fire Weather Index, population density, tree species and land cover) influence forest fire resulting burnt area between the years of 1980 to 2019.

Supported by other similar studies focusing on the impact of given variables on forest fire burnt area, a GIS grid-based analysis was made for the burnt area for mainland Portugal, for the period of study, where a variety of statistical techniques were applied to understand its relation (from more basic correlation between variables, to a characteristic fire size (CFS) applied to distinct variables).

This research showed that *Eucalyptus globulus* is related with bigger burnt areas, as well as leading to bigger CFS, when compared with *Pinus pinaster* and *Quercus suber*; agro-forested land cover areas seem to be less fire prone than forested land cover areas; Fire Weather Index (FWI) has an important impact on the CFS, and decadal CFS has dramatically increased since 1980 to 2019.

The results suggest that forest management in agro-forested areas dramatically reduces both the total burnt area as well as the CFS. There is a strong correlation between these areas and the presence of *Quercus suber*, which may indicate that this combination is less vulnerable to fire.

Keywords: GIS, forest fires, burnt Area, characteristic fire size, spatial analysis, mainland Portugal, FWI, *Eucalyptus globulus*

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List of abbreviations/acronyms

APCOR: Portuguese Cork Association

CFS: Characteristic Fire Size

CTI: Indepdent Technical Commission

EFFR: European Forest Fire Ranking

FWI: Fire Weather Index

GIS: Geographical Information Systems

ICFN: Forest and Nature Conservation Institue

IPCC: Intergovernmental Panel on Climate Change

IPMA: Sea and Atmosphere's Portuguese Institute

1. Introduction

This study will use GIS as a tool to analyse the patterns of forest fires in mainland Portugal, using forest data between 1980 to 2019, and it aims to understand the possible relationship between the burnt area and several key variables that determine the impact of forest fires. These include the Fire Weather Index (FWI), population density, dominant tree species in mainland Portuguese forests (*Eucalyptus globulus, Pinus pinaster and Quercus suber)*, as well as other land cover classes, namely the forested and agro-forested areas.

The total burnt forested area in mainland Portugal has been increasing over the last 40 years, when the burnt area per year increased from 75,000 ha in the decade of the 1980s to more than 150,000 in the first years of the 2000s (Beighley and Hyde, 2018). In 2017, a combination of factors such as extreme climatic events (such the Ophelia hurricane) and record temperatures over prolonged time periods, and a very extensive area of forest with very poor management (Beighley and Hyde, 2018), has led to the biggest fires ever witnessed in Portugal, consuming around 500,000 ha of land, and causing 115 fatalities. In addition, the total burnt area in 2017 in Portugal alone corresponded to more than 50% of total burnt area of the countries located in the South of Europe. (Guerreiro et al, 2018). In 2018, the burnt area dramatically reduced from 500,000 ha to 38,000 ha, yet Portugal was still the country with the biggest single fire event in Europe. (ICFN, 2018)

By analysing the total burnt areas between 1980 and 2019, we conclude that the maximum burnt area per year has been increasing. In fact, only 31% percent of the years between 1980 and 1999 had a total burnt area above 100,000 ha. When the same analysis is applied to the years between 2000 and 2019, in 12 out of 19 years (63%), the total burnt area reached and surpassed 100,000 ha. (Beighley and Hyde, 2018)

When analysing the 2017 forest fire impacts of burnt areas per land use, 40% of the burnt areas corresponded to forests (around 200,000 ha). From these, around 50% corresponded to *Pinus pinaster* areas, and 39% corresponded to *Eucalyptus globulus*. (Guerreiro et al, 2018). This also led the highest CO^2 emissions since 2010, with an increase of 9% when compared with emission levels from 2016. In addition, 2017 was also the year with the biggest net emissions related with land use since 1990, with a positive value of 7.2 Mtons of CO2. (PEA, 2020).

There are several factors that can contribute to burnt area as a result of forest fires, however, these can be divided in two separate sets of factors, namely the natural factors and the anthropic factors. For the natural factors, general variables such as climate, land cover, tree species, forest structure, wetness indices, amongst others, can be included (Fernandes 2007). For the anthropic factors, indicators like population density, population age, economic use of the land, income from agricultural or forestry related activities, forest fire management strategies, and funding of firefighting corporations are examples of the wide range of possible factors that can have an impact on the total burnt area.

In order to contribute to a better understanding of forest fire issue in mainland Portugal, it was decided to perform an analysis in relation to the incidence and spread of forest fires in mainland Portugal, which can lead to a clearer awareness of the variables that affect the incidence of forest fires.

There are numerous studies regarding this issue applied for mainland Portugal, based on very recent data and advanced methodologies which produced a variety of extremely interesting and important scientific papers on the matter, which include the following amongst many others: Fernandes, 2019a; Fernandes et al., 2019; Silva et al., 2019, Nunes et al., 2019; Nunes et al., 2019b; Guerreiro et al., 2018; CTI, 2017; Beighley and Hyde, 2018; Palheiro et al., 2006; Viegas et al., 2004. Although these are not being analysed in finer detail in this section, such references and its content shall be addressed in later sections of this work.

Therefore, the objective was to approach the subject of forest fires in mainland Portugal from a fresh perspective, that could give us a different insight regarding this issue. This could be achieved by using the concept of characteristic fire size introduced by Lehsten et al. which, by analysing a large dataset over a long period of time, would allow to understand what fire size better describes a given fire regime, for an area of study. (Lehsten et al., 2014; Lehsten et al., 2016)

This strategy allowed us to filter the burnt area by different variables, enabling us to understand what fire size better described a relation between burnt area and a given variable (such tree species), or how it behaves through time (for this analysis it was decided to use the decade as the unit of time). By then comparing different variables within the same variable group (decades within a decadal group or various tree species within a tree species group), it would give us better insights into what is the fire behaviour in different contexts.

This awareness that can be gained from characteristic fire size can aid forest management decision makers in better understanding not only trends in the burnt area from different angles of analysis, as it can better inform them as to how these variables affect fire behaviour, as some of these are part of a wider dynamic phenomena (such is the fire weather index), or as a result of various variables acting at the same time (this is mostly noticeable when analysing the decadal fire size behaviour).

Therefore, by having a better understanding of the impact of the analysed variables on the burnt area, it will allow decision makers to have more confidence in coarser scale analysis that will define general trends, which is a strong position to then work at finer scales, permitting the development of tailored strategies to smaller geographies of analysis that can have a direct impact on the reduction of the burnt area due to forest fires.

1.1 Aims and Objectives

Our aim with this work is to generate new scientific knowledge that can generate new questions, that might help with the mitigation of forest fires in mainland Portugal. To achieve this, we intend to have a better understanding on how the variables examined in study can affect forest fires, while presenting a fresh perspective on the burnt area analysis with characteristic fire size.

To enable a clearer understanding of the phenomenon of forest fires, it was decided to create four hypotheses that will guide this analysis, and given our results, these will be discussed and then assessed, allowing us to appreciate if it is possible to confirm these, or not.

Therefore, based on both our experience of witnessing forest fires in mainland Portugal, as well as by the scientific research upon them that have been released over the years, our theory is that there are certain variables that describe conditions that make the forests more vulnerable to forest fires than others. Our hypotheses are as follows:

1. Total burnt area increased since 1980 until 2019, and we expect to see this phenomenon translate to a linear trend of increase for the burnt area, as we expect to see an increase in the decadal characteristic fire size.
2. Higher Fire Weather Index (FWI) values have a direct impact on the burnt area, and we expect a positive correlation between FWI and burnt areas. In addition, we expect that characteristic fire size increases with increasing FWI values.
3. Areas with lower population density are more vulnerable to forest fires than areas with higher population density, therefore we expect to see a clear negative correlation between population density and burnt areas.
4. Although *Pinus pinaster* was the most affected tree species in the 2017 forest fires in mainland Portugal, we hypothesise that *Eucalyptus globulus* contributes more to the total burnt area of this territory when compared with *Pinus pinaster and Quercus suber.* Finally, we expect that the characteristic fire size of *Eucalyptus globulus* to be bigger than that of the other presented species.

2. Literature Review

2.1 Introduction

The study of the complexity of forest fires in mainland Portugal entails an understanding of different phenomena, such as fire behaviour in the context of a forest fire, the ecological characteristics of the forest, and how these are affected by related social and economic aspects. These factors are essential to contextualize the results that will be further presented in this study, since the forest can be perceived as both a natural as well as an anthropic entity.

This chapter will focus on the literature available on these topics, with an important focus on the Portuguese situation, yet always trying to complement such knowledge with different perspectives produced elsewhere.

2.2 Forest Distribution in mainland Portugal

Throughout time, the relationship between people and forests have changed, being mostly visible in the last century where there was the biggest and fastest change in lifestyle that society has ever witnessed. Portugal is not an exception and such changes have created new and intricate dynamics between communities and the forest, with direct impact on the fire pattern regimes in this territory.

Mainland Portugal has a total of 3,200 thousand hectares of forest, which the predominant species are the *Eucalyptus globulus* (26% of the total area), *Quercus suber* (22% of the total area) and *Pinus pinaster* (22 % of the total area) (ICNF, 2015). Portugal is also one of the countries with the smallest public forest in world, with only 3% of the forest being considered to be property of the state. The average of this value for Europe is of 44%, while worldwide this same figure rises to 74%. (ICNF, 2017).

Privately owned forest can be divided in two types of parcels: the south and north parcels. The first are characterized by its considerable size, mostly exploring species such as *Quercus ilex* and *Quercus suber*. The latter species is the main and only source of cork production in Portugal, and it corresponds to 34% of the total area of cork production in the world. In addition, this industry employs 8310 employees, and corresponds to 1% of total Portuguese exports, corresponding to a net export value of 816 million €. (APCOR, 2018)

The parcels located in the north are of small or very small dimension and are mainly characterized by the presence of *Eucalyptus globulus* as well as *Pinus pinaster*, given the main aim of such parcels is the production of wood as a fuel, as well as its use as raw material for furniture production, paper pulp production and other related wood products. These industries employ around 75 thousand employees in Portugal, however, the direct employment related with wood production employs around 85 thousand people. (Louro, 2015).

In 2003, 49% of the forests in Portugal were related to economic activities, where 70% of these corresponded to larger parcels in the south (mostly related with cork production), and the remaining 30% corresponded to small or very small units in the centre and north of the country. The remaining 51% of the forest was distributed as follows: 2.5% were public forests, 7.5% corresponded to paper pulp related parcels, 12.6% represented communal forests, while the remaining 28.4% corresponded to privately owned parcels (Coelho, 2003). At the time, it was estimated that the remaining area (28.4% of the total forested area) was formed by small parcels owned by private owners that were not integrating their forests into any agricultural regime, where around 25% of these did not live in the area where their forested parcels were located.

Therefore, around 40% of the forest corresponded to both parcels owned by proprietors that did not integrate their forests into any agricultural regime, as well as to communal forests. It might be assumed that considerable areas of these forests were not under any forest management. (Coelho, 2003).

2.3 Forest management in mainland Portugal

As previously presented, there are numerous factors that can contribute to the existence of forest fires, yet it seems unanimous that the lack of management in the Portuguese forests leads to the existence of massive fires. (Beighley and Hyde, 2018; Fernandes, 2007; Fernandes, 2009; Nunes et al, 2019; Guerreiro et al, 2018; CTI, 2017).

In fact, when assessing the burnt areas in managed and unmanaged parcels, we conclude that unmanaged areas gave a higher burnt area when compared with the managed ones. The fact the latter had a reduced fuel volume, led to a direct impact on the size of the burnt area. (Guerreiro et al, 2018).

It is impossible to analyse the management of forests in mainland Portugal without understanding the impact on private ownership of these areas, as well as the shift of importance that this has had for surrounding communities, and therefore, the main agent of forest management in these local forests.

Since the democratic revolution in 1974, there were profound transformations in Portugal, including changes in the economic paradigm. During the dictatorship, there was a very strong desire to maintain a rural economy, while after 1974 there was a noticeable effort to develop the industrial sector near the cities, which subsequentially led to development of these areas as well.

Given the very low investment in access connecting the coastal areas with the interior, there was a disproportional development on the areas with better access (on the coast), in contrast with areas in the interior. Such disproportionality is still very noticeable in Portugal, being one of the most recurring topics in its politic debate.

Such disparity in resources and development led to an increasing migration of people from the rural areas to the urban ones. The following table (Table 1) demonstrates this situation, where between the decades of 1970 and 1980 there is the highest increase in urban population, when compared with the previous three decades (Albergaria, 1999).

As a result, some agricultural parcels that once were managed are now abandoned, including the ones that were converted into forested areas, but given the maintenance costs are practically abandoned. The following figure (Figure 1) demonstrates this situation, since during the interval between 1968 and 1985, it is possible to observe a sharp decrease in the agricultural area (in green), a sharp increase in the uncultivated fields (in red), and an increase in the forested areas (in brown). Therefore, areas that once could contribute to control fires are now areas that promote the rapid expansion of fire throughout the landscape. (Beighley and Hyde, 2018)

Table 1: Urban population in Portugal, between 1940 and 1980

Year	1940	1950	1960	1970	1980
Urban Population (in millions)	2	2.3	2.54	2.71	**3.26**
Difference (in millions)		0.3	0.24	0.17	**0.55**

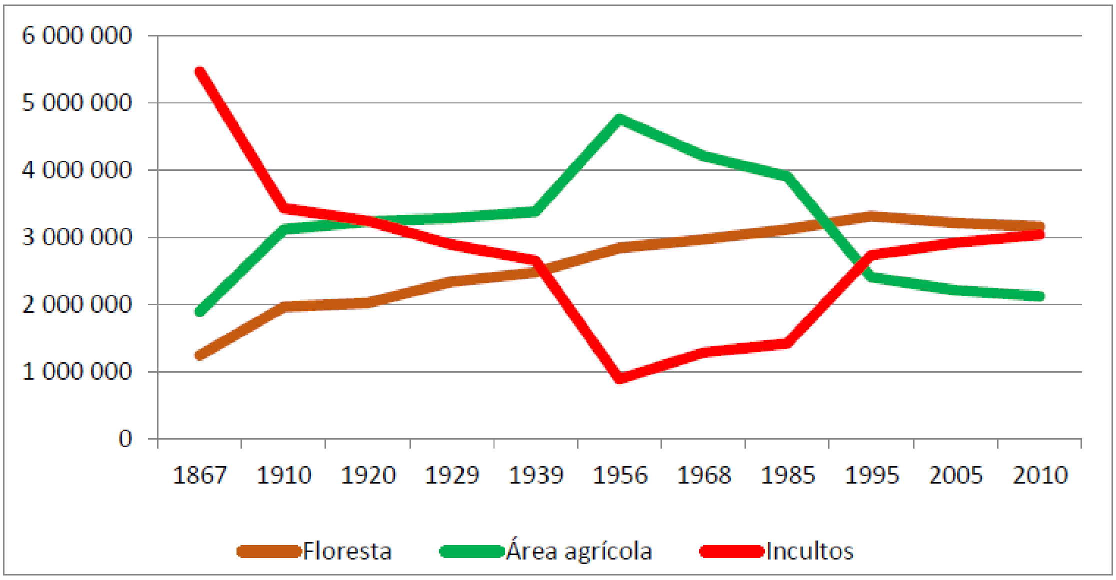


Figure 1: Evolution of the main Land Use types in Portugal between 1867 and 2010 (in hectares). Brown Line – Forest; Green Line – Agricultural Area; Red Line – Uncultivated Fields (Mendes, 2017)

The abandonment of agricultural areas led to a natural expansion of the forest, where fast growing species such as *Pinus pinaster* expanded throughout the territory. Yet, in the areas where the forest was still a source of income to its proprietors, it is common to observe the tendency to promote *Eucalyptus globulus*, given its rapid growth and associated income. This led to the development of extensive and continuous forests, characterized solely by two species –*Eucalyptus globulus* and *Pinus pinaster* – leading to high levels of combustibility if left unmanaged. (Mendes, 2017)

An example of this is the abundance and uncontrolled proliferation of highly flammable species such *Eucalyptus globulus*. This situation is often related with the fact that some of these parcels are producing plants that do not meet the standard to be used as a paper pulp, losing their commercial value. In the face of such a situation, the proprietors often cut their losses by stopping their investments in these parcels, leading to an abandonment of any forest management strategy, and the uncontrolled proliferation of the vegetation. (Beighley and Hyde, 2018)

In fact, given the high fragmentation of privately owned parcels in mostly northern mainland of Portugal, in association with the decrease of the rural and agriculture related communities, the cost of forest management for a private owner increased, so much so that the costs of managing such parcels will not allow some of these owners to have any profit from their forested areas. (Mendes, 2017).

As consequence, abandoned areas that suffer from cyclical forest fires without any forest management will lead to forest structures that are low and closed (where the understory is dense enough to block most of sunlight). Indeed, Nunes et al. (2019) has noted that, despite the fact *Pinus pinaster* and *Eucalyptus globulus* are the species that most burn in Portugal, stand structure seems to be more important to fire behaviour than the tree species that comprise the stand itself. (Nunes et al, 2019)

Fernandes' (2007 and 2009) position reinforces this statement, since the researcher considers that is somewhat risky to consider that these two species should be considered undesired, given their fire prone characteristics. The base argument is that the forest formations are, ultimately, more important than the type of species that is present on that territory.

Indeed, the same author analyses the fire behaviour using three distinct metrics, namely the rate of spread, fireline intensity and crown fire potential. The analysis was made under different scenarios including different species (where *Pinus pinaster* and *Eucalyptus globulus* are included, amongst other species), but also introduces the forest stand structure in model (tall and open forest; tall and closed forest; low and open; and low and closed) (Fernandes, 2009). This concluded that low structure will always promote the fire reaching to the treetops, dramatically increasing its intensity. However, while a closed and low structure will not promote a quick-fire spread, this structure will lead to very high or extreme levels of intensity. An open and low structure will promote a faster spread of the fire, but with a decrease in its intensity.

