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Biophysical drivers of fire regimes in Central Portugal

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Abstract

The spatial and temporal properties of burned areas are a major component of fire regimes. We analyse three parameters related to burned area within central Portugal, and then investigate the degree to which their variation is influenced by a set of biophysical drivers. Using civil parishes as units of analysis, we study three complementary parameters over a reference period of 44 years (1975-2018): cumulative percentage of parish area burned, Gini concentration index of burned area over time, and area-weighted total number of wildfires. Cluster analysis is used to aggregate parishes into groups based on similarities regarding burned area parameters. A classification tree model is then employed to assess the relative capacity of each driver to differentiate between groups of parishes. Drivers included slope, summer temperature and spring rainfall, land use/land cover (LULC) type and patch fragmentation, and net primary productivity. Results allowed to distinguish four parish types in terms of burned area features and show that these can be significantly differentiated by the biophysical drivers, of which LULC, slope and spring rainfall are the most important. Among LULC classes, shrubland and herbaceous vegetation play the foremost role, followed by agriculture. Our results highlight the importance of vegetation type, availability, and rate of regeneration, as well as that of topography, in influencing burned area patterns in the study area, while suggesting that other drivers, likely of a social nature, should also be taken into account.

1. Introduction

Understanding the drivers of fire regimes is highly important due to the damage regularly caused by wildfires. Among the southern European countries, Portugal is one of the most affected despite its relatively small size (San-Miguel-Ayanz et al., 2020). The largest burned areas tend to occur in the forest/shrubland dominated central sector of the country, which has been the subject of several studies (Catry et al., 2010; Maia et al., 2012), and was the most affected by the extreme wildfires occurred in 2017 (Benali et al., 2021).

In a recent work, we employed three complementary variables to express fire regime over a 44-year study period in Central Portugal, and we quantified the influence of a set of 12 biophysical drivers over each fire regime variable using ordinal logistic regression (Bergonse et al., 2022). Drawing upon those results, we intend to differentiate fire regimes in Central Portugal by integrating the three fire regime descriptors, and to characterize their interactions with biophysical conditions.

The study area corresponds to NUTS 2 Centro, comprising 28 199 km^2 within central mainland Portugal (Figure 1). This region is marked by a high variability regarding wildfire hazard and its control factors (Oliveira et al., 2020), with 49.7% of the region classified in the High and Very High hazard classes. The 972 civil parishes

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(*freguesias*) of the study area are the spatial units of analysis, which vary in extent between 1.98 km^2 and 373.50 km^2.

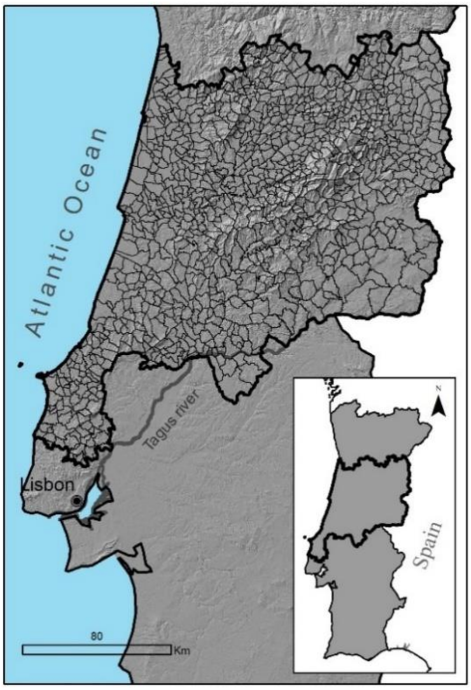


Figure 1 – Location and limits of the study area within mainland Portugal (NUTS 2 Centro), including parish limits. Parish boundaries were extracted from the official administrative map of Portugal (CAOP), produced by the Portuguese Directorate-General of the Territory (DGT).

