Environmental Factors Affecting Wildfire Burned Area In South-Eastern France, 1970-2019

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Abstract. Forest fires burn an average of about 440,000 ha each year in southern Europe. These fires cause numerous casualties and deaths and destroy houses and other infrastructures. In order to elaborate suitable fire-fighting strategies, complex interactions between human and environmental factors must be taken into account. In this study, we investigated the spatio-temporal evolution in burned area over a 50-year period (1970-2019) and its interactions between topography (slope inclination and aspect) and vegetation type in south-eastern France by exploiting Geographic Information System databases. Burned area decreased sharply after 1994, with the advent of the new fire suppression policy which focused on rapid extinction of fires in their early phase. The geographic distribution of burned area has also changed in the last 25 years, mainly in regions where large fires occurred (Var department). In other parts, even though forest fires are still frequent and occur in the same geographic locations, the total extent of the burned area is significantly reduced. Slope orientation presents an increasingly important role every decade, S-facing slopes have the greatest burned areas and increase their proportion each decade, while the opposite is observed for N-facing and W-facing ones. Fire increasingly favors low and intermediate slopes after the sharp decrease of burned area in 1990. The largest part of the BA is strongly associated with the location of sclerophyllous vegetation clusters, which exhibit high fire proneness while simultaneously expanding the region. On the contrary, natural grassland numbers decline through time as the proportion of area burned increases.

1 Introduction

Forest fire is a common and important element of the earth system (Bond and Keeley, 2005) that is capable of severely disturbing natural ecosystems and threaten human welfare and wellbeing throughout the globe. The Mediterranean climate is characterized by hot and dry summers which favor fire ignition and propagation. Consequently, wildfires are particularly active around the Mediterranean basin and Mediterranean-climate areas and are considered to have a plethora of environmental and socioeconomic impacts (Miller et al., 2009; San-Miguel-Ayanz et al., 2013; Ganteaume et al., 2013).

Forest fires burn an average of 440,000 ha each year in the Euro-Mediterranean region which corresponds to about 85% of the total burned area (BA) in Europe (San-Miguel-Ayanz et al., 2020). Out of the 5 principal Euro-Mediterranean countries

concerned by forest fires (France, Greece, Italy, Portugal and Spain), France has the lowest amount of BA (San-Miguel-Ayanz et al., 2020). It also has the smallest potential burnable area since only the southern Mediterranean fringe is concerned by forest fires. France, Spain, Italy, and Greece all show similar trends in decreasing decadal BA in 1980-2010; of the 5 southern Euro-Mediterranean states, only Portugal has experienced a progressive increase during this same period (San-Miguel-Ayanz et al.,

35 2020). It should be noted that BA are generally decreasing despite increases in summer temperatures throughout the Euro-Mediterranean zone (Pokorná et al., 2018; Rodrigues et al., 2020), and this can be attributed to more efficient fire-fighting strategies (Fox et al., 2015; Ganteaume and Barbero, 2019).

Forest fire spatial distribution, size and frequency is associated with several factors which have been systematically studied to better understand the spatial patterns, improve fire management and prevention planning. These factors are highly interactive

40 and can be categorized into two main groups: i) environmental and ii) anthropogenic. Environmental factors generally include fuel characteristics (e.g type, water content), topography (e.g slope, altitude) and weather conditions (e.g temperature, humidity, wind) while anthropogenic factors include the characteristics of the transitional zone between wildland vegetation and artificial areas in the Wildland Urban Interface (WUI).