A tall structure, on the other hand, will not promote the fire reaching the treetops, which will make the fire less intense. A closed and tall structure will still promote the fire intensity, while decreasing the spread rate of fire, yet these are considerably lower than the ones presented for a closed and low structure.

In cases where the forest management of areas with a mix forest of *Pinus pinaster* and *Eucalyptus globulus* is not adequate, this can correspond to a "recipe for a disaster" (CTI, 2017).

2.4 Fires in the mainland Portuguese forest

Portugal occupies one of the highest positions in the European forest fire ranking – EFFR, making this one of the countries that is most affected by forest fires in Europe. (San-Miguel-Ayanz et al, 2019). As was previously presented, we can briefly identify some of the reasons for this performance: Demographic changes that led to an exodus from rural to urban areas, resulting in land use alterations that produced agricultural and forested areas without any management strategy. Additionally, high property fragmentation does not promote investment in forest management, nor for the planning and prevention of forest fires (CIT 2017, Guerreiro et al, 2018). (Table 2, Figure 2)

Table 2: Comparison of burnt area related metrics between mainland Portugal and all other countries in the European forest fire ranking - EFFR (San-Miguel-Ayanz et al, 2019)

Area	**Average number of burnt trees (2008 - 2017)**	**Proportion of total burnt trees (%)**	**Average burnt area in ha (2008 - 2017)**	**Proportion of total burnt area (%)**
All countries (EFFR)	64,725	100%	409,245	100%
Portugal	18,485	29%	136,107	33%

In Portugal, around 98% of the fires have a human related ignition (Figure 3) and when compared to its neighbour country Spain, this has a lower total number of human related ignitions, even though it has 5 times the area of Portugal, and 4 times its population size. (Beighley and Hyde, 2018)

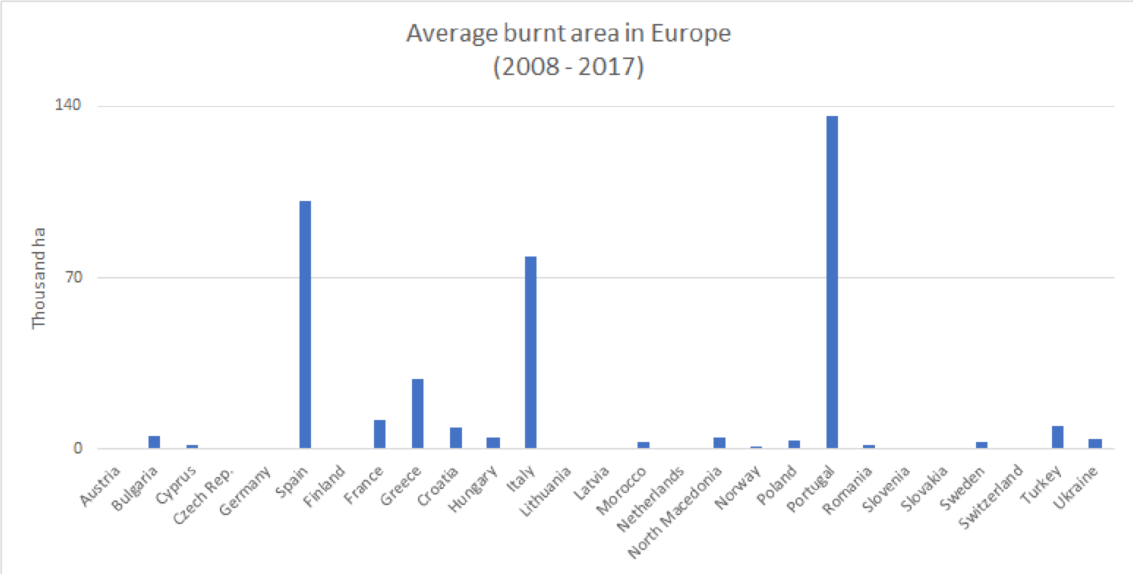


Figure 2: Absolute values in the EFFR (San-Miguel-Ayanz et al, 2019)

The majority of the fires are directly caused by negligence where it includes not only the lack of management of the forested areas, as well as the type of actions used to dispose of the biological waste from land clearance or other activities. In some cases, the strategy used to dispose of it is by burning it, which under unfortunate conditions, can lead to uncontrolled and immense fires. (Figure 3) (San-Miguel-Ayanz, 2019, AGIF, 2018)

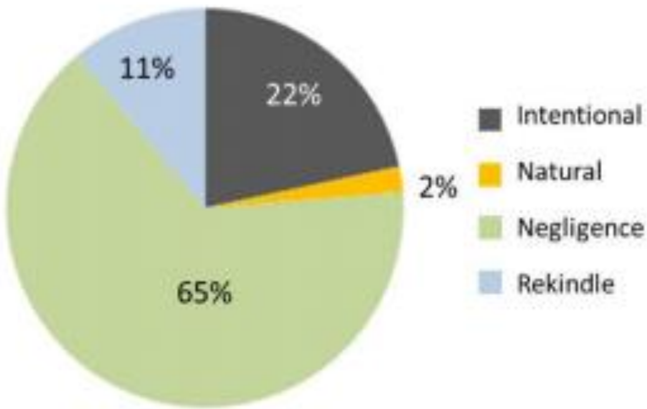


Figure 3: Main causes of rural fire in Portugal, in 2018. (San-Miguel-Ayanz, 2019)

Given the combination of a very poorly managed forest with changes in the climate that will promote forest fires, the effectiveness of a reactive strategy is gradually reducing to the point that it is impossible to control the extent of forest fires. Therefore, the investment should focus on pre-emptive strategies, such as forest management (CTI, 2017; Guerreiro et al, 2018).

It is then imperative to understand the forests of the study area, as well as what makes these fires to spread so fast and with such intensity, to the point of consuming countless of thousands of hectares in just one event.

According to Fernandes (2007), forest fires are mainly dependent on three distinct natural variables, specifically the vegetation, topography, and weather conditions. The next subsections will analyse these variables and how these can affect forest fires.

2.4.1 Vegetation

The vegetation is the main fuel that leads to the proliferation of forest fires, although not all can be considered as such, since the tree trunk and some of living branches are normally not affected by the fire (Fernandes, 2007). The combustion is fuelled, mainly, by very dry dead thin vegetation elements, and the fire intensity is directly proportional to the volume of fuel. While the progression of a fire in grassland can be considered to be fast but not very vigorous, when this is applied to wood heavier contexts, its progression is slower, but it releases considerable amounts of heat. (Fernandes, 2007)

Since the humus layer is not capable of sustaining combustion with flame, the main contributors for such phenomena are both the horizontal and vertical vegetation. If there is a dense and high understory, with the presence of small trees, the fire can easily reach the treetops, which will dramatically increase its intensity. (Fernandes, 2007).

When considering the total burnt area in Portugal in 2017, 49% of the burnt area corresponded to forested areas. In terms of percentage of forest species, 50% of the burnt forested area corresponded to area of *Pinus pinaster*, while 39% corresponded to *Eucalyptus globulus*. (Guerreiro et al, 2018)

In fact, the most common species combination in the centre and north of Portugal, in a mixed forest scenario, is precisely *Pinus pinaster* and *Eucalyptus globulus*, since these correspond to fast growing tree species. This corresponds to the most fire prone species combination, given the rather high volume of litter these species produce. (Fernandes, 2007)

Yet in the case of the *Eucalyptus globulus,* it is important to note that the chemical composition of its leaves, rich in volatile organic compounds, can have a direct impact on its flammability. These compounds include isoprene and monoterpene, such as 1.8-cineol and α-pinene, where younger trees emit higher fluxes of these compounds than older specimens. Interestingly, with higher temperatures (near to 40°), there is a higher emission of these compounds – mostly 1.8-cineol – which can have a direct effect on the flammability of the area (Nunes and Pio, 2001). In addition, in the presence of high winds, its bark can travel for considerable distances, and if still burning, can lead to new ignitions away from the original fire. (Guerreiro et al, 2018)

As previously presented, different authors agree that forest structure has a bigger impact on the fire vulnerability of forest fires than the tree species that dominate a given area. Here, open and tall structures correspond to more a more resilient forest to fires, since although this structure would promote fire spread over fire intensity, it would dramatically reduce crown fire risk. (Fernandes, 2009; Nunes, 2016)

Given the characteristics of the forest structures and species flammability, we can conclude that a closed and low forest, where the predominant species are the *Pinus pinaster*, *Eucalyptus globulus* and several different shrub species under the *Acacia* designation, correspond to the most fire prone forests, and despite the fact that the fire spread rate can be moderate, the fire intensity can be very high due to well-developed shrub layer with high fuel loading. This will result in a vertical fuel continuity, which can contribute to an extreme crowning potential. (Fernandes, 2009)

2.4.2 Climate

Mediterranean ecosystems are prone to wildfires, given the cooler wet seasons there can be a considerable vegetation growth resulting in accumulation of fuel, and the dry and hot seasons will bring very low levels of vegetation humidity, enhancing the spread of fire. The concept of “fire weather” encapsulates precisely the latter, where atmospheric conditions are more favourable to the development of forest fires.

Given the climatic characteristics of the Mediterranean area, vegetation has adapted to the summer arid conditions, as well as to the lack of nutrients of the soils. This adaptation leads to a slower decomposition which increases the fuel accumulation.

Alongside precipitation, the two characteristics that are important to the fire spread are the relative humidity, as well as the air temperature. The first will have a direct impact on the fuel drying process, while the second will enable the ignition temperature to be reached with less energy, allowing the fire to progress faster.

Lastly, the presence of wind will have a decisive effect on the fire unpredictability, since this will fuel the combustion with oxygen and will push the heat towards different areas, that can contribute to the rapid-fire spread, or even the ignition of secondary fires, which can spread the fire in opposite directions. In addition, phenomena like storms or hurricanes (as it happened in 2017, with hurricane Ophelia), will increase the flow of oxygen in conjunction with hot and dry air masses. (Fernandes, 2007)

When considering the climate in the Iberia Peninsula, the north-western portion of the Peninsula can be considered more humid than other regions, which has led to the intensification of the commercial plantation of fast-growing species, such as *Eucalyptus globulus* and *Pinus pinaster*, which only aggravates the problem. (Pastor et al, 2019)

Yet, climatic importance in fires in the Iberian Peninsula is not clear. As an example, in the East of the Peninsula, FWI values seem to be increasing, as it is the fire season length, yet the fire incidence is very low when compared with the NW (Silva et al., 2019).

In addition, only a residual percentage of fires in Portugal have a natural cause (San-Miguel-Ayanz, 2019), and it can be difficult to associate the burnt area of a territory to its climate since these seems to be related to human activities. The relationship is not linear such that the hotter areas have the larger concentrations of burnt area.

With global warming comes an uncertainty about what the climate future could be like. This warming can lead to hot extremes of temperatures in inhabited regions, and depending on the region, it can lead to heavy precipitation, deficit in precipitation or even drought. Yet there are differences between the direct outcomes of an increase of global temperature by 1.5° or 2° by 2100, respectively (IPCC, 2018).

In fact, such scenario has been projected by the Portuguese Institute for Sea and Atmosphere (IPMA) and it can be divided in two scenarios: RCP4.5 and RCP8.5. The first corresponds to a scenario where the radiative forcing is stabilized between 4.5 and 6 W/m^2 after 2100, while the latter corresponds to a scenario where the radiative forcing reaches 8.5 W/m^2 or higher by 2100, and continues to increase for some time (IPCC, 2013). (IPMA, 2015)

For the RCP4.5 scenario, it is possible to observe an increase of the annual mean temperature for Portugal of almost 1° between 2011 and 2040, where the average mean temperature corresponds to 14.4°, while the precipitation levels are very variable, being noticeable a considerable drops of precipitation values between 2011 and 2040, where the mean value corresponds to 966 mm. (Figures 4 and 5)

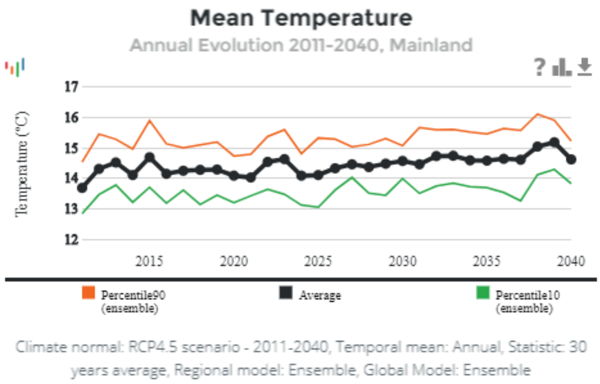


Figure 4: Mean temperature forecast values for 2040, for mainland Portugal – RCP4.5 (IPMA, 2015)

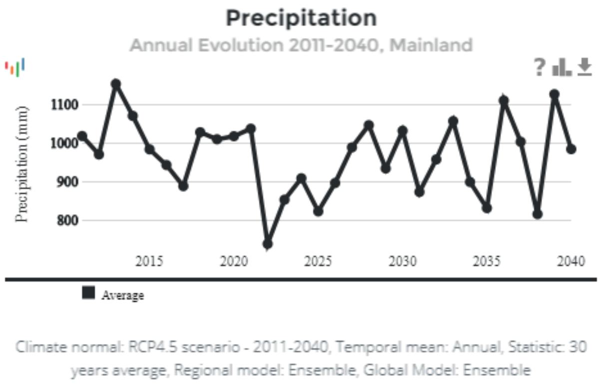


Figure 5: Mean precipitation forecast values for 2040, for mainland Portugal – RCP4.5 (IPMA, 2015)

For the RCP8.5 scenario, it is observable a rise of annual mean temperature from 2011 to 2040 of around 1°, with a mean average temperature of 14.6°. The precipitation values are also quite variable, since there is bigger amplitude of values, when compared with the RCP4.5 scenario, yet the mean annual precipitation value is of 946 mm. (Figures 6 and 7)

Therefore, it seems clear that the future climate of Portugal (at least up to 2040) is going to be hotter and drier, when compared with the reference values of 2011. Yet, when analysing the precipitation for 2011 to 2040, it is also important to identify that there are periods when the precipitation can be higher than 2011 (in some cases exceeding annual mean values of 100 mm), that are followed by sharp decreases in the mean precipitation values. Such situations might create optimal conditions for forest fire events, given the accumulation of fuel that occurred during a wetter period, and as a result of a sharp decrease in the precipitation, the humidity levels of the fuel can be considerably low.

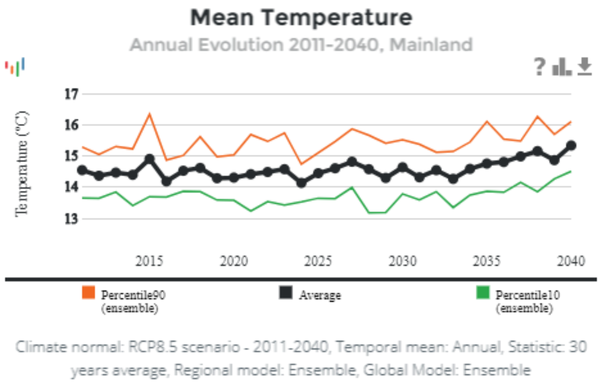


Figure 6: Mean temperature forecast values for 2040, for mainland Portugal – RCP8.5 (IPMA, 2015)

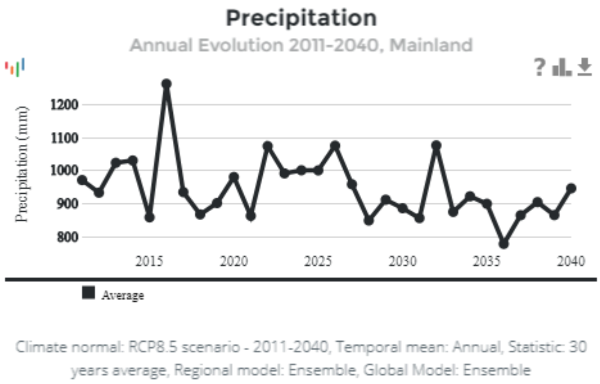


Figure 7: Figure 5: Mean precipitation forecast values for 2040, for mainland Portugal – RCP8.5 (IPMA, 2015)

2.4.3 Topography

Topography is one of the variables that can have a decisive impact on the forest fires. Steep areas can be affected by what is known as the “chimney effect”, when the hot air produced by the fire rises upwards, which can lead to a very fast uphill progression.

The variances of topography can considerably influence the unpredictability of the fire, making it very difficult to control. As an example, South facing slopes are more exposed to the solar radiation, leading to drier and hotter fuel, while North facing slopes are cooler and more humid, leading to a more intense vegetation development, which can increase the fire intensity.

Topography can also directly affect the temperature and wind direction in these regions. Higher regions can be exposed to stronger winds, while narrower areas might funnel the wind, increasing it speed and having a direct impact on the intensity and unpredictability of a fire. (Fernandes, 2007)

However, and given the scale of our analysis, we are not considering topography in the analysis presented in this study.

3. Methods

3.1 Introduction

To ensure that we follow a strategy that is consistent with the scientific method, we are following the "Principal Informational Components, Methodological Controls, and Information Transformation of Scientific Process" (or simply as "wheel of science", as it is more commonly known), proposed by Walter L. Wallace (Wallace, 1971).