2. Data and Methods

2.1. Data collection and pre-processing

2.1.1. Fire regime parameters

Fire regime characteristics were described with three parameters for the period 1975-2018 (44 years), following Bergonse et al. (2022). All were obtained from annual burned area maps produced in vector format by the National Forests Service (ICNF). The cumulative percentage of parish area burned (CPAB) was used to measure the propensity of each parish to burn extensively over time. Area-weighted wildfire frequency (AWWF) was calculated as the total number of wildfires recorded within the parish over the study period, divided by its area (km^2). The Gini Concentration Index (GCI) of burned area over time was adopted as an indicator of the temporal concentration of wildfire damage. It was applied to the annual burned areas of each parish over the 44 years and expressed as percentage. Ranging between 0 and 100, the GCI allows to differentiate parishes where most burned area is concentrated in a small number of years (high values), from those where the burned area is more regularly distributed over time (low values), regardless of the extent of that burned area.

Out of the total of 972 parishes, 35 (3.6%) never burned during the study period, having therefore no values in any of the fire regime parameters. These were removed from all analyses.

2.1.2. Biophysical drivers

A set of 12 biophysical drivers was considered (Table 1), which we previously demonstrated to be significantly associated, separately, with the three fire regime parameters under analysis (Bergonse et al., 2022).

Table 1- Description and characteristics of the potential fire regime drivers. Data sources and methods of calculation are described in Bergonse et al. (2022).

Type	Variable code	Variable	Temporal extent	Original spatial Resolution	Units
Topography	**SLO80**	Slope percentile 80	n.a.	25 m	º
Climate	**RFAJ**	Mean cumulative rainfall April-June	1970-2000	Approx. 1000m	mm
	TPJS	Mean monthly temperature July-September			^{0}C
Biomass	**NPP**	Net Primary Productivity	2000-2014	500 m	KgC/m^2
Land use/Land cover (LULC)	**AGR**	% parish area occupied by agriculture	1990-2018	Vector data. Minimum mapped area 1 ha	%
	OAK	% parish area occupied by cork-oak and holm-oak forests			
	EUC	% parish area occupied by eucalyptus forests			
	INV	% parish area occupied by forests of invasive species	1995-2018		
	CON	% parish area occupied by forests of coniferous species other than maritime or stone pine	1990-2018		
	BRD	% parish area occupied by forests of broadleaved species other than eucalyptus, cork-oak and holm-oak			
	SHR	% parish area occupied by brushland and spontaneous herbaceous species			
LULC patch fragmentation	**FRAGF**	Fragmentation of forest patches	1995-2018		centroids/ha of forest

2.2. Statistical techniques

Hierarchical cluster analysis was employed to identify groups of parishes with similar behaviour regarding the fire regime parameters. Clustering was performed using Ward's method, an agglomerative process which begins with as many clusters as cases, successively agglomerating clusters using the solution that minimizes within-cluster variance (Everitt et al., 2011). Prior to inclusion, the three fire regime parameters were converted into z-scores, to ensure an equal contribution regardless of contrasting value ranges (Maroco, 2007).

SPSS's CRT tool was then employed to build a classification tree model with the purpose of assessing the capacity of the biophysical drivers to differentiate between clusters. A 10-fold cross-validation procedure was adopted, with the Gini index being used as criterion of impurity for node splitting.

3. Results and discussion

3.1. Cluster analysis

A four-cluster solution was chosen taking into consideration a preliminary analysis of distances between clusters and the fire characteristics of the clusters identified.

FR1 (includes 450 parishes) is characterized by the lowest CPAB, the highest GCI, and the lowest AWWF values (Fig. 2-A). This fire regime is marked by the lowest extension of burned areas and the lowest wildfire frequency within the study area, with the resulting damage being relatively concentrated over time (corresponding to the highest GCI obtained). Spatially, it occurs mostly along the coastal swath and in the SE extreme of the study area (Figure 2-B).

FR3 (86 parishes) expresses opposite characteristics in relation to FR1. It has the highest CPAB values, as well as the highest AWWF and the lowest GCI. This indicates relatively frequent wildfires, which produce very extensive burned areas over time and result in a temporal dispersion of the damage. It occurs exclusively in the NE and the northern limit of the study area. FR2 (401 parishes) occupies an intermediate position between FR1 and FR3 regarding all three fire regime parameters. Spatially, it concentrates on the central and eastern portions of the study area.