The wheel of science is based on cyclical process with four main stages: theory; generalisation (or prediction); experiment and interpretation of experiment. The first corresponds to a hypothesis, that can be formulated via observation or an experiment. The second stage corresponds to the generalisation of a concept to create conditions to test it.

The experiment is the stage where the generalisation is tested, ideally under different conditions, so the scientist can understand what are the possible factors that affect the studied phenomenon. This is followed by the interpretation of the experiment, where new concepts can be developed, and new observations may lead to new understandings of the same reality.

The cycle is closed when the scientist refines the original theory, or in some cases, disproves it completely. Regardless of its outcome, the cycle restarts, either with old or new unanswered questions, that will lead to more generalisations, experiments, and development of new ideas.

The following descriptions of our methodological approach will be divided in two distinct groups: the spatial methods, where we shall describe the processes that were used to extract and process the geospatial related data; and the statistical methods, where we describe the main statistical methods that we have used to achieve our results.

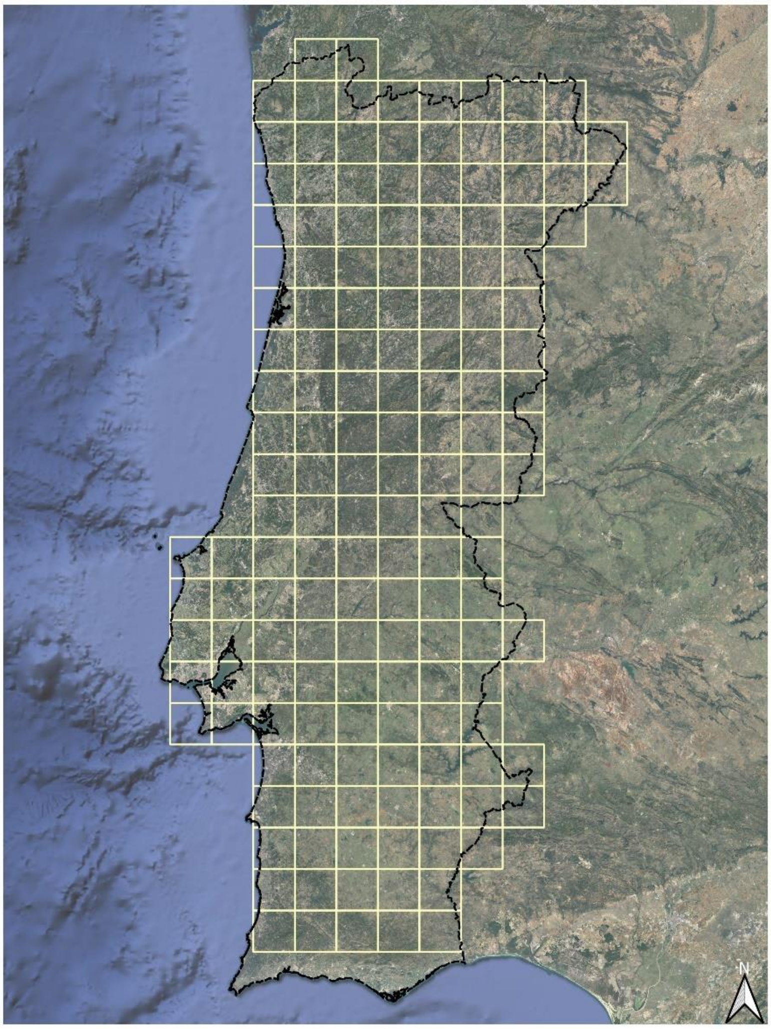
3.2 Geospatial methodology

In order to combine all variables of study into a common frame of work, it was necessary to define a resolution of analysis that would enable an assessment of correlation between forest fires and variables of study, for the period between 1980 and 2019.

Each gridcell contained values for the following variables: Fire Weather Index (FWI) score, population density, tree species dominance (the dominance of Eucalyptus globulus, Pinus pinaster and Quercus suber, both as the cumulative sum of the three and each individual value), and finally the land cover distribution pattern of the area (in this report we have just used the land covers of Forests and Agro-forests). More detailed information regarding these variables and corresponding datasets is provided later in this chapter and in the "Data" chapter.

Studies such as Lehsten et al., 2014 and Archibald et al.,2010, provided us with the initial guide we needed to develop a spatial strategy to tackle the problem. This was based on a spatial grid approach, where each gridcell would represent an area of the territory and it would enclose several variables for that specific location. Since the area of study corresponded to mainland Portugal, it was clear that we would have to use a relatively fine resolution given the size of the country, yet it would have to be coarse enough to allow a meaningful statistical assessment.

It was then decided to adopt a square grid of 625 km^2 as our study resolution (25 km by 25km square grid). Although this corresponded to a much finer scale than the used in referred base studies (Lehsten et al., 2014; Archibald et al., 2010), this proved to allow the necessary diversity in terms of some of the continuous variables such the FWI and population density. (Figure 8)



Coordinate Reference System: ETRS89/TM06 Portugal
1 : 2, 300, 000

Figure 8: Analysis base grid cell

Once all the spatial analyses were concluded, it was imperative to apply more specific statistical analysis to retrieve a meaningful set of results, enabling the understanding of the relation between the interannual variability of forest fires and the different variables.

Such statistical analysis included correlation and principal components, as well as the estimation of the characteristic fire size of the forest fires in Portugal for the study period. This allows to understand what class of fire contributed the most to the total burnt area of a given study area for a given period. (Lehsten et al., 2014).

3.2.1 Fire Weather Index

The Fire Weather Index (FWI) corresponds to a forest fire danger rating, where the high ratings correspond to high danger of forest fire (Wagner, 1987). This index is based on climatic variables such as temperature, rainfall, wind speed and humidity, which are used to estimate a number of indices (fine fuel moisture, duff moisture code, drough code, which are then used to calculate initial spread index and built-up index), resulting in a final fire weather index score.

Since the FWI dataset was our only source of climatic data (although it includes different variables and sub-indices that are of major importance to forest fires), it was imperative to take the best of this data. However, we do not have data regarding the start date and extinguish date for most fires in our database (solely the year), therefore, it was then decided to use the 95% percentile of the daily values of the month with the greatest number of fires, in the temporal range of this analysis (1980 to 2019).

However, since the dataset used to extract such information only covered the period from 1980 to 2015, for the years between 2016 and 2019, it was impossible to perform the same assessment, so the months chosen to represent the years were based on estimations based on the available data

The only exception made was with the year of 2017. In this year, it was decided to use the 95% percentile of months of June and October. This was because this corresponded to the year with largest burnt area ever registered in Portugal, with the highest number of human casualties, there was a collective effort to better understand what led to such circumstances, resulting in the production of two dedicated reports for the events that happened in both June and October. (CTI, 2017; Guerreiro et al, 2018).

Such approach would enable us to tackle two obstacles to our analysis. On the one hand, by selecting the month that would represent each analysed year, based on the fire occurrence for each year, it was possible to eliminate the outlier situations where, because of an odd combination of factors, the higher index values would concentrate in months with less fires.

On the other hand, criteria such the use of the mean values for the year would certainly not allow for the estimation of meaningful statistical correlations, since the amplitude of the maximum and minimum values could be lower, and therefore not allowing a statistical correlation. Moreover, and given the climate of Portugal, winters can be quite wet and not prone to the proliferation of fire, which could defeat the purpose of the use of such a dataset.

3.2.2 Population Density

The 25 km^2 grid strategy would also be beneficial to accommodate the population density continuous values. Since most of forest fires occur in remote areas, where the population density per km^2 would be 0, only by understanding the wider context would it be possible to achieve a more meaningful correlation between the fires and the population density.

Because there was a considerable exodus of population from the most interior and rural areas of the country to the more urban and coastal areas of this territory, it was important to include such variability across the years of analysis. As was previously described, although the used dataset would only cover the period from 2000 to 2019, it was possible to retrospectively estimate the values from 1980 to 2000 based on statistical studies on the matter at hand (Albergaria, 1999).

However, it can be argued that the resolution used for the population density could have been adjusted for this study, since squares of 25 km^2 could include both rural and urban areas, where the population density can be substantially different, resulting in some diluting of the population density values.

However, we are very comfortable with the current resolution and the results it produced. Other resolutions were tested and the values for this variable did not vary substantially, which lead us to believe that a 25 km^2 is not only well adjusted to the other variables it is also well adjusted to the population density. Ultimately, there must be a compromise between the detail of analysis and the performance of all variables within a single frame of work, and we believe that this was achieved.

3.2.3 Tree species and land cover

While the grid had very interesting results for the FWI and population density variables, this could not be directly implemented when it came to the assessment of tree species and land cover for these gridded areas.

It was decided to include the top 3 most represented species in the mainland Portuguese forests, that correspond to *Eucalyptus globulus*, *Pinus pinaster* and *Quercus suber*. Together the area dominated by these species corresponds to around 70% of the total forest area (ICNF, 2015)

For the 3 tree species included in the study, there was an important obstacle on how the continuous variables were to be presented for each grid cell, since the dataset would represent the percentage of dominance of each tree species per km^2. Since our smallest unit of analysis was the hectare, it was decided to convert the original dataset to hectares (100 by 100m grid), and sum the proportion of dominance values of the three species, resulting in a composite that would be the total dominance of all three species together. As a result, the final composite had considerably higher values than any of the three individual datasets, mostly for areas where the three species were present.

The individual species grid data was also used, so it was possible to understand how each individual fire in our database would affect each of them. This allowed us to later estimate the characteristic fire size for each species.

For the land cover dataset, the approach was similar, despite the fact that this dataset corresponded to a discrete variable, based on the land cover type. It was decided that only the land covers that were related with forested areas would be integrated with forest fires would be included in study.

It was then decided to exclude all areas that were agricultural, except for the agro-forestry areas. The rationale behind this is related to the fact that agricultural areas can have quite distinct characteristics from forested areas, so the parameters that were created to estimate the fire weather index (the only climatic variable used in this study) would not necessarily apply in agricultural areas.

Due to the type of species that are produced in the agricultural areas, which would have an impact on the volume of fine fuel present in those areas, to watering techniques that could maintain more constant wetness indices throughout the year, and even the management of those areas, preventing situations and behaviour that could lead to more fire prone conditions, all these factors make these areas quite different from forest in the context of this study.

However, we have decided to maintain an exception to the agro-forestry related areas since these are the main areas where most *Quercus suber* are present in the Portuguese territory. As previously mentioned, this species in the only source of raw material for the cork production, which corresponds to around 1% of the Portuguese exports. (APCOR, 2018)

Although most of these areas have distinct characteristics from most forests, to exclude these areas would mean to exclude an important fraction of tree species in the territory, which could exclude an analysis of the impact and the relation of fires with these species. Therefore, it was decided to include these in the study, with the caveat that these might have distinct characteristics from most of the forested areas in Portugal.

3.3 Statistical methodology

To answer our research question, it was necessary to extract meaningful statistical conclusions from the spatial data that was collected, and it was achieved using R. This programming language is very popular amongst the academic and scientific community since its completely free and a very powerful statistical computational tool.

Using such a tool enabled us to better explore the statistical characteristics of our spatial data, by understanding the correlation between the burnt areas and the different variables, as well as to understand the statistical importance of each variable to the value of each burnt area. In addition, it allows the plotting of the data based on principal component analysis, which leads to possible data clustering. This can be important to help us understand what values are more related with a uniform general category (or categories) within the analysed data.

It was also possible to estimate the characteristic fire size for the study period. To achieve this, it is imperative to bin all fires according to their sizes in a logarithmic scale, where the resulting mid-points of each bin (or the mean fire size of the bin) as well as the number of fires per bin are multiplied, resulting in a total burnt area per bin. Please note that we have used the mean fire size of the bin as $m_k = \exp{(\xi_k)}$, where ξ_k corresponds to the mid-point of kth interval in a log scale. Lastly, a non-linear model is fitted to this normal distribution, based on the parameters μ and σ, as well as scaling factor based on the sum of total burnt area of the characteristic fire size. (Lehsten et al., 2014).

Such analysis allowed us to understand what is the best fire size that better characterizes a given perspective of analysis. This was firstly applied to the general dataset, enabling us to better comprehend what fire size best characterized all the fires present in the database. However, given such strategy can be very versatile and be adjusted to different analysis, it was decided to expand this exercise to other forest fire related analyses.

Therefore, the characteristic fire size analysis was applied to the fires once these were aggregated by its respective decades, based on the year these events occurred, which can lead to interesting and very necessary discussions regarding past actions and what should drive present and future forest management strategies.

This strategy was also applied to the FWI values present in our study, which enabled us to better understand the complexity of the relationships between this variable and total burnt area between 1980 and 2019. Lastly, the same exercise was performed to assess how these fires affected *Eucalyptus globulus*, *Pinus pinaster* and *Quercus suber*, and how can the characteristic fire size can be described for fires affecting these individual species.

3.4 GIS processes and R integration

As it was previously referred, the methodology used in this work was based on the studies Lehsten et al., 2014 and Archibald et al., 2010, where a spatial type of approach was used to analyse the data. GIS applications (such as QGIS or ArcGIS) were then crucial to allow the initial processing of the data as well as the creation of a suitable data structure that would allow further statistical computations.

Since this work used several data sources it was decided to adopt Transverse Mercator (TM) as the project projection, and the European Terrestrial Reference System 1989 (ETRS89) as our main coordinate reference system. It was then needed to convert all data sources with different projections and/or coordinate systems to the referred ones, as well as to ensure these were clipped to the boundaries of our study area (mainland Portugal).

Once the grid was laid across the study area, each gridcell was then numbered with a unique identification number, so this could be identified regardless the year of analysis. Since this was a study that covered a period of 39 years, it was crucial to keep the same geospatial structure (gridded area), so the data would represent precisely the same area each year, enabling comparative analysis, therefore it was decided to replicate the same grid for each individual year of study.

Once the grid was established, the data could be adjusted to it. Our only vector data source was the yearly burnt area between 1980 and 2019, and it was imperative to overlay the grid over these shapes, enabling to understand the size (in ha) of the burnt area, per gridcell. All the remaining datasets were raster based, which led to two different processes: for datasets such as the FWI and population density, an initial processing was needed to ensure that the data was adjusted to existing framework before it could be extracted to its corresponding year grid. For the other datasets (tree species and land cover) it was decided to convert these to a size that would enable further comparable analysis (ha) to later apply the “Zonal Statistics” process. This enable us to count the number of gridcells or sum the values of the tree species and land cover datasets, by each individual gridcell from every single year specific grid.

These processes then allowed us to have the data in a format where we could have all the variables values, for the different years, by individual gridcell of analysis in a single document. This was then exported to R, where all the statistical data was analysed and it was possible to compute the characteristic fire size model, as well as other statistical values of analysis such as correlations, data clustering, relative importance and principal component analysis.

4. Data

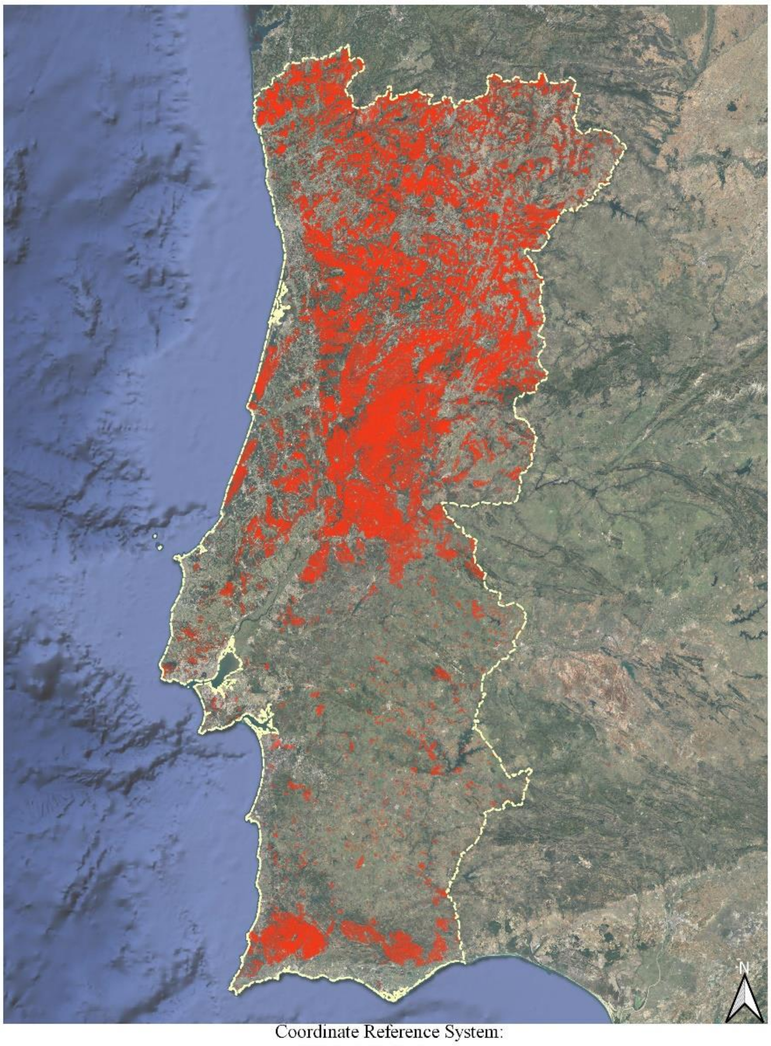
To have a better understanding of the complex phenomena of forest fires in mainland Portugal, one needs to be tactical when it comes to data collection. Digital data is being created at an unprecedented fast pace; therefore, it is crucial to understand our data sources, and how these can be accurate and reliable.

This analysis uses 5 distinct datasets, including Burnt Areas, Fire Weather Index, Population Density, Tree Species Density and Land Use.

All the datasets were adjusted to the ETRS89/ Portugal TM06 coordinate reference system (EPSG: 3763). The datum of such reference system corresponds to the European Terrestrial Reference System 1989, and its ellipsoid is GRS 1980. This is a Transverse Mercator projection type, its unit of measure is the meter, and it is mostly applied to the Portuguese territory, with its Prime Meridian selected to be Greenwich (EPSG.IO).

4.1 Burnt Areas and Fire Occurrences

To analyse forest fires in mainland Portugal, it would be imperative to access data that could describe the fires. The Burnt Areas dataset was retrieved from geographic data portal from the ICNF (ICNF IDE, 2021), which is the official institute that produces the national forest inventories for Portugal and is one the responsible organisations to ensure that the different nature conservation related strategies are put in place by the different region and local institutions. (Figure 9)



Coordinate Reference System:
ETRS89/TM06 Portugal

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Figure 9: Burnt area in mainland Portugal, from 1980 to 2019

This dataset corresponds to the yearly cartography of fires that occur in the Portuguese territory, ranging from the years of 1975 up to 2020. This cartography is mixture of in situ surveys of the burnt areas, with older descriptive records of burnt areas, as well as satellite imagery analysis. (ICNF, 2020)

This dataset corresponds to the most complete assessment of the burnt areas in Portugal since 1975, however, it is possible for every single fire event to be registered in the database, as well as not being possible to have access to times and dates of fire start and extinguishing for most of the years. It was crucial to find a reliable source of data regarding the burnt areas, since this corresponds to the base of all analysis throughout this work, and we believe that this dataset is up to that standard, even though we assume that it might lack some accuracy in earlier years.

It was also possible to retrieve a distinct dataset that focused on the fire occurrence (from 1980 to 2015), rather the burnt data. Despite the fact our analysis is solely based on the burnt area, this revealed itself to be an important ancillary dataset to have when analysing the forest fires issue in mainland Portugal, given its detail of information that it provided to the user. (ICFN)

4.2 Fire Weather Index (FWI)

Environmental conditions are crucial to the behaviour of forest fires, and in some situations, these can correspond to the direct cause for the start of fire events.

The FWI dataset was retrieved from the Global Fire Weather Database (GFWED) developed by NASA. (NASA, 2020). This global dataset was based on the Canadian FWI system, and its has been driven by different Global Modelling and Assimilation Office (GMAO, 2021a) related products, such as MERRA-2 (GMAO, 2019) and GEOS-5 (GMAO, 2021b), amongst other data sources. The data collected for GFWED dates back as 1980.

This dataset was our single source of environmental related data, since this model was purposely developed to understand the fire vulnerability of an area, which includes a wide variety of variables and indices, that result in a fire danger index (Figure 10).

Such variables correspond to temperature, rainfall, wind speed and relative moisture, which serve as base to understand three distinct indices: fine fuel moisture, duff moisture and drought. Once these are determined, these will be used to understand a second set of indices related with fire behaviour – the initial fire spread and build up index. Finally, these allow the creation of a last index, the fire weather index, which can be used to identify areas that are more prone to fire. (Wagner, 1987)

Since this is a model that was built for the Canadian territory, there was a possibility that such approach could not be applicable to the Portuguese territory. However, there are countless instances of studies that used this specific model, across very different geographies and contexts, whose results proved to be quite positive.

As some examples, J. de Groot et al., 2006 understood that high values of fine fuel moisture content (FFMC were directly correlated with a dramatically increase of fires, and the use of initial spread Index (ISI) could be used to understand the difficulty in controlling fires in the country.

When applied to Slovenia, it was possible to understand that the fire danger classes produced by this model were consistent with fire activity. (Šturm, 2011). In Greece, the FWI also performed quite positively since it was possible to understand it was highly correlated with fire occurrence, and moderately with burnt area. (Dimitrakopoulos et al, 2010).

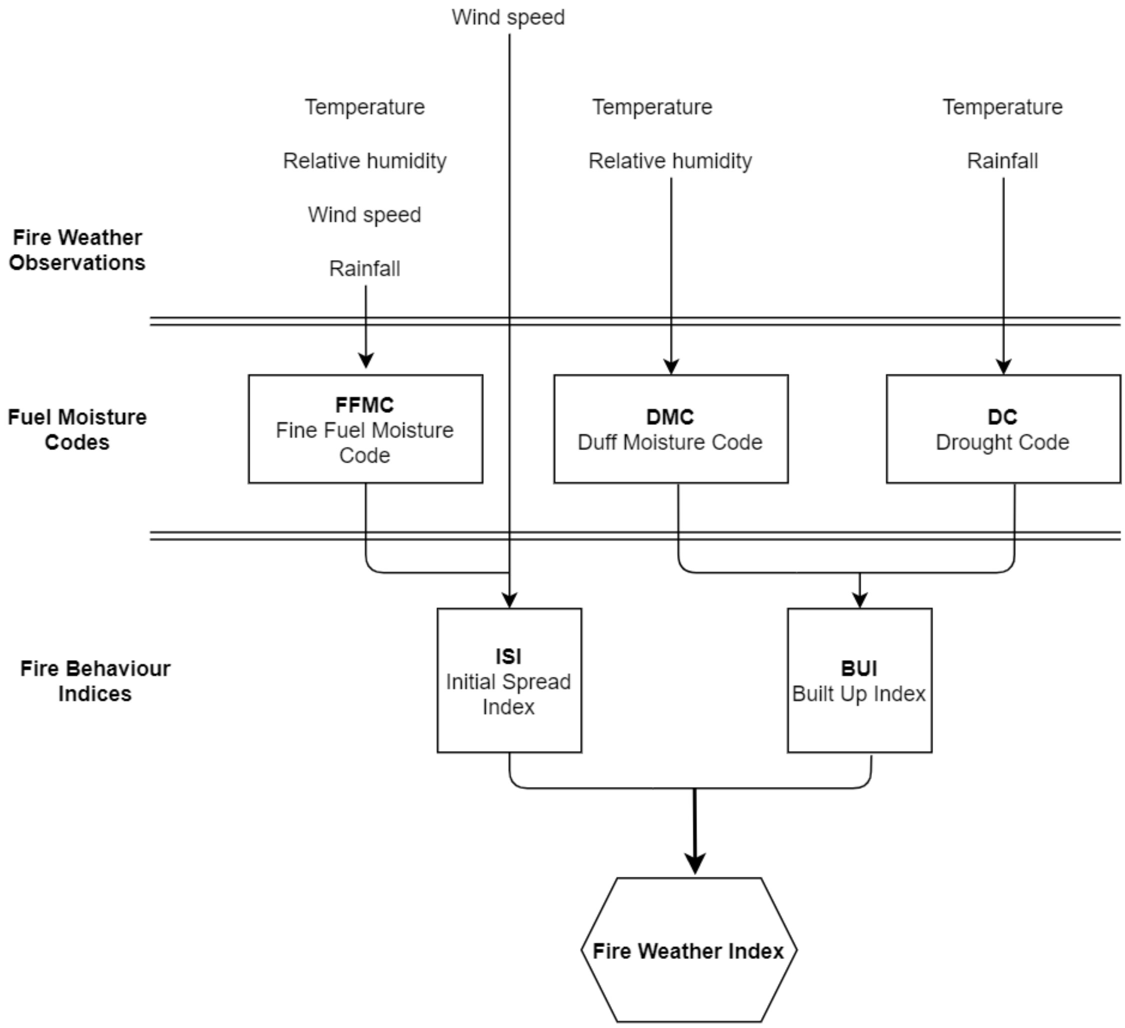

Figure 10: Fire Weather Index model

The FWI was also previously successfully applied to the Portuguese territory, where it was possible to produce a good correlation between the FFMC and different tree species, as well as the ISI and rate of spread. It was also possible to create a calibration for the FWI values across the territory, based on number of fires and burnt area (Viegas et al, 2004).

The FWI continued to perform well in the Portuguese context when, in a different study where ISI and BUI were treated as independent variables in fires affecting *Pinus pinaster,* the first variable accounted for 84% of the rate spread variation. Therefore, it was possible to associate the fireline intensity with the fire weather index model, creating a dedicated fire danger class system for areas where *Pinus pinaster* is the predominant species (Palheiro et al, 2006).

4.3 Tree Species

As it was previously mentioned, the predominant species in the Portuguese forest correspond to *Eucalyptus globulus* (26%), *Quercus suber* (22%) and *Pinus pinaster* (22%) (IFN, 2015), however, and taking the year of 2017 as a reference, 90% of burnt forested area corresponded to *Eucalyptus globulus* and *Pinus pinaster*, with distributions of 39% and 50%, respectively.

Therefore, it would be interesting to understand how the areas where these tree species are most present would relate with forest fires in Portugal, and if there is any statistical evidence that can be used to support a future forest management strategy.

It was then decided to use the very detailed European forest dataset provided by the European Forest Institute, developed by Brus et al., 2011 This is a dataset that displays twenty tree species groups across Europe, based on the NFI of eighteen countries, with a resolution of 1km. This product enabled us to have a detailed distribution of these three species in continental Portugal, where the percentage of dominance of each tree species was present at a grid cell value. (Figure 11)

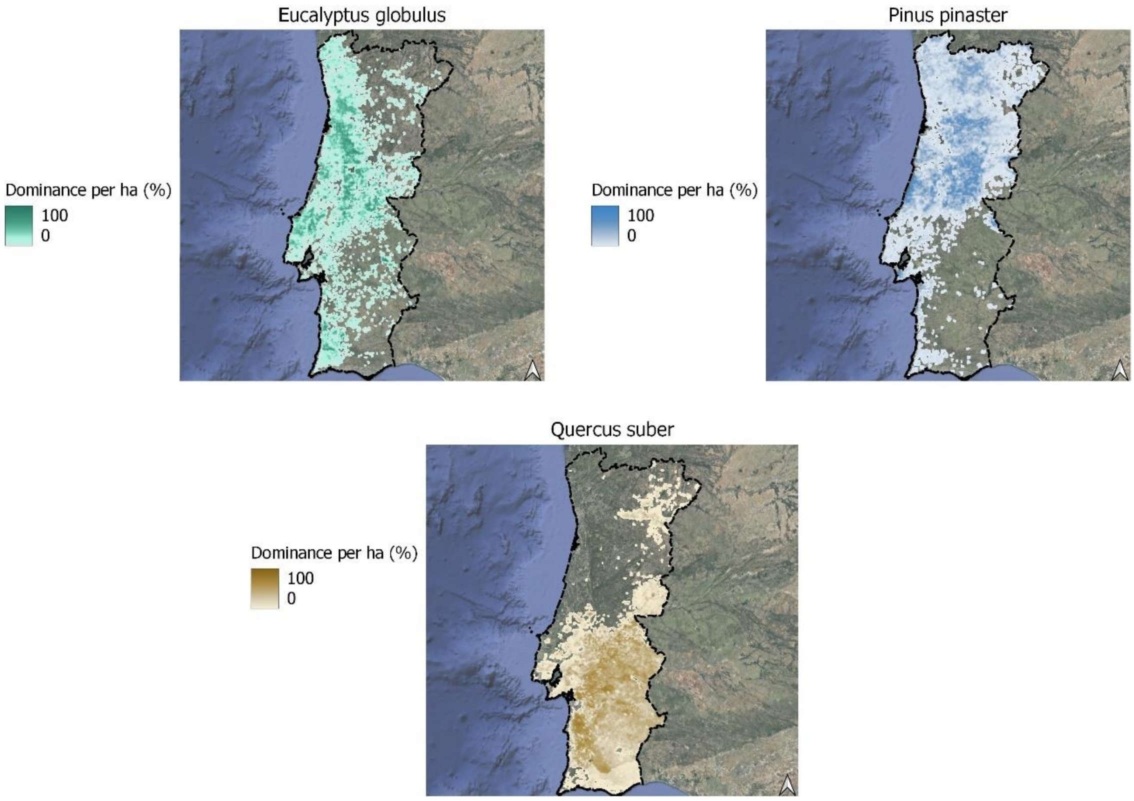

Figure 11: Distribution of tree species across mainland Portugal

4.4 Land Cover

The impact of the fires in Portugal is expected to be closely related with the land cover of the territory burned. Therefore, it would be interesting to examine the areas that could be more prone to fire and analyse the relation between this and forest fires in Portugal.

The land cover dataset used was the Corine Land Cover dataset, which is produced within the Copernicus project. This product presents an interesting temporal range of analysis, from 1990 to 2020, which enables the user to understand the changes in the land use of the studied territory (Copernicus, 2020).

Such an analysis was made for the Portuguese territory, and although there were changes in the land cover over the last 30 years, there were no substantial changes in terms of the land cover when it comes to the forested areas. As mentioned before, there was a substantial change in the way agricultural and forested areas were used in Portugal from 1974 onwards, where a considerable number of hectares of land were abandoned and therefore not managed (Beighley and Hyde, 2018), but there was not a severe transformation in the land cover.

Thus, it was decided to use the most recent land cover dataset, not only because there was a necessary evolution in the technology and methods to create more accurate representations of the land cover, but also because the total burnt area trends suggest that these have been increasing over the years.

By analysing the various land cover classes in the product, it was clear that only two would be pertinent to the scope of this analysis, corresponding to Forest and Agro-Forested classes.

The rationale behind is not related with the fact that there are no fires within urban or industrial areas (as an example), but these fires have always an anthropic factor. Also, our environmental variables (FWI) are closely related with fire behaviour in a natural environment, so to consider other areas that do not have the characteristics that are included in the FWI model would make any analysis meaningless.

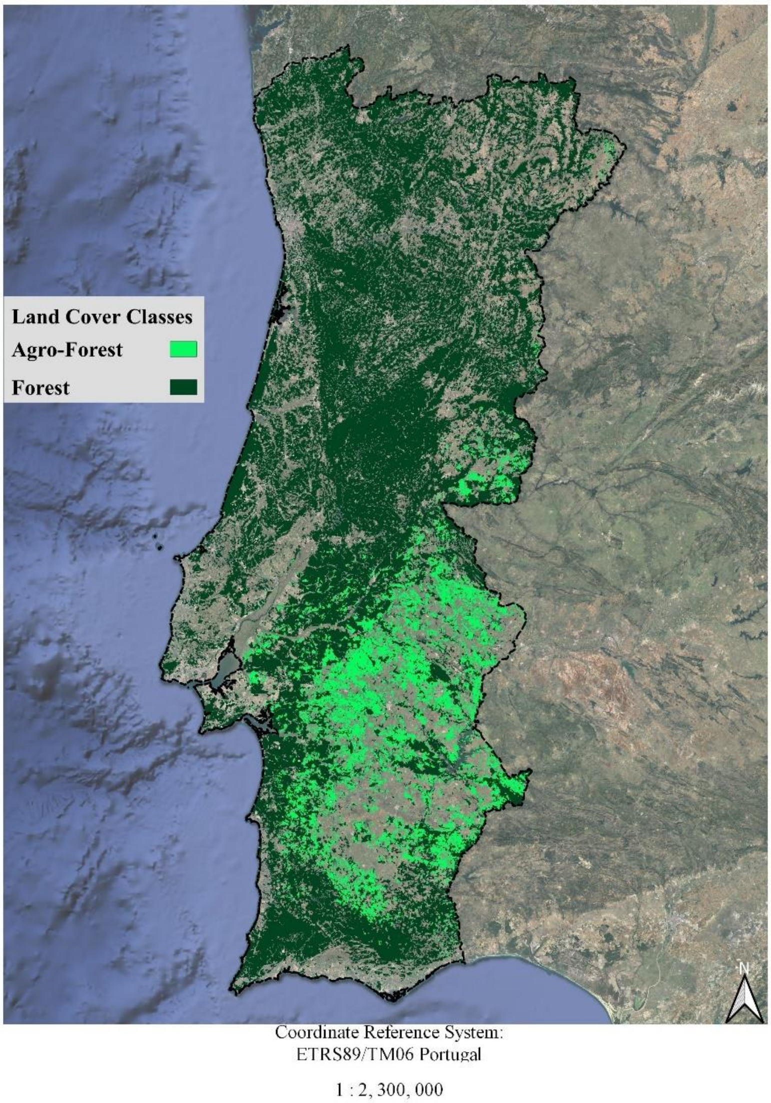

Figure 12: Land cover in mainland Portugal (forest and agro-forest distribution)

4.5 Population Density

Since there is a connection between forest fires, society, and its transformations, it would be interesting add an anthropic dimension to this analysis. For that effect, it was decided to include a population density dataset that would give us a perspective of not only the current population density, but also its evolution in recent years.

Therefore, population related data was collected from the World pop online platform, which specializes on the creation of global population related datasets. The method used to derive the data are based on land cover analysis, as well as by a random forest regression-based mapping approach (Worldpop, 2021).