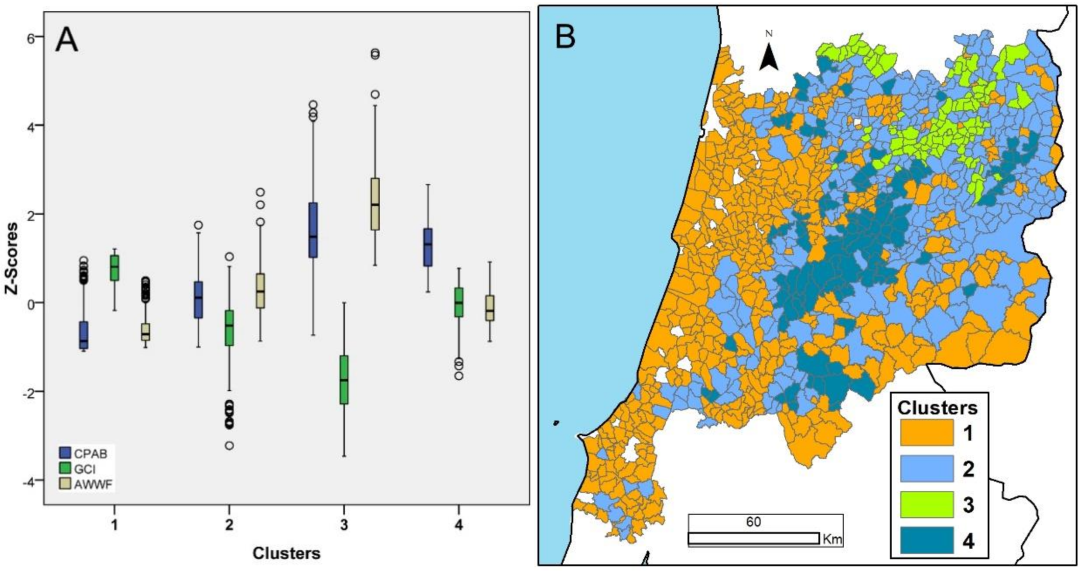


Figure 2 - (A) Box-plots for the values of the three fire regime parameters associated to each cluster/fire regime. Values expressed as z-scores. For each variable, the box includes the 1st and 3rd quartiles as well as the median. The whiskers identify the maximum and minimum values excluding outliers. Outliers (shown as circles) are defined as values between 1.5 times and 3 times the interquartile range, respectively above the 3rd quartile and below the 1st quartile; (B) Spatial distribution of the four clusters/fire regimes.

Finally, FR4 (102 parishes) has the second highest CPAB and the second lowest AWWF, resulting in the second highest temporal concentration of damage (GCI), and indicating relatively extensive but infrequent wildfires. It is mostly concentrated in the central sector of the study area.

3.2. Classification tree model

The CT model correctly classified 72.4% of all parishes, with the accuracy being slightly lower (68.7%) when independently validated using a 10-fold cross-validation process (Table 2). The overall accuracy demonstrates that the biophysical drivers are strongly related to the FRs within the study area. Regarding FR-specific accuracy, results show a notable contrast between the first three FRs (minimum accuracy 69.9%, maximum 82%) and FR4, with only 38.2% of all parishes correctly classified. This indicates that FR4 cannot be adequately discriminated using only the set of biophysical drivers employed in this study. Social variables, such as road or population density, can influence fire regimes, as previously shown in other studies (Pausas & Fernández-Muñoz, 2012; Rogers et al., 2020), and could eventually improve the accuracy of the classification.

Table 2 – Classification accuracy for the final tree model and for the tree models produced in association to the 10-fold cross-validation procedure. FR-specific accuracy values are for the final tree model.

Observed	**Predicted**				**%**
	1	**2**	**3**	**4**	**Correct**
1	369	70	1	10	**82.0**
2	58	209	17	15	**69.9**
3	0	22	61	3	**70.9**
4	17	42	4	39	**38.2**
		Final tree accuracy			**72.4**
		Cross-validated accuracy			**68.7**

All 12 biophysical drivers were integrated into the CT model (Figure 3). The percentage of shrubland and spontaneous herbaceous vegetation (SHR) was the most important driver, closely followed by spring rainfall (RFAJ). Slope (SLO80) and agriculture (AGR) have about half the importance of SHR and RFAJ, whereas eucalyptus forests (EUC), broadleaved species other than eucalyptus, cork oak and holm oak (BRD), and net primary productivity (NPP) have a relative importance between 40% and 50% of SHR. The remaining drivers vary in relative importance from about 30% down to less than 10%.