However, this dataset only went as far back as 2000, and given the profound social transformations since the 1974 with the Democratic Revolution, as well as the rural exodus that was felt across Europe during the 20th century, it was decided to estimate the values of previous years based on known population density values for the different counties of Portugal (Albergaria, 1999). This way, it would enable us to analyse the population density and its impacts on forest fires with a dataset in a fashion that could accurately describe the gap between 1980 and 2000. (Figure 13)

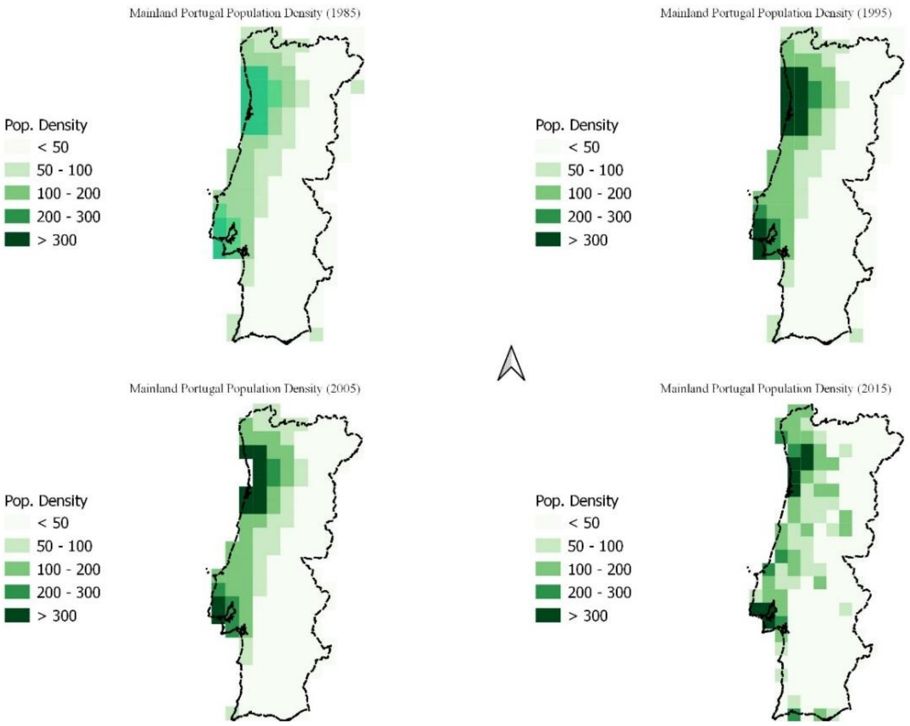

Figure 13: Population density in mainland Portugal, for the years of 1985, 1995, 2005 and 2015

5. Results

The current section is divided in two-subsections. The first section corresponds to the relationship between the burnt area in mainland Portugal between the years of 1980 and 2019 and variables including FWI, population density, tree species, forested areas and agro-forested areas.

The second subsection describes further analysis with respect to the total burnt area, namely with the use of the characteristic fire size approach. This will allow us to understand if there are any trends based associated to a specific feature, such as decadal distribution, tree species or FWI specific values.

5.1 Burnt area and relation with variables of study

The fire database used in this study comprised of 4543 fire events between the years of 1980 and 2019, varying from 0 to 38,000 hectares. In 2017, and for the first time since fires were recorded in Portugal, the total burnt area reached the 500 thousand hectares. Similar sized fires can be identified for the years of 2003 and 2005, yet these did not surpass a total burnt area of around 450 thousand hectares (Figure 14).

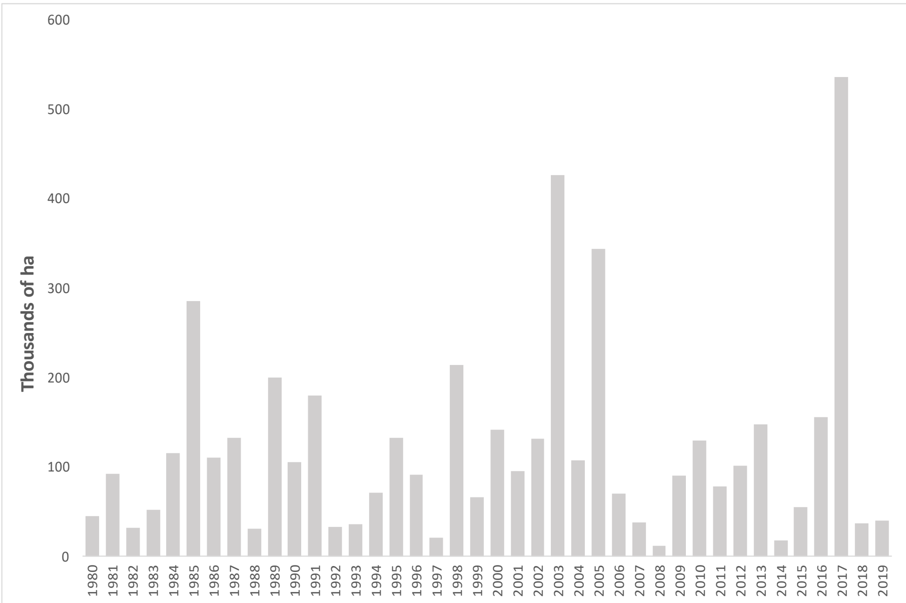

Figure 14: Total burnt area per year, between 1980 and 2019, in mainland Portugal

There is not a clear linear trend between years and burnt area size. It was decided to apply a linear model to the dataset based on these two variables, however, this was not suitable for the data provided, given the very high p-value (0.47), as well as the small multiple R-squared (0.0014) and adjusted R-squared (-0.012). Therefore, and despite the fact that from 2000 onwards its possible to observe increasingly higher peaks when it comes to total burnt area, there is no linear growth trend.(Figure 15)

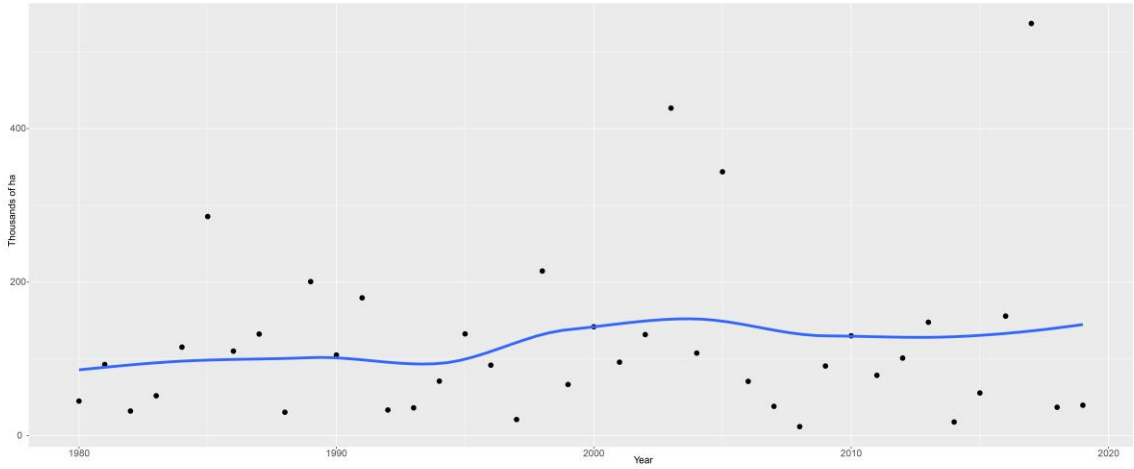

Figure 15: Non-linear behaviour of burnt area per year, between 1980 and 2019, in mainland Portugal

When analysing the data in terms of decadal burnt area values, it is possible to understand that, again, the behaviour is not linear. When comparing the total values for the decades of 1980 and 1990, the total value of burnt area for the latter decreased by 15%, however, it is during the following decade of 2000 that the biggest decadal burnt area can be observed, where it has increased 35% when compared with the value of the decade of 1990s. The last decade of study beginning in 2010 had a smaller burnt area when compared with the previous decade, yet it includes the record burnt area year of 2017. Although the increase growth oscillates between positive and negative growth, there is a growing trend of decadal burnt area. (Table 4, Figure 2)

Table 3: Decadal total burnt area in mainland Portugal

Decade	Burnt area (ha)	Increase rate
1980 - 1989	1,096,377	
1990 - 1999	952,047	-15%
2000 - 2009	1,458,716	35%
2010 - 2019	1,300,382	-12%

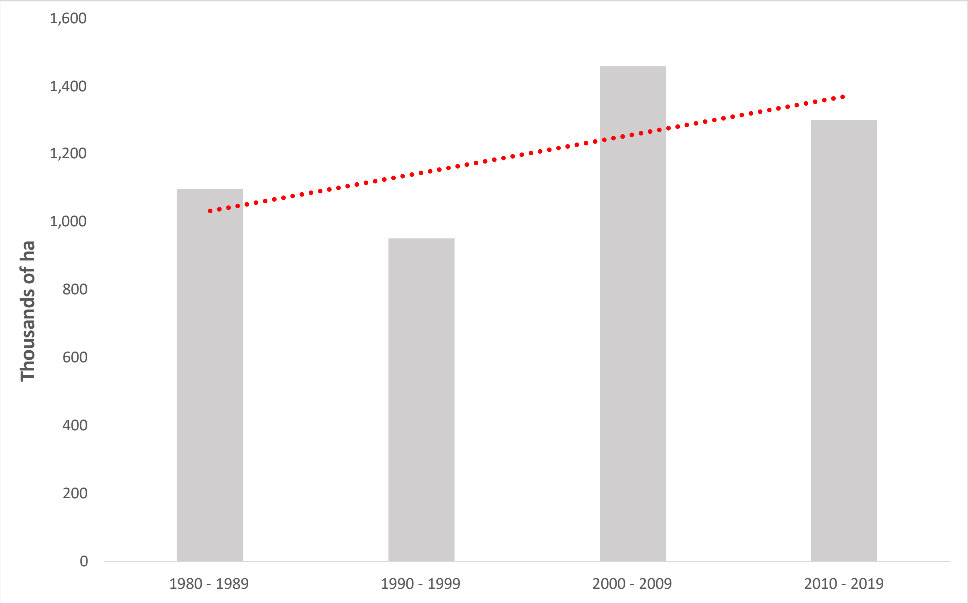

Figure 16: Burnt area per decade in mainland Portugal

As described above, the phenomenon of forest fires is a very complex subject with a wide variety of factors that can contribute for its fire spread and fire intensity, which have a direct influence on the total burnt area of a given fire event. In this study we are not going to analyse the influence of some of these factors in specific fire behaviours (however such analysis can be found in Fernandes, 2007; Fernandes, 2009; Fernandes, 2019; Nunes, 2019, amongst others), but rather look at the general phenomenon of forest fires in mainland Portugal, and how this correlates with factors such FWI, population density, tree species, forested areas, and agro-forested areas (Figure 9 and 17).

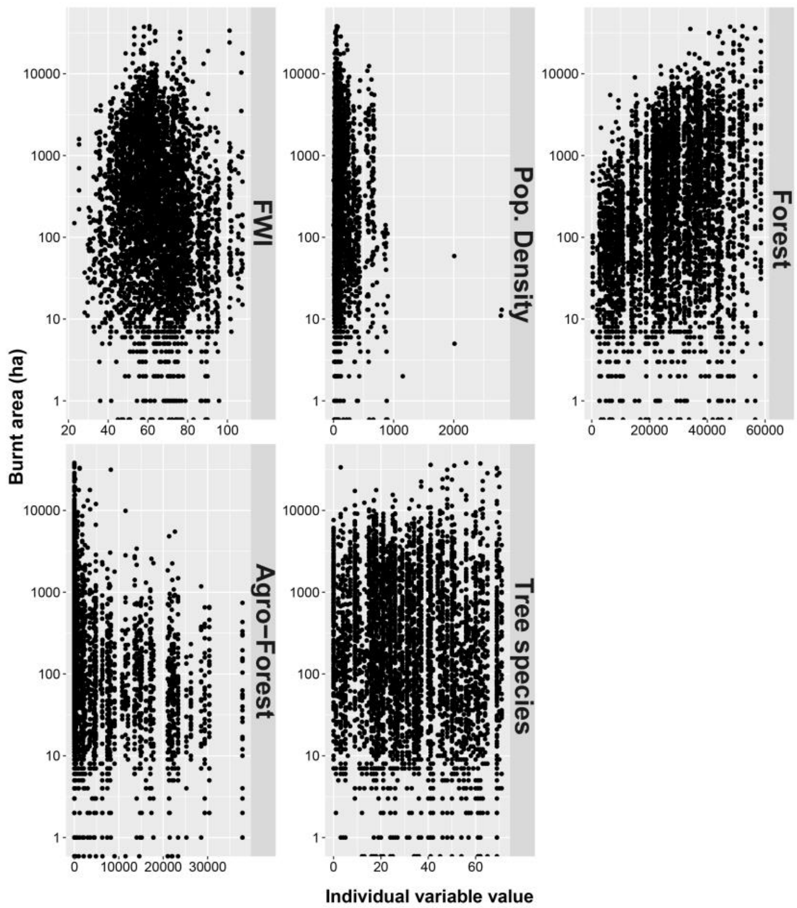

Figure 17: Individual burnt area plotted against all other variables

As it observable in Figure 9, burnt areas have been mostly concentrating on the North and Centre of the territory, where the north-west and central regions seem to be the most affected by forest fires during the study period. It is also important to note that such burnt areas are also present in the most southern areas of the country. There is, however, a distinguishable difference between the north and the south of Portugal, since an important portion of what can be considered the central south and south of the country has been considered less affected by fires when compared to north.

When analysing the plot that describes the position of each fire event and its burnt area against the corresponding value of each factor considered for this study (Figure 17), it is perceptible that the relation between all the variables considered is complex. In visual terms, the relation between the burnt area and population density seems to be most straightforward to understand, since most fire events with disparate associated burnt areas seem to occur in areas with small population density. This is somewhat expected since bigger forested areas do not usually include big communities, yet the unmanaged growth of forests over once agriculture related used areas certainly adds some complexity to this phenomenon. (Mendes, 2017)

A similar visual assessment can also be made for relation between burnt areas and the agro-forested areas, since most fires seem to occur in areas where this specific land-use type seems to be less present. In fact, most of these agricultural forests are present in Alentejo region, which coincides with the area of the territory that seems to be the least affected by forest fires during the study period.

For the remaining factors (FWI, Forested areas and Tree Species) this visual assessment is less clear, since the burnt areas seem to spread considerably over the range of each individual factor's value. For the FWI, it appears that the fire events that resulted in higher burnt areas are located in areas with relatively small index values when assessing the entire range affected by these fire events. The opposite seems to be visually perceptible for the forested areas, where fire events that resulted in larger burnt areas seem to occur in areas with bigger forested areas. For Tree Species, thought, there is no visual feature that can be inferred from the plot.

When assessing the correlations between all variables and the burnt area, there is a strong positive correlation with forested areas and a negative correlation with agro-forested areas. The remaining variables present low correlation values (between -0.01 and 0.04), which seems to indicate that there is no significant correlation between the burnt area and such variables. (Table 5)

Table 4: Correlation and P-values between Burnt area and all other variables

Variable	***R***	**P-value**
FWI	-0.04	0.002
Population Density	-0.07	0.625
Tree Species	0.03	0.024
Forested Areas	0.26	0.000
Agro-forested Areas	-0.17	0.000

The relative importance of each variable to the burnt area presents a similar result, where forests are considered the most important factor the burnt area between 1980 and 2019, followed by agro-forested areas. We interpret the importance of the agro-forested areas to the burnt area with the lack of fires in areas where this land cover is dominant, which is supported by the correlation values.

Lastly, FWI, population density and tree species seem to be the least important factors to the burnt area in mainland Portugal for the study period, which is also backed up by the correlation results previously presented (Figure 18).

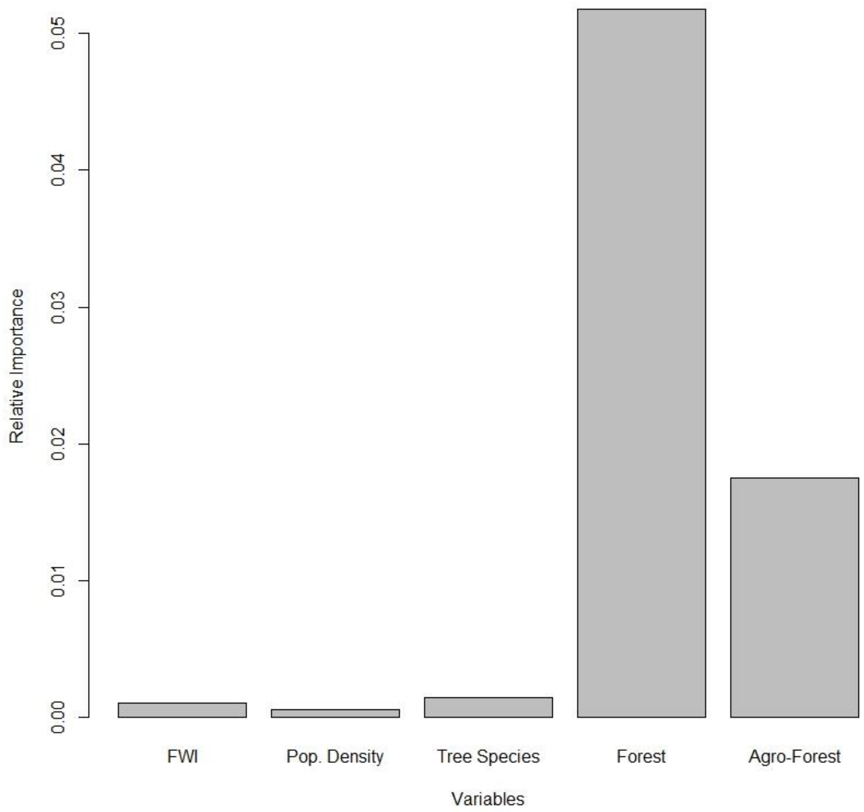

Figure 18: Relative importance of all variables to the burnt area in mainland Portugal

By doing a principal component analysis of the results it allowed us to confirm what the previous correlation and relative importance seem to be showing, with an exception for tree species. In this case, both forests and tree species factor seem to be the most influential variables to burnt area (BA), since these are closer to it. The remaining factors are considerably further away when compared with forested areas and tree species, which can be interpreted as being less influential to total burnt area. (Figure 19).