To facilitate interpretation of the influences of biophysical drivers, Figure 4 shows the values of each driver in each of the four FRs.

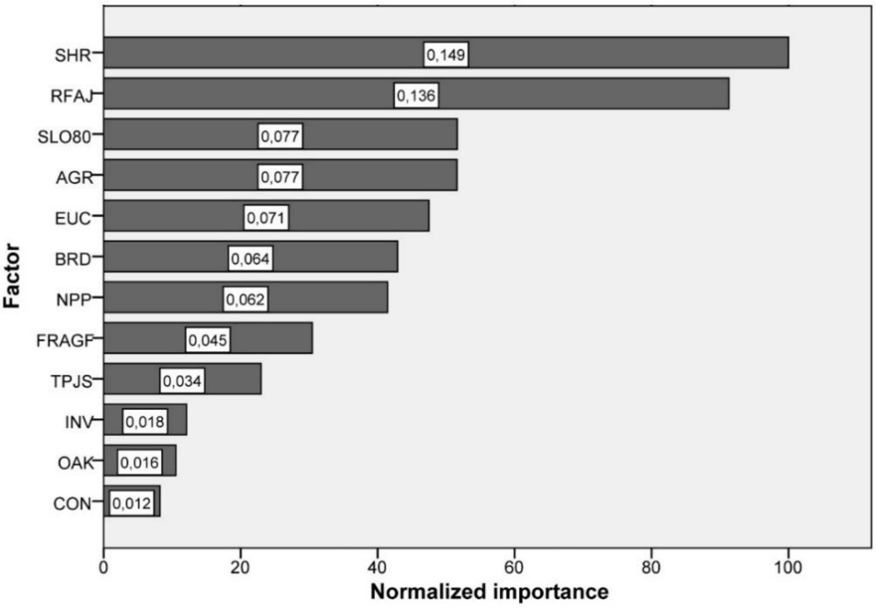
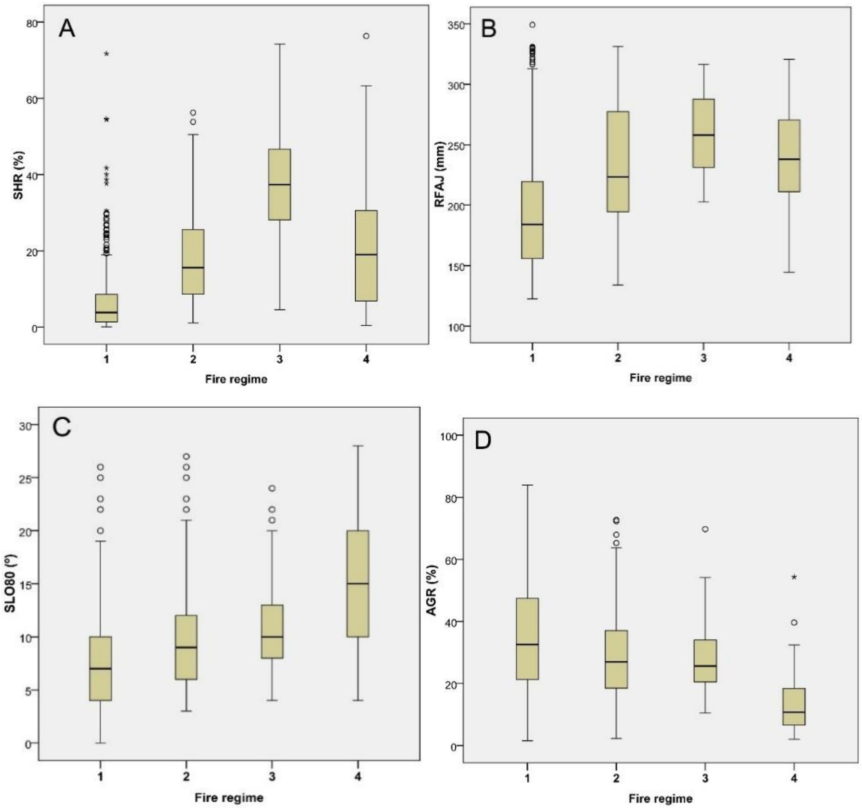


Figure 3 – Importance of each biophysical driver for the classification tree model, shown normalized by the most important driver (SHR).



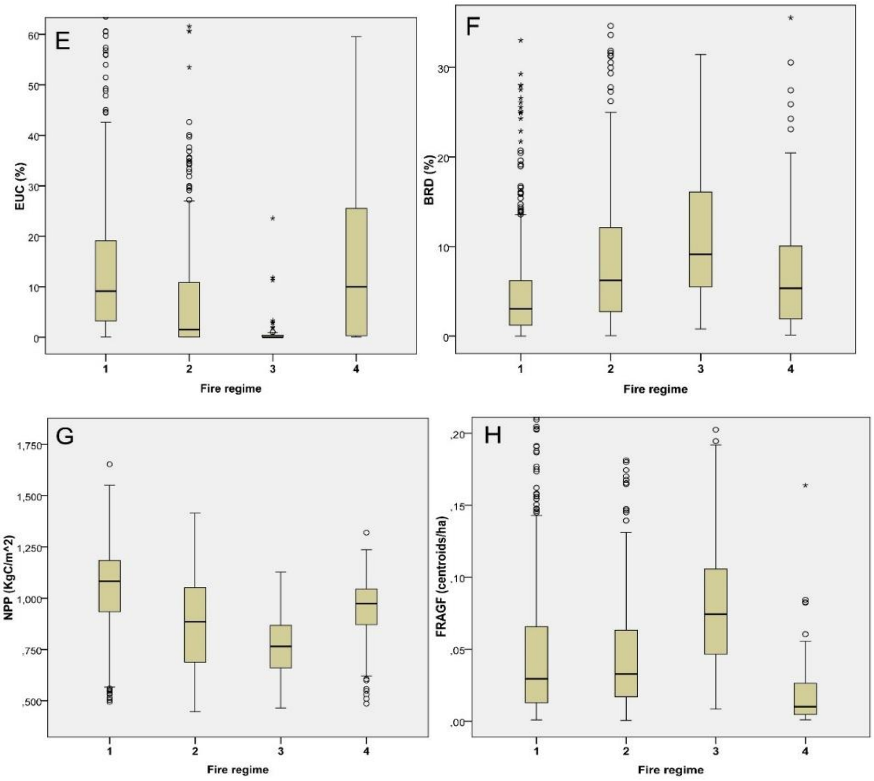


Figure 4 – Boxplots for the values of each biophysical driver in each of the four fire regimes, by decreasing order of importance in the classification tree model. A – SHR; B – RFAJ; C – SLO80; D – AGR; E – EUC; F – BRD; G – NPP; H – FRAGF. The four lowest importance drivers are not shown because their very small values and high level of dispersion in all FRs do not indicate clear patterns. Circles identify potential outliers, defined as situated between 1.5 times and 3 times the interquartile range below the 1st quartile and above the 3rd quartile. Asterisks identify potential extreme outliers, exceeding 3 times the interquartile range below or above the 1st and the 3rd quartile.

FR1 has the lowest percentage of parish area occupied by shrubland, the lowest spring rainfall, the lowest slope and the highest percentage of area occupied by agriculture. These are the four most important variables in the CT model, and their values in FR1 are in accordance with its low CPAB and AWWF. FR1's low shrubland proportion likely contributes to its low cumulative burned area (CPAB) and fire frequency (AWWF), since this landcover type's fire-proneness and quick regeneration promotes extensive and frequent fires (Bergonse et al., 2022; Moreira et al., 2009; Oliveira et al., 2014, 2020), as seen in FR3. Spring rainfall is linked to vegetation growth and thus fuel availability during the warmer summer months, therefore having a positive influence both over AWWF and CPAB (Bergonse et al. 2022), as highlighted by different authors (Oliveira et al., 2012; Xystrakis et al., 2014). Low spring rainfall values will, conversely, be associated with both low wildfire extensiveness and frequency, as seen in FR1. Slope promotes wildfire spread (Marques et al., 2011; Parente & Pereira, 2016), with the lowest slope values in the study area being in accordance with the minimum CPAB values shown by FR1 in relation to all other FRs. Finally, the higher proportion of agricultural land is also expected to contribute to the low CPAB and AWWF of this fire regime, due to its low fire-proneness (Moreira et al., 2009; Oliveira et al., 2014).