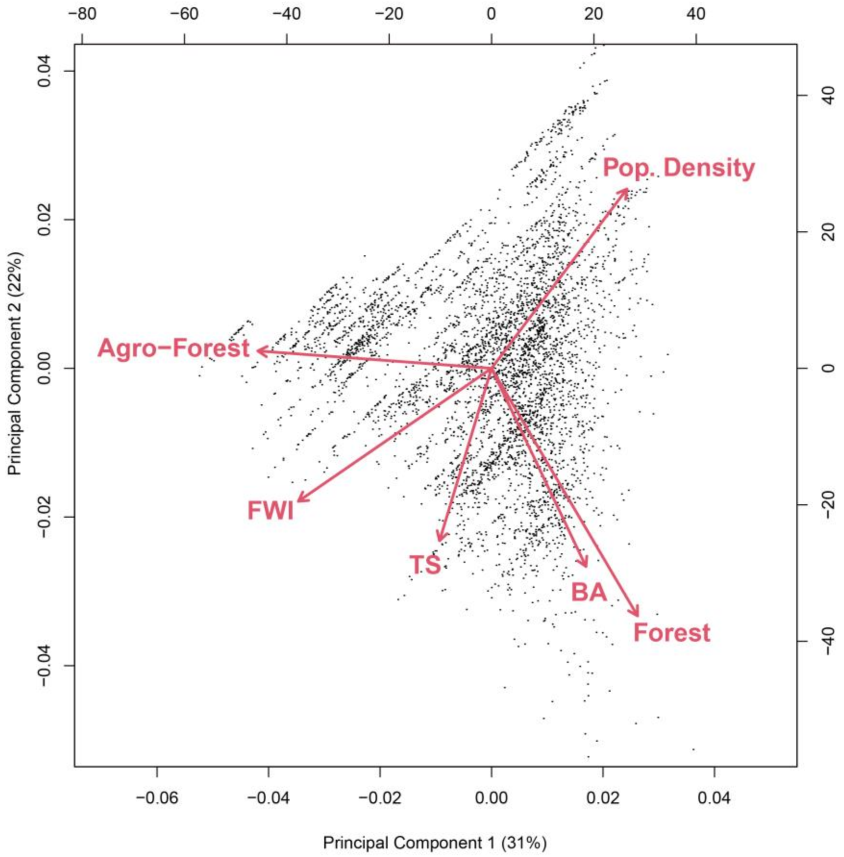

Figure 19: Principal component analysis between the burnt area and all other variables

It was decided to assess the direct impact of *Eucalyptus globulus*, *Pinus pinaster* and *Quercus suber* on the total burnt area between 1980 and 2019, and it was possible to determine that *Eucalyptus globulus* and *Pinus pinaster* burnt areas correspond to around 46% of the total burnt area for the study period. (Table 6)

Table 5: Burnt area per tree species, between 1980 and 2019, for mainland Portugal

Species	Total Burnt Area (thousands of ha)	Percentage of total burnt area
Eucalyptus globulus	1,395	28.40%
Pinus pinaster	843	17.10%
Quercus suber	151	3.10%

Given the obtained results, it was decided that clustering the data between the burnt area and all individual factors could offer additional assurance of the obtained results. This was mostly related with the relation between burnt areas and FWI, since all results were pointing to a meagre relation between these two phenomena. A k-means clustering was then applied to the dataset, dividing this into two separate groups ($n = 2$) (Figure 7).

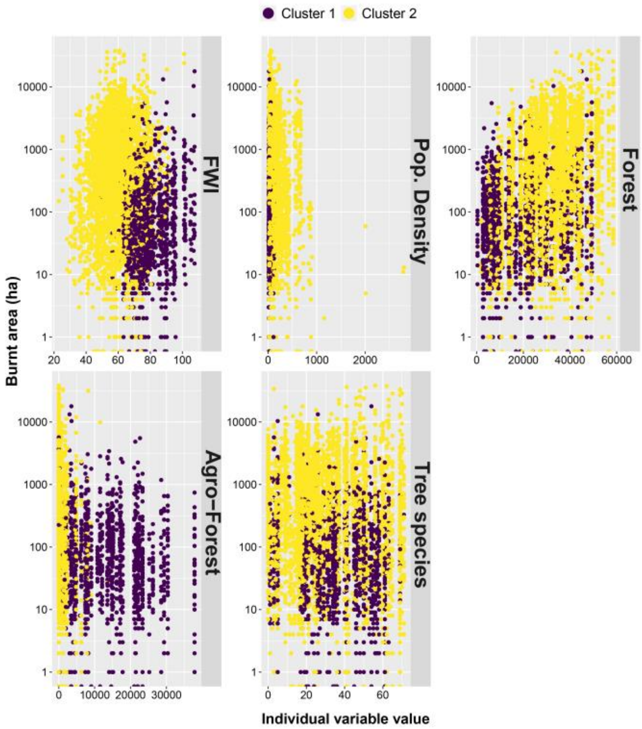

Figure 20: K-means data clustering between burnt area and all other variables (n=2)

This data clustering exercise based on the figure analysis did not, however, show any noteworthy results when it comes to identifying groups or trends that other means have failed to do. Yet, in the burnt area and FWI clustering, an area between the FWI values of 60 and 100 was highlighted, where the burnt area seems to be lower when compared with FWI values below 60. This was somewhat unexpected, since the higher the FWI value is, the more likely it is for fires to develop, yet the reducing the complex phenomenon of forest fire to this simple statement can certainly lead to an incomplete analysis of this conundrum.

5.2 Characteristic fire size analysis

Forest fires in Portugal vary quite substantially in terms of magnitude when it comes to the resulting burnt area, as it does in terms of the tree species that this affects, or even in terms of its spatial and temporal scale. Given such high variability in different dimensions, it would be interesting to apply the concept of characteristic fire size (CFS) to our study case, since this allows us to understand what fire size class contributes the most for the total fires of a given angle of analysis (Lehsten et al., 2014).

By applying this concept to the entire dataset, it is noticeable that the characteristic fire size is located between the logarithmic fire classes 8 and 9, more specifically 8.36 (which correspond to around 4272 ha). This means that the fires that better describe the spatial fire regime in mainland Portugal between the years of 1980 and 2019 were not the mega-fires that resulted in a burnt area of more than 10 thousand hectares in a single fire event, but rather the smaller ones that produced a burnt area of around 4 thousand hectares. Such a statement is somewhat expected, since fires such as the ones observed in 2003 and 2017 are considerably different from the mean fire size for the country (Figure 21).

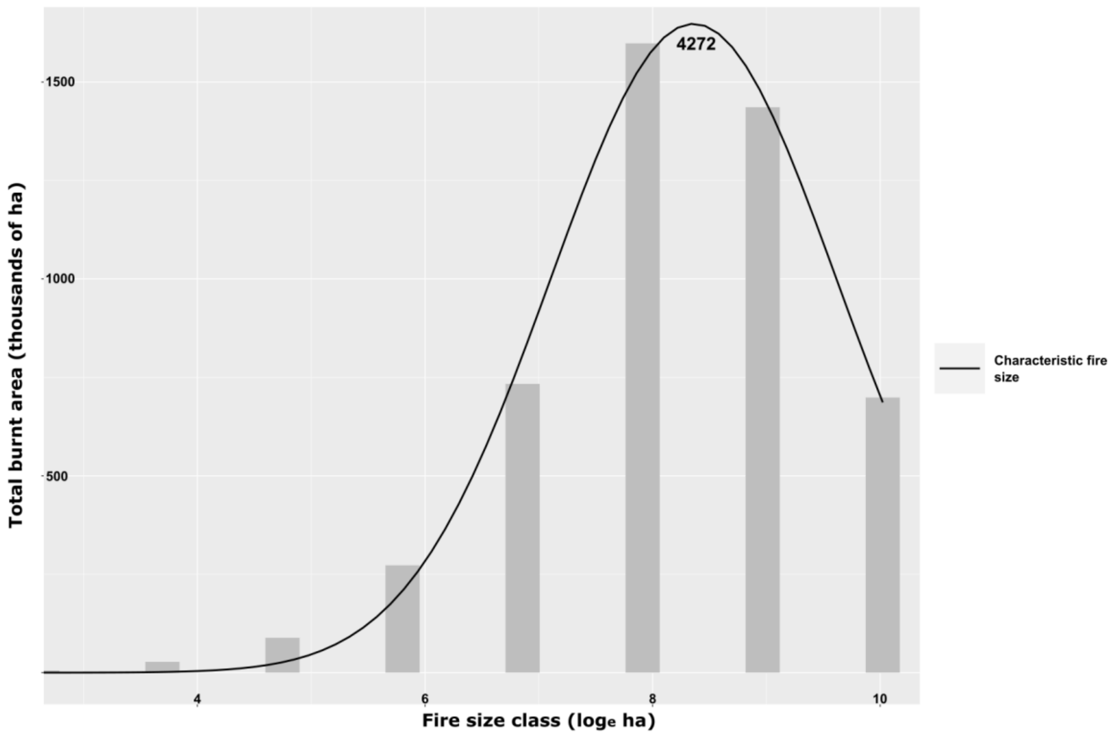

Figure 21: Characteristic fire size for mainland Portugal, for the period between 1980 and 2019

As previously presented (Figure 16), there is an increase of decadal burnt area from the decade of 1980 until 2010, where the 2000s are the decade with the highest burnt area. By assessing the characteristic fire size for the four decades of study, we conclude that there seem to be a gradual increase of characteristic fire size per decade (Figure 22, Table 8).

Despite the fact the decade of 2010 through 2019 had a smaller total burnt area than the previous one, the characteristic fire size from the last decade of study (8391 ha) is considerably bigger when compared with the same indicator for the decade of 2000 through 2009 (3229 ha).

Table 6: Increasing decadal CFS values (1980 to 2019)

Decade	CFS (ha)	Growth rate
1980 - 1989	1958	n/a
1990 - 1999	2231	14%
2000 - 2009	3229	45%
2010 - 2019	8391	160%

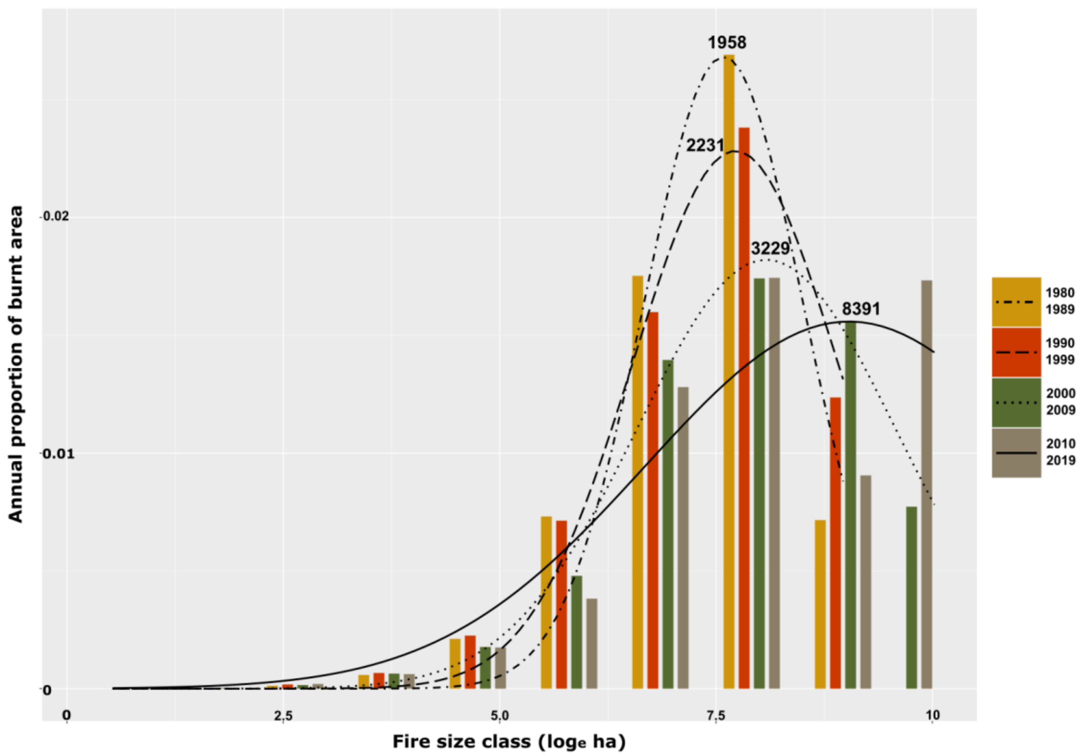

Figure 22: Decadal characteristic fire size for mainland Portugal, for the period between 1980 and 2019

Both Figures 21 and 22 give interesting insights when it comes to understanding the phenomenon of forest fires in Portugal, yet it takes the forest as a homogenous feature, where in truth this can have a quite significant levels of variability, not only in terms of dominant species, but also in terms of structure and management.

Such variability of factors can have a direct impact on the behaviour of forest fires; thus, it was decided to apply the same strategy to the tree species variable, enabling us to understand if there is any trend that could be associated to a specific tree species. This strategy was not applied, however, to the rest of the mentioned variables (such forest structure or forest management). We consider though that such approach could be useful in future studies and would help to further characterize the forests in mainland Portugal.

Mainland Portuguese forests most predominant species are *Eucalyptus globulus* with a dominant presence on 26% of the forest, followed by *Quercus suber* and *Pinus pinaster*, both with a dominant presence of 22% of the forest. (IFN, 2015). However, that most common species combination in Portugal correspond to a mix of *Eucalyptus globulus* and *Pinus pinaster* (Fernandes, 2007), which also corresponds to the areas of the country most affected by forest fires between 1980 and 2019 (Figure 9).

The characteristic fire size was then estimated based on the proportion of burnt areas per individual tree species considered (*Eucalyptus globulus*, *Pinus pinaster* and *Quercus suber*), per year of analysis (Figure 23).

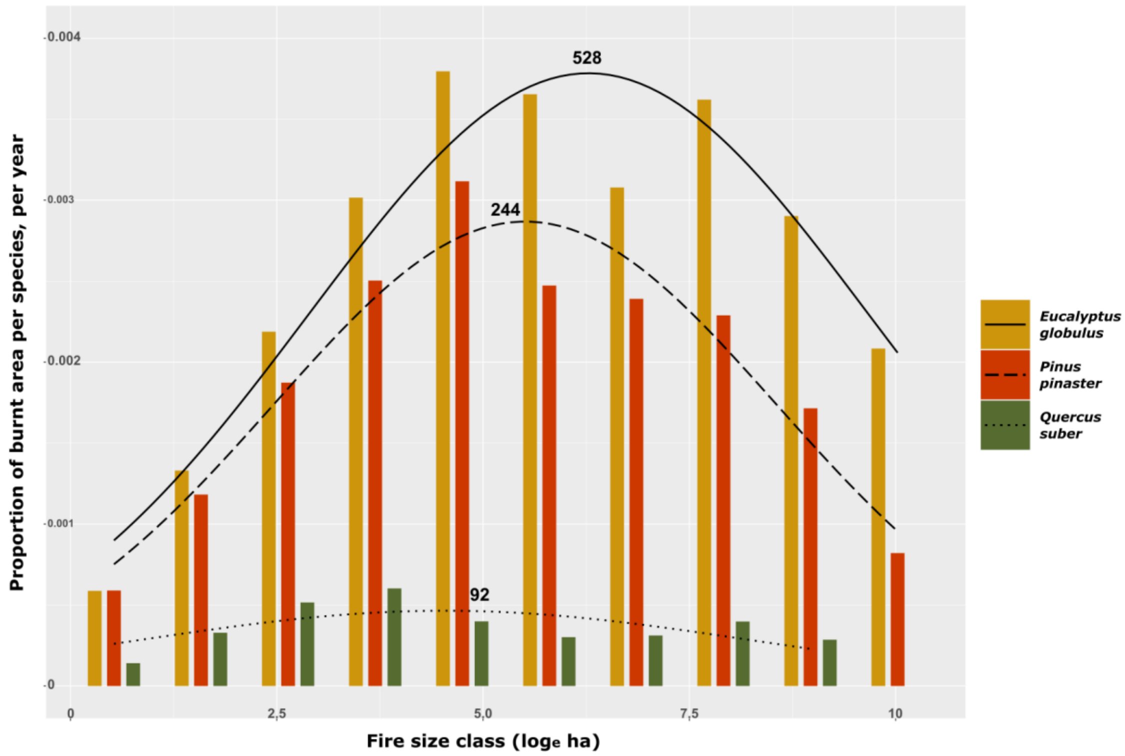

Figure 23: Characteristic fire size for mainland Portugal, by tree species (Eucalyptus globulus, Pinus pinaster and Quercus suber)

It is quite interesting to note that the characteristic fire size varies for each tree species, being the *Eucalyptus globulus* the species with the biggest characteristic fire size (528 ha), followed by *Pinus pinaster* (244 ha) and lastly, *Quercus suber* with 92 ha.

Lastly, it was decided to apply this approach to the FWI variables. Although all the presented results seem to point in the direction of a somewhat weak relationship between this factor and the total burnt area, we decided such analysis could give us an insight into the reasons behind these results.

It was then decided to divide the FWI values in three groups based on the calibrated FWI for the Portuguese territory (Viegas et al, 2004). This study created a calibrated table of FWI thresholds for 5 risk classes, from low to extreme, where its noticeable that there is a considerable variability in each risk class based on its geographical location.
The threshold values for each class were defined either by the data (in the case of the minimum and maximum FWI present in the dataset), as well as by the estimation of the median values for the “Moderate”, “High”, “Very High” and “Extreme” categories present in Viegas et al. (Table 7, Figure 24).

Table 7: FWI class thresholds for Figure 11

Risk	Min FWI value	Max FWI value
Moderate risk	20	40
High risk	40	65
Very High risk	65	75
Extreme risk	75	110

The results of such exercise show that the class of FWI higher than 75 concentrates the highest value of characteristic fire size (5539 ha), which corresponds to a significant increase when comparing to all other FWI classes. When analysing the behaviour of the characteristic fire size for these classes it is not clear that a higher FWI value will result in larger burnt areas, since the characteristic fire size is slightly bigger for the “High Risk” class (2249 ha) than what is to the “Very High Risk” class (2132 ha).

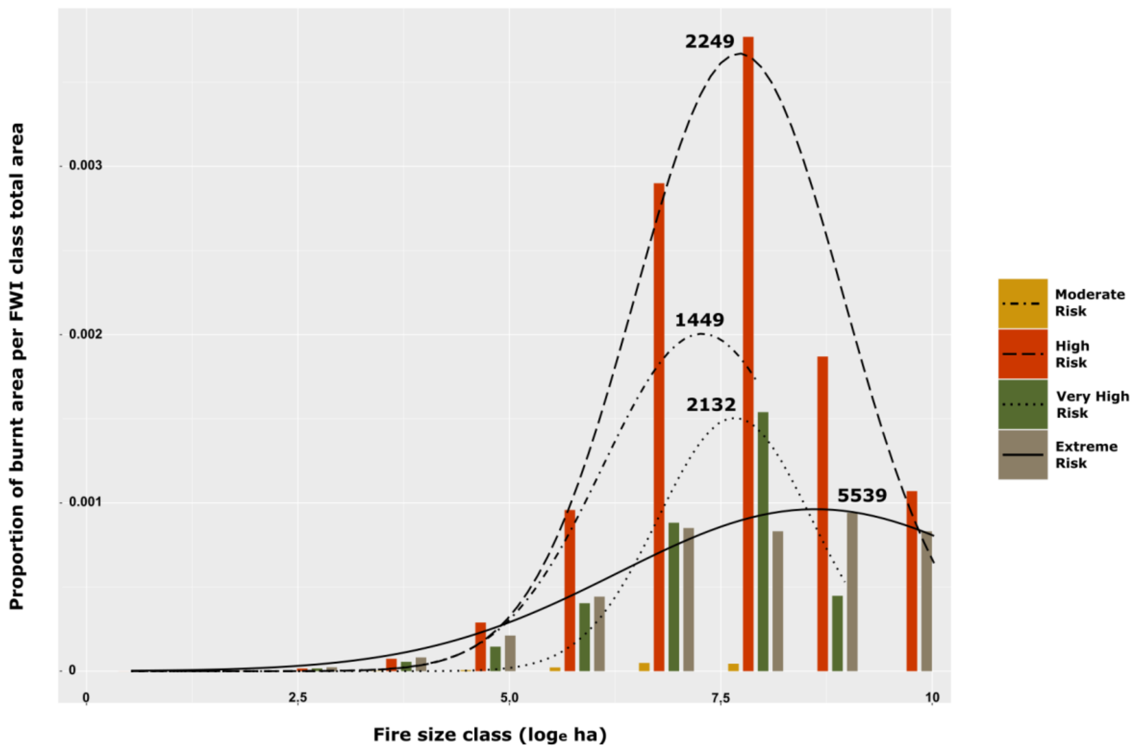

Figure 24: Characteristic fire size based on FWI grouped values

When analysing Figure 9, one may conclude that most fires that occurred in the mainland Portuguese territory from 1980 to 2019 were located, mostly, in the north and centre of the territory. By filtering by the maximum FWI values for each grid cell of analysis, there are distinct maximum values throughout the territory (Figure 25). While in the northwest, the maximum FWI values for the period of study reaches 78, on the centre of the territory these values rise to 91, while the southwest registers the highest FWI values, with 108.

In general, these thresholds can be described as follows: For the north of mainland Portugal, the “Low” class is defined by values below 10 to 20, while the “Extreme” class values correspond to values higher than 40 to 55; for the central region the “Low” class correspond to values below 10 to 20, while the “Extreme” class is defined by values over 45 to 70. Finally, for the south region, the “Low” class is situated below values of 25 to 40, while the “Extreme” class related to values higher than 70 to 75 (Table 8). (Viegas et al., 2004)

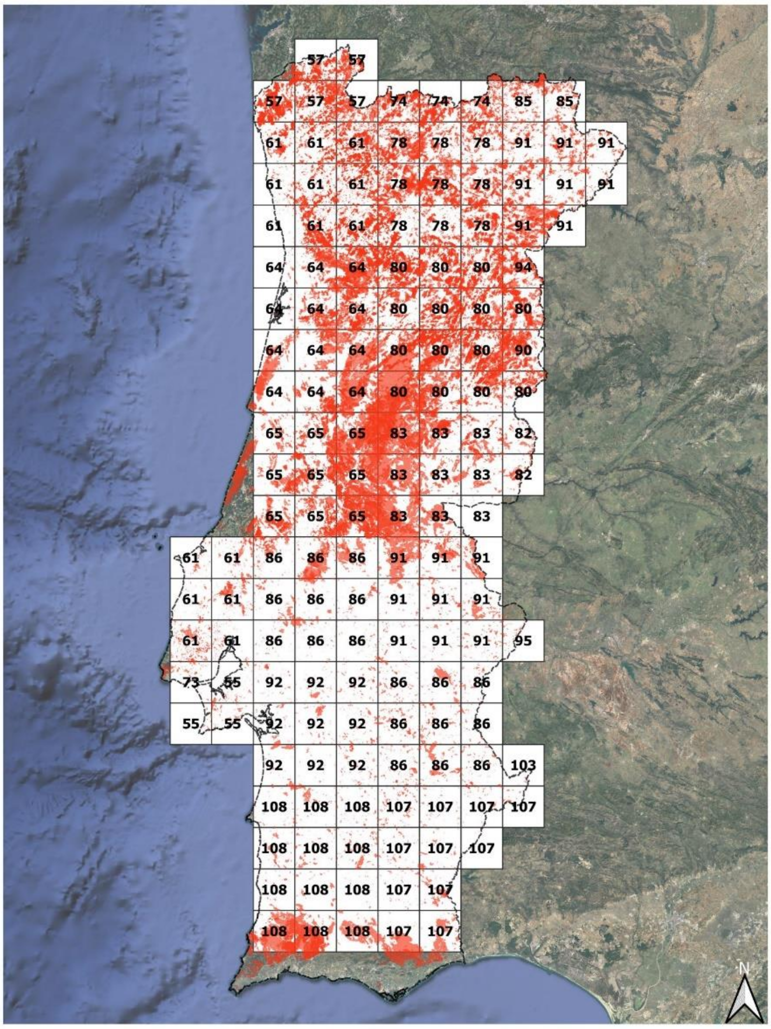

Figure 25: Burnt area per max FWI per grid cell

Table 8: Calibrated FWI values by classes, for mainland Portugal (adapted from Viegas et al., 2004)

Region	Low risk	Moderate risk	High risk	Very High risk	Extreme risk
North	< (10 to 20)	10 to 20 - 15 to 30	15 to 30 - 25 to 45	25 to 45 - 40 to 55	> 40 to 55
Centre	< (10 to 20)	10 to 20 - 15 to 35	15 to 35 - 25 to 50	25 to 50 - 45 to 70	> 45 to 70
South	< (25 to 40)	25 to 40 - 35 to 50	35 to 50 - 50 to 65	50 to 65 - 70 to 75	> 70 to 75

By analysing Figure 25 and Table 8, we conclude that the highest burnt area is not necessarily associated to the highest FWI values. In fact, when the entire range of FWI in mainland Portugal for the study period is considered, as well as the total burnt area for each individual value during the same period, the highest burnt area values are associated to mid-range FWI values. (Table 9)

Table 9: Ranking of FWI values per total burnt area

Rank	**FWI**	**Burnt area (thousands of ha)**
1	63	330
2	60	298
3	57	282
4	61	245
5	54	236
6	62	215
7	56	208
8	53	205
9	72	200
10	64	149

6. Discussion

The following section will focus on the presented results previously presented and integrate them into the scientific discussion of the complex phenomena of forest fires in mainland Portugal.

The first subsection will focus on the general CFS analysis of mainland Portugal, which is useful to set the general context regarding the impact of forest fires in this territory and what general assumptions can be extracted from it

After this, a section will follow a structure driven by the hypotheses presented at the introductory section, which correspond to sub-sections related with decadal burnt area analysis; followed by a FWI and burnt area discussion; population density and burnt area analysis, land cover and tree species relation with burnt area assessment; and finally, two subsections focused on the limitation of this analysis as well as on a outlook regarding this subject of study

Lastly, when applicable, each sub-section will also contain two sub-sub sections, where one will solely focus on the CFS size analysis, while the other will oppose the hypothesis made in the introductory section with the findings made throughout this work.

6.1General CFS Analysis

As it was previously described in the methodology section, this strategy aims to identify which fire size class contributed the most to the total burnt area for a given analysis. (Lehsten et al., 2014)

The general CFS analysis for mainland Portugal focused on the period between 1980 and 2019, and it included all the fires without any type of spatial or temporal filter.

By analysing Figure 21, it can be inferred that the classes that better describe the fires in mainland Portugal, for the period of study, corresponds to the 7.9 and 8.9 in the log scale (2700 and 7300 ha, respectively), where the highest burnt area value occurs at 8.3 in the log scale, corresponding to 4272 ha. Therefore, this is the fire size that better describes the forest fires during the 39-year period of study.

This result is somewhat alarming, considering that a mega-fire is generally described by a fire over 10 thousand hectares. According to Ferreira-Leite et al., a mega-fire can be defined as a fire that consumes areas that, as a result of structural changes (as abandonment), the forest became more vulnerable to big fires, with high intensity; that burnt more than forested related ecosystems and affect other ecosystems and fires whose spread is considerably fast and is highly resistant to extinguish related methods. (Ferreira-Leite et al., 2013).

We consider that there are several variables that can impact on the size of forest fires (some of them explored in this study), yet it would be interesting to understand what the comparison between Portugal CFS and other countries would be, since this metric seems to of special interest of analysis.

Indeed, by understanding this value at a national scale, we can understand what underlying circumstances and forest related managerial strategies are lacking and possibly what variables are most important to the development of fires of that size. In the case of mainland Portugal, fuel continuity with closed and low structures could correspond to two main factors for such high CFS value (Guerreiro et al., 2018; Fernades, 2009; Nunes et al., 2016)

6.2 Burnt area between 1980 and 2019

Regarding the relation between the burnt area and this temporal variable we have hypothesised that total burnt area has been increasing since 1980 until 2019, and we expect to see this phenomenon translated in a linear trend of increase for the burnt area, as we expect to see and increase on the decadal characteristic fire size.

As presented in the previous section, there is not a linear trend of the decadal burnt area, although it possible to observe higher burnt area size peaks after 2000. When it comes to the decadal burnt area, it seems that the behavioural pattern seems to be oscillating between decades with higher burnt area, followed by a decade with a smaller total burnt area when compared with the previous one. Yet, the total burnt area of the two respective decades after 2000 is higher than the two decades prior to 2000. (Tables 3 and 4, Figures 15 and 16)

Although there are a several factors that can contribute to such an increase, climate change must be taken in consideration as one of the main drivers of such an increase, which is expected to continue in the years to come given the trends that indicate the occurrence of periods of temperature rise with lower levels of precipitation (Nunes et al., 2019b).

In fact, this will not only lead to severe fuel “aridity” conditions (related not only with the fine fuel moisture content, but also with the extreme fire regimes that are gradually becoming the norm), but it will also improve the conditions for pests’ outbreaks and invasive species proliferation. Such a situation will lead then to more fire prone forests, which results in bigger burnt areas and consequent release of considerable amounts of carbon dioxide to the atmosphere, adding to the current warming process cycle. (Nunes et al., 2019b)

As previously mentioned in this study, abandonment of once agricultural areas led to unmanaged forest development, leading to a connectivity of fuel across the landscape (Fernandes, 2019), which can also be considerably important in the increase of the decadal burnt area shown in Figure 16.

A representative example of such phenomenon could be the fact that some areas of Northwest of Portugal have burnt 3 times between 1975 and 2006 (Silva et al, 2019). This example demonstrates not only the recurring nature of forest fires, it also illustrates the lack of forest management in some areas, to the point where in the period of 30 years, the same area is affected by 3 different fire events.

This can be related with the fact some of the most predominant species in the Portuguese forests (*Eucalyptus globulus and Pinus pinaster*) that have relatively faster development when compared to other species, leading to lower stands with high density of understory vegetation, which results in fires with high levels of fire intensity (Guerreiro et al, 2018; Fernandes 2007).

Characteristic fire size analysis of decadal burnt area

To produce the CFS analysis by decade, it was necessary to aggregate the burnt areas per decade and perform individual CFS assessments for each decade, that were finally integrated in a single graphic representation (Figure 22).

When comparing the results for this assessment and the total burnt area per decades (Figure 16), it can be observed that both graphs do not follow the same trend. While the latter seem to oscillate between higher and lower total burnt area per decade (although with a clear positive trend), the decadal CFS analysis displays a continuously increasing value of CFS per decade (Table 8).

The increase of CFS between the decades of the 2000s and 2010s is particularly alarming, since the increase of 160% means that the fires became much larger, more intense and with a faster spread ratio in the space of 10 years. In addition, the base value for the decade of the 2000s was considerable for a country the size of Portugal, mostly when such a CFS value already corresponded to a considerable increase when compared to the previous decade of the 1990s.

The differences between the decadal CFS analysis and the total burnt area per decade can be explained, mostly, due to the fires that occurred in the years 2017 and 2018, when some of the biggest fires ever registered in the country have occurred.

There are several possible causes for such an increase in the CFS that could be related with current climate change, where Portugal is expected to become a progressively hotter and drier country (based on the reference values of 2011), where the precipitation can oscillate between periods of very low or very high precipitation levels (IPMA, 2015), leading to higher accumulation of drier fuel that might be base of more extensive fire events.

Another possible cause for such an increase could be related with the lack of management in the Portuguese forests, related with the abandonment of rural areas that were once agricultural areas, but also due to the lack forest related managerial strategies in situ (CTI, 2017; Guerreiro et al., 2018; Mendes, 2017).

Hypothesis vs. results: Analysis of burnt area between 1980 and 2010

We consider that this hypothesis was partially confirmed. There is not a clear linear growth of burnt area when assessing the burnt area between the years of 1980 to 2019, yet the total burnt area of the two decades after the year 2000 is bigger than the two decades prior to this year.

There is, however, a clear increase of the characteristic fire size per decade of analysis, which might be indicator that the fire regime in mainland Portugal has changed from the decade of the 1980s to the decade of the 2010s.

6.3 Relation between burnt area and FWI

Concerning the relation between the burnt area and FWI, we have hypothesised that higher FWI values have a direct impact on the burnt area, and we expect a positive correlation between FWI and burnt areas. In addition, we expect the characteristic fire size increases with FWI values.

Despite the fact that climate is one of the main drivers to the existence and extent of forest fires, its statistical correlation with burnt area is not straightforward. As it was presented in Table 2, the burnt area had a negative correlation of 0.04, which can be interpreted as a value that defines no significant correlation. In addition, this variable did not perform particularly well with respect to the relative importance of each variable to the burnt area, nor with respect to principal component analysis (Figures 18 and 19).

Thus, and by analysing Figure 25, and Tables 8 and 9, forest fires affected more areas with lower absolute FWI values, rather than higher FWI values, mostly driven by the higher number of fires that occurred in areas with lower FWI values. Yet, given the different characteristic of each area of study (such as climate, biodiversity, forest structure and dominant species, amongst others), the FWI values might have different impacts throughout the territory.

Consequently, FWI values should be calibrated based on the mainland Portugal's different variables that can impact on fires. According to Viegas et al., it is possible to create a 5 class

FWI scale (Low, Moderate, High, Very High and Extreme) and associate a given FWI value to one specific category, according to the interval of each class. (Table 8) (Viegas et al., 2004)

By analysing Figure 25 and Table 8, it's possible to verify that the FWI with bigger burnt areas are between the values of 40 and 63, and since most fire events for the period between 1980 and 2019 occurred mostly on the north and centre of the mainland Portuguese territory, these could very well be in areas where the calibrated fire risk would correspond to "Very High" or "Extreme". The fact the burnt area is mostly associated to these mid-range values (when comparing with the complete FWI range), can explain the low correlation value between the burnt areas and FWI values (Table 9).

This idea of regional variability converges with recent studies on the matter, where fire weather index values were correlated with the days that there were fires of the different sizes, creating FWI thresholds for each fire size type. The author found that lower thresholds correlated better with lower fire sizes then when compared to bigger fire sizes, and vice versa. This study concludes that there is an important regional variation associated to fire size classes threshold (Fernandes, 2019).

Other wider spatial analysis studies focusing on the Iberian Peninsula have concluded that there is a correlation between burnt area and FWI for the Iberian Peninsula, yet climatic importance to fires is not clear. As an example, in the East of the Peninsula, FWI values seem to be increasing, as it is the fire length season, yet the fire incidence is very low when compared with the NW. (Silva et al., 2019)

Both the studies presented above are characterized by a higher resolution of analysis when compared with the present report, which could have contributed for better description of the relation between the burnt area and FWI values.

Characteristic fire size analysis of FWI and burnt area

The objective of integrating such CFS analysis was, on the one hand, to understand why the low correlation values between FWI values and burnt area, as well as the poor performance on all other analysis. On the other hand, it would be important to understand to what extent this could FWI influence burnt areas, for the considered period.

Regarding the first issue, Figure 24 seems to illustrate what has been addressed above regarding the relation between burnt area and FWI values, where the intermediate class of “High” has a bigger burnt area associated with it, yet this must be put into regional context, since the FWI thresholds of different regions will vary considerably (Figure 25).