FR3 presents opposite characteristics to FR1, showing the maximum percentage of shrubland and the maximum values of spring rainfall, as well as second highest slope values. This fire regime has also the lowest percentage of eucalyptus among all four FRs, which would seem contradictory given the relative fire-proneness of this LULC (Meneses et al., 2018; Xanthopoulos et al., 2012). However, this suggests that the fuel availability behind FR3's high CPAB is mostly dependent on shrubland and its faster response to spring rainfall. This is confirmed by FR3's low Net Productivity Ratio, the lowest among all FRs, which is indicative of a relatively reduced forest cover. Nevertheless, FR3 is marked by the highest incidence of forests of broadleaves other than eucalyptus, cork oak and holm oak of all FRs. As this LULC class has a positive effect over CPAB and AWWF (Bergonse et al., 2022), this suggests that forest-type fuels also have some importance in FR3.This fire regime also shows the greatest burned area extension (CPAB), despite having the highest forest patch fragmentation of all FRs. Although a high level of fragmentation can be expected to constrain extensive wildfires (Gralewicz et al., 2012; Ryu et al., 2007), the dominant fuel type in FR3 is shrubland; therefore, even if each individual wildfire is constrained in its spread, the quick regeneration of fuels will nonetheless allow for frequent burning, leading to an important accumulation of burned area over time.

FR4 shows a relatively high cumulative burned area (CPAB), which is in accordance with its biophysical characteristics: a relatively high percentage of shrubland, high spring rainfall, the highest slope inclination, and the lowest percentage of agriculture. This fire regime also shows a relatively high percentage of eucalyptus forests. The importance of forest cover in FR4 is indicated by the relatively high Net Productivity Ratio, suggesting that, unlike FR3, this fire regime is more dependent on slowly regenerating forests for fuel instead of shrubland. The high damage concentration over time (GCI) found can be linked to the degree of forest patch fragmentation, the lowest amongst all FRs, indicating the potential influence of fuel and forest continuity to the occurrence of higher damages even when wildfire frequency (AWWF) is low. This suggests the importance of creating fuel discontinuities at the landscape level to prevent large and severe wildfires (Benali et al., 2021).

4. Conclusions

Four distinct fire regimes (FR) can be differentiated within central Portugal. FR1 occurs along the coastal area and in the southeasternmost limit and is marked by the least extensive burned area and the lowest wildfire frequency, as well as the maximum temporal concentration of damage. FR2 occurs in most of the centre and eastern sectors. It is marked by more extensive burned areas and more frequent wildfires than FR1, as well as lower temporal concentration of damage. FRs 3 and 4 are characterized by the most extensive burned areas, and contrast in terms of wildfire frequency and temporal concentration of damage. FR3 occurs mostly in the NE of the study area. It has the most extensive burned area of all, as well as the most frequent wildfires, with burn damage dispersed through time. FR4, occurring mostly in the central sector, has slightly less extensive burned areas, but a much lower wildfire frequency, with the damage being more concentrated in time. LULC, slope and spring rainfall are the most important drivers of these distinct fire regimes. The most relevant LULC classes are shrubland/spontaneous herbaceous vegetation and agriculture, the first due to its fire-proneness and quick regeneration, and the second due to its constraints over wildfire spread. Slope facilitates wildfire spread, whereas spring rainfall promotes fuel availability for burning later in the year. Despite the good discriminating capacity of the classification tree model, other drivers, likely of a social nature, might also influence the fire regimes in the study area.

5. Aknowledgments

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