Additionally, the areas that burnt the least correspond to the predominance of agro-forested areas. This also coincides with the region with highest FWI values yet with a considerably lower burnt area when compared to the north of the territory.

Therefore, this difference cannot be explained solely by the distinct impact of FWI in different regions (Viegas et al., 2004), yet agro-forested areas can also correspond to better managed forests which may impact on the total burnt area between 1980 and 2019.

On the influence of FWI on fire size, and while the difference regarding total burnt area for the FWI class of “High” is of 2.4 million ha bigger when compared with “Very High” class, in terms of the CFS value, the characteristic fire size for the class “High” is only 117 ha bigger than the characteristic fire size for the “Very High” class. This is an interesting result since there seem to be a direct impact of FWI when it comes to size of fires (higher FWI values will lead to drier fuels, and therefore a bigger fire vulnerability), however this seems to have a lesser impact on the total burnt area.

Such a trend is also observed when considering the CFS of the “Extreme” FWI class, where the fire size that better characterizes this class is of 5539 ha, which corresponds to almost the double the CFS value presented for the previous analysed classes.

Such results are also in line with other studies produced for mainland Portugal, where a relation between fire spread, size, and intensity with FWI values. (Silva et al., 2019; Fernandes, 2019)

Hypothesis vs. results: FWI and burnt area analysis

We consider that our hypothesis was inconclusive, and the relation between FWI and burnt area is much more complex than what we expected. It seems that the low and mid-range of our FWI scale can contribute more with respect to the number of fires (and therefore a cumulative bigger burnt area), while higher FWI values can lead to less fires but larger fires.

Regarding the characteristic fire size, it seems that higher FWI leads to larger-sized fires, however this is not observable when comparing the FWI classes of “High” and “Very High”. However, it is possible that the difference between number of fires per class had an impact on this assessment, given the dramatic difference between absolute burnt area and characteristic fire size between the two classes.

6.4 Relation between burnt areas and population density

When it comes to the relation of population density and burnt areas, we hypothesized that areas with lower population density are more vulnerable to forest fires than areas with higher population density, therefore we expect to see a clear negative correlation between population density and burnt areas.

However, population density was always the indicator that had a worse performance when compared with all other indicators in the correlation, relative importance, and principal components analysis (Figures 18 and 19).

Despite the fact that some literature focused on forest fires in mainland Portugal attributes an important focus on population density as a factor that can contribute to the development of ideal conditions for the proliferation of big forest fires (CTI, 2017; Guerreiro et al., 2018; Mendes, 2018; Beighley and Hyde, 2018), we could not find a meaningful statistical relation between the burnt area and such indicator.

There could be range of arguments that can explain such negative result. The first could be related with the resolution of analysis that was not adequately adjusted to this phenomenon, preventing the extraction of any meaningful statistic relation between the two variables.

Since our burnt area dataset extended all the way up to 1980, but our population dataset would only cover the period from the year 2000 onwards, as it was presented in the methodology section, it was decided to use previous statistical data on the population density for the period of 1980 to 2000 (Albergaria, 1999), and integrate it into the dataset. This could have had a negative impact on the dataset, mostly on the values before 2000, since the methodology used might have resulted in less accurate and reliable data.

Lastly, it is possible that the relation between the variable of the population density and forest fires might not be as clear as what is commonly assumed (at least for the case of mainland Portugal), which may require a more in-depth analysis of this conundrum, with different strategies than the ones explored to date.

As an example, Silva et al. have concluded that, for the northwest of Portugal burnt areas and population have increased, while in the centre of the country both variables have decreased. There can be a relation between the spatial patterns of property and population since the northwest seems to present more complex spatial patterns than the centre. On another hand, a lower population can be related to a more dense and unmanaged forest (which can lead to bigger burnt areas), but also to less ignitions (Silva et al., 2019; Nunes et al., 2016).

Hypothesis vs. results: Population density and burnt area analysis

We consider that our results were inconclusive when it comes to understanding the relation between population density and burnt areas. It appears that this relation might be much more complex than what was anticipated, and it might be necessary to integrate population density with other socio-economic factors in order to have a clear understanding about the relation between these two phenomena.

The complexity of this relationship has also been highlighted by other studies (Silva et al., 2019), which may determine that there is a clear need to have a better and deeper understanding of this issue.

6.5 Relation between burnt area, land cover (forests and agro-forests) and tree species (*Eucalyptus globulus, Pinus pinaster and Quercus suber)*

We have hypothesised that *Eucalyptus globulus* contributes more to the total burnt area of this territory when compared with *Pinus pinaster* and *Quercus suber*. Plus, we expect that the characteristic fire size of *Eucalyptus globulus* to be bigger than the other presented species.

It has been decided to group both the land cover and tree species analysis, since both are effectively intertwined. It is not possible to perform a fair assessment of the impact of a given tree species without understanding its context, as it is difficult to analyse a forest related context without including the specific characteristics of the tree species present in the same context.

The analysis presented on the previous section highlighted a strong relationship between land cover and burnt areas, more specifically between forested and agro-forested areas. While there seems to be a strong correlation between the burnt areas and forested areas, there also seems to be a negative correlation between burnt areas and agro-forested areas. (Table 5).

This strong relationship between land cover and burnt areas is confirmed by both the relative importance of variables to burnt areas, as well as the principal component assessment (Figures 5 and 6). While the relationship between burnt area and forested areas may be clearer, the relationship of the first variable with agro-forested areas might be more complex.

The first noteworthy feature of these agro-forested areas is the strong correlation between these areas and the *Quercus suber* species ($R = 0.77$), in contrast with the considerably lower correlation values when compared with *Eucalyptus globlus* ($R = -0.24$) and *Pinus pinaster* ($R = -0.39$). In addition, the proportion of burnt areas per *Quercus suber* per species, per year, is considerably smaller than any of the other two analysed species (Figure 23).

The same consistency of results cannot be described for the relationship between tree species and burnt areas, since the correlations and relative importance exercises show that tree species seems to have no significant correlation and little relative importance to burnt areas

(Table 5, Figure 18). However, the principal component analysis showed tree species as being the second most influential variable to burnt area after forested land covered areas (Figure 19).

Such inconsistency can be explained by the disparity of total burnt area per tree species and as consequence on the percentage of total burnt area per species. While both *Eucalyptus globulus* and *Pinus pinaster* correspond to around 46% of the total burnt area between 1980 and 2019 (29% and 17%, respectively), *Quercus suber* corresponds to solely 3% of the same area. (Table 6) This discrepancy in the burnt area might have led to a small correlation value, as well as to a lower relative importance to the burnt area, when tree species seem to be present in almost half of the burnt area in mainland Portugal for the period of study.

Although not a consensus opinion across the academic community, some studies suggest that some species should be promoted in the Portuguese territory to the detriment of *Eucalyptus globulus and Pinus pinaster*, such as *Quercus suber*. The rationale behind such a statement relates with less flammable treetops, as well as a lower development of understory vegetation, which can contribute to important breaks in fuel continuity throughout the landscape (Guerreiro et al., 2018).

Another important aspect that distinguishes forested from agro-forested areas corresponds to the forest management that is visible in the latter areas. Since these correspond to agricultural areas based on forest related products, there is a bigger investment in such areas, not only to promote their productivity but also to ensure that the risk of damage by fire is reduced, making these areas less vulnerable to fire.

Some researchers point out that stand structure is the most important variable when it comes to assessing the behaviour of fire. While low structures will always promote the fire reaching to the treetops, dramatically increasing its intensity. However, while a closed and low structure will not promote a quick-fire spread, it will lead to very high or extreme levels of intensity. (Nunes et al, 2016; Fernandes, 2009)

Tall structures, on the other hand, will not promote the fire reaching the treetops, which will make the fire less intense. A closed and tall structure will still promote the fire intensity, while decreasing the spread rate of fire, yet these are considerably lower than the ones presented for a closed and low structure (Fernandes, 2009).

Yet, and given the current freely available resources, it is considerably challenging to assess what type of structure is present in a given forested area of analysis. Some existing methods are applied using very high-resolution data, and although very innovative, do not yet give any hints when it comes to machine learning strategies in order to automate the classification process of forest structure. (Novotný et al, 2011; Paletto and Tosi, 2009; Loi et al., 2017).

We consider that it would be important to develop the capabilities that could be used to assess such variables in forested contexts. This would allow decision making institutions and organisms to have a better understand of their forests, allowing for better forest management for their areas of influence.

Characteristic fire size analysis of tree species and burnt area

By observing Figure 23, one can argue that *Eucalyptus globulus* has the biggest CFS value (528ha), followed by *Pinus pinaster* (244 ha), while *Quercus suber* has the lowest value of 92ha.

This means that the fire that better characterizes forest fire that affect *Eucalyptus globulus* is twice as large as the ones that better characterise *Pinus pinaster* fires, and around 5 times larger than the same type of fires for *Quercus suber*.

Such significant values can be related with a wide variety of factors. Given the fact that *Eucalyptus globulus* is a species whose chemical composition of leaves is rich in volatile chemicals, it may directly impact on this species higher flammability when compared with other species. (Nunes and Pio, 2001; CTI, 2017). Yet such impact on fire behaviour is deemed as irrelevant by other authors given the low value of oil content in the litter, and the predominant effect of fuel load and structure (Fernandes et al., 2019).

In addition, since this produces a considerable amount of litter (as *Pinus pinaster*), there is a considerable production of understory growth that, if not managed, can have a considerable vertical expansion which leads the fire to treetops (Fernandes, 2007).

The presented results seem to be in line with other studies that suggest that species such as *Quercus suber* are more resistant to fire, not only because these have fewer flammable treetops, but also due to the lower volume of understory development, which prevent treetop fires, as well as breaks fuel continuity (CTI, 2017).

Other studies suggest that *Eucalyptus globulus* had no impact on the fire regime in mainland Portugal since these were massively introduced in the territory, during the decade of the 1980s. Despite the fact its cover has tripled in mainland Portugal since that decade, this did not translate on a higher share of *Eucalyptus globulus* burnt area. (Fernandes, 2019)

It is also noted that forests contribute less than other types of land cover (mostly when compared to shrublands, but also to some agricultural areas), with the exceptions of the years of 2003, 2005 and 2017, where forest as land cover had a bigger impact on the total burnt area than in any other land cover. (Fernandes, 2019). As it can be observed, these three years correspond to the biggest burnt area per year ever recorded for mainland Portugal (Figure 14), which could mean that, in the context of solely a forest fire, *Eucalyptus globulus* has a considerable impact in forest fires.

Yet, for the fires of 2017, *Eucalyptus globulus* sole plantation areas with understory have burnt more (14%) than double when compared to the ones without understory (6%) (Guerreiro et al., 2018).

There seem to be a lack of consensus regarding the impact of *Eucalyptus globulus* in the fire regime in mainland Portugal. The results of our CFS analysis could be related not only with the species itself, but also with the forest structure associated to the burnt areas.

It is important then to reinforce the idea that, most *Quercus suber* dominant areas are located within agro-forested land cover areas, which given the production and economic dimensions of such, would entail that these forests are constantly managed, which would reduce their fire vulnerability.

It would be interesting to perform this type of CFS analysis in other areas of study, with more detailed and high-resolution data that would enable the discussion regarding the impact of tree species on managed and unmanaged forested related contexts.

Hypothesis vs. results: Tree species and burnt area analysis

We consider that our hypothesis was confirmed, since we have demonstrated that *Eucalyptus globulus* has burnt more than any other species and has a bigger percentage of proportion total burnt area when compared to other species, as well as its characteristic fire size is almost double when compared with the same metric for *Pinus pinaster*, and 5 times larger than that of *Quercus suber* CFS.

However, and despite the fact we consider the presented results statistically trustworthy, there are many variables other variables of study that prevent a more certain understanding regarding the relationship between *Eucalyptus globulus* and burnt areas.

Several produced studies suggest that forest structure and management are the driving factor for forest fires in mainland Portugal, and although there are some tree species more prone to fire, its influence is not substantial (Fernandes et al., 2019; Nunes et al., 2019)

Despite the fact all studies aim to analyse situations that can correspond to a close representation of the real conditions of fire, we consider that such is not always possible yet, given the complexity of the forests and its mutating nature.

6.6 Errors and limitations

Although we consider that the presented results accurately describe forest fire phenomena in mainland Portugal, it should be said that there is room for improvement and to perform further analysis regarding this issue.

We have based our entire research on the fire database available for mainland Portugal, and although this dataset is the best source of processed geospatial data available, it is possible that it might contain errors. These can be translated as mislocation of fires, their geographical spread (and therefore, burnt area), or even fires that were simply not recorded at all. We believe that such errors are certainly more present for the earlier years of this dataset, when it is now almost impossible not only to collect data about forest fires, but to cross check and validate it.

Most of the data in the dataset used also does not contain any information regarding start date and time of the fire or when this was extinguished. Such details would allow a better understanding of the relation between burnt area and FWI (as an example), since this variable is more suspectable to high variability, given its intrinsic nature.

These data issues can certainly create errors in our analysis that we cannot measure, since we do not know of a better resource that contains geospatial data regarding mainland Portugal burnt area to compare it with.

In addition, the data used for the population density related analysis was extracted from the Pop Data platform, however such a dataset would only cover the study area from the year 2000 onwards. Given the dramatic transformations of Portuguese demography after 1974 (Albergaria, 1999), it was important to demonstrate these differences on the dataset. However, such an exercise might have negatively impacted the dataset, and given the simplicity of the strategy, it might have created a less accurate and reliable dataset for the years between 1980 and 2000.

6.7 Outlook

As was demonstrated in this study, the issue of forest fires in mainland Portugal is a subject that is still a big issue for this country, as it still generates debates amongst the scientific community regarding the influences that certain tree species have, but also concerning the impact of forest management and forest structure in the resulting burnt area of forest fires.

Although most of the fires are still the result of anthropic actions (AGIF, 2018), it was decided to analyse the forest fires from a structural perspective, rather from a social one. However, it would be interesting to understand if there are any socio-economic variables that influence the existence of forest fires in Portugal, allowing the managerial authorities to take specific actions to not only improve the conditions of such communities, but also to contribute to a decrease of yearly burnt area in the country.

The concept of CFS introduced by Lehsten et al., allows the research to take a step further into understanding the context of fires, and mostly the different impacts that a given variable of analysis might have in different fire size classes (Lehsten et al., 2014).

It would be interesting to apply such an analysis to other strategies of analysis of Portugal (with different resolutions, using different datasets and variables of study), but also to understand what the CFS behaviour is in other contexts in the Iberian Peninsula and Mediterranean. Given the fact these geographical areas might be one of the ones most affected by climate change, it would be important to reinforce the network of knowledge about this issue.

It would also be interesting to have a more detailed understanding of the exact FWI related conditions, not only at the location where a given fire proliferated, but at the time it started, the time it was extinguished, and all the way throughout its existence, since this would enable a more complex and intense analysis of the impact of the FWI in the forest fires.

We haven't analysed the impact of fire fighting in the fire extension, and how this can affect total burnt area. However, it would be interesting to analyse firefighting funding and how it relates with fire size, enabling us to understand the relationship between funding fire fighting forces and total burnt area of their area of influence.

Throughout this analysis the concept of "forest structure" and "forest management" was frequently used. In any of the dedicated analysis this was included as a variable of study, however, it is widely accepted as this being one of the most prominent variables when it comes to forest fires (Nunes et al., 2016; Fernandes et al., 2007; Fernandes et al., 2009; Fernandes et al., 2019).

It would then be interesting to understand how real the possibility of analysing such metrics as forest structure or forest management is. The inclusion of these variables in GIS-related works could have a considerable positive impact, not only to understanding its real impact on forest fires, but as well to aid decision making entities by adopting better and more efficient forestry managerial strategies.

Finally, it would be of interest to include in the analysis a wider range of anthropic variables, not only population density but other metrics (such as income, population age, and others), enabling the establishment of a relationship between burnt area and social features that can have an impact on forest fires.

7.Conclusion

The issue of forest fires in mainland Portugal is extremely complex, and this territory has been experiencing progressively larger fires throughout time, which is a trend that seems likely to continue unless action is taken.

Between the years of 1980 and 2019, it is not possible to identify a linear trend when it comes to the total burnt area per year, yet decadal fire and fire size has increased from the year 2000 onwards.

The relationship of burnt area with variables such as Fire Weather Index (FWI), population density, tree species or land cover (only forested and agro-forested areas were included in the study) is not always clear, but while FWI can have a direct impact on fire size, a significant relationship between burnt area and population density was not detected. For the remaining variables, and since there is a geospatial relation between the two, we verified that agro-forests and *Quercus suber* are related to a considerably smaller burnt area when compared with *Eucalyptus globulus, Pinus pinaster* and forested areas.

The existence of better forest management of agro-forested areas where the dominant species in this land cover type is *Quercus suber* can be significant to the reduction of forest fires. In fact, the intrinsic characteristics of this species that concede less vulnerability to fire, allied with better managerial practices when it comes to forest structure can correspond to a strategy of successfully mitigate burnt area.

In contrast, less well managed forests, with a structure that can lead to fuel continuity seem to be more prone to forest fires, mostly if these are dominated by *Eucalyptus globulus* and *Pinus pinaster*. It seems that the fire size of the former can be considerably larger when compared to the other species in analysis, which brings yet another contribution to the discussion regarding the role of this species in fire and in Portuguese forests.

Current climate change predictions suggest that climate will become progressively hotter and drier, which are perfect conditions for the development of forest fires. It is then urgent that action is taken to mitigate such risks and to better prepare our forests and biodiversity for the years to come.

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