Among the environmental characteristics, several studies provide evidence of spatial patterns relating topography to forest fire

45 probability (Dickson et al., 2006; Padilla and Vega-García, 2011) and burnt area (Nunes et al., 2016). Slope aspect can determine the fuel type, fuel moisture and fuel density which influences flammability (Holden et al., 2009) though its impact on incoming solar radiation. Additionally, aspect influences the degree of ecological change related to fire (fire severity) is (Birch et al., 2015; Estes et al., 2017; Parks et al., 2018). In the northern hemisphere, south-facing slopes receive higher solar radiation during the day than northern slopes which enhances burn severity in many studies (Alexander et al., 2006; Oliveira

50 et al., 2014; Oliveras et al., 2009) but not all (Broncano and Retana, 2004). In addition to fire severity, other studies (Mouillot et al., 2003) demonstrated that south-facing slopes Corsica (France) also burn more frequently than other exposures. On the North shore of the Mediterranean, South-facing slopes frequently have more housing than north-facing slopes, and this may contribute to a greater number of ignitions (Fox et al., 2018). High slope inclination increases rate of spread, affects fire propagation and fire intensity (Capra et al., 2018) while also influencing the fatality rate (Molina-Terrén et al., 2019). Csontos

55 and Cseresnyés (2015) observed an exponential velocity increase in upslope fire spread with the increase in slope inclination whereas downslope fire spread velocity was unaffected by slope angle and was similar to rates detected on flat terrain. Elia et al., (2019) found that the probability of fire ignition increased with elevation and slope in southern Italy.

The role of vegetation is complex and can be influenced by flammability (Michelaki et al., 2020; Molina et al., 2017) or spatial patterns of vegetation in the landscape (Curt et al., 2013). Fuel continuity affects fire propagation contributes to determine BA

60 (Duane et al., 2015; Fernandes et al., 2016). Shrublands are regarded as fire prone areas in a number of studies (Mermoz et al., 2005; Moreira et al., 2011; Oliveira et al., 2014), and the probability of large fires in landscapes with dense shrublands is greater than in forested ecosystems in the Mediterranean basin (Moreira et al., 2011; Ruffault and Mouillot, 2017). According to Mermoz et al., (2005) fire proneness of shrublands could be related to their recovery rate since shrublands can regenerate faster and favor fuel accumulation in a short time unlike forests which take longer to recover and spread. Overall, in Europe,

65 other vegetation types, such as grasslands, are also considered to be fire prone (Oliveira et al., 2014). Cultivated areas are the least fire prone types, mainly because of their low combustibility, and their geographic proximity to built-up land covers which facilitate rapid fire detection and suppression (Moreira et al., 2011). Forested areas are found to be more fire prone than cultivated areas but less than shrublands (Moreira et al., 2011). More specifically, broadleaved forests are usually less prone to burning than coniferous species which present a greater fire hazard (Moreira et al., 2009; Oliveira et al., 2014).

70 Many studies have focused on determining relationships between fire behavior and driving factors (Mhawej et al., 2015), and the relative level of importance of factors can vary from one region to another, the environmental and socioeconomic contexts, and the scale of a study (Moritz et al., 2005; Lafortezza et al., 2013; Ganteaume and Long-Fournel, 2015). In addition, few studies have examined how efficient fire suppression strategies impact the spatial distribution of BA. Identifying spatial patterns and the main driving forces that determine fire distribution provide useful information for fire and civil protection

75 agencies, and it assists in allocating appropriate firefighting resources and in designing proper prevention actions especially in the Mediterranean area (Moreira et al., 2011).

The objective of this study is to quantify changes in BA spatial patterns induced by a major shift in fire suppression strategy that was initiated in the early 1990s in South-eastern France. The time interval under study spans 5 decades (1970-2019) and includes the relation of BA with respect to environmental factors such as a) topography (slope inclination and slope orientation)

80 and b)vegetation type. Although several studies have investigated the relationships between burned area and environmental factors, none has covered such a long-time interval based on burn scar polygons, nor have they been explicitly related to changes in fire suppression methods.

2 Data and Methods

2.1 Study area

85 The study area is comprised of a subset of the 3 administrative departments with the greatest BA in continental France (only Corsica has greater burned area) according to the official database for forest fires in the French Mediterranean area (promethee.com): Bouches-du-Rhône, Var, and Alpes-Maritimes (Table 1, Fig. 1). The areas within the departmental limits that were excluded, represent surfaces that cannot burn such as: i) marshlands in the westernmost part of Bouches-du-Rhône and ii) high alpine mineral surfaces located in the northern part of Alpes-Maritimes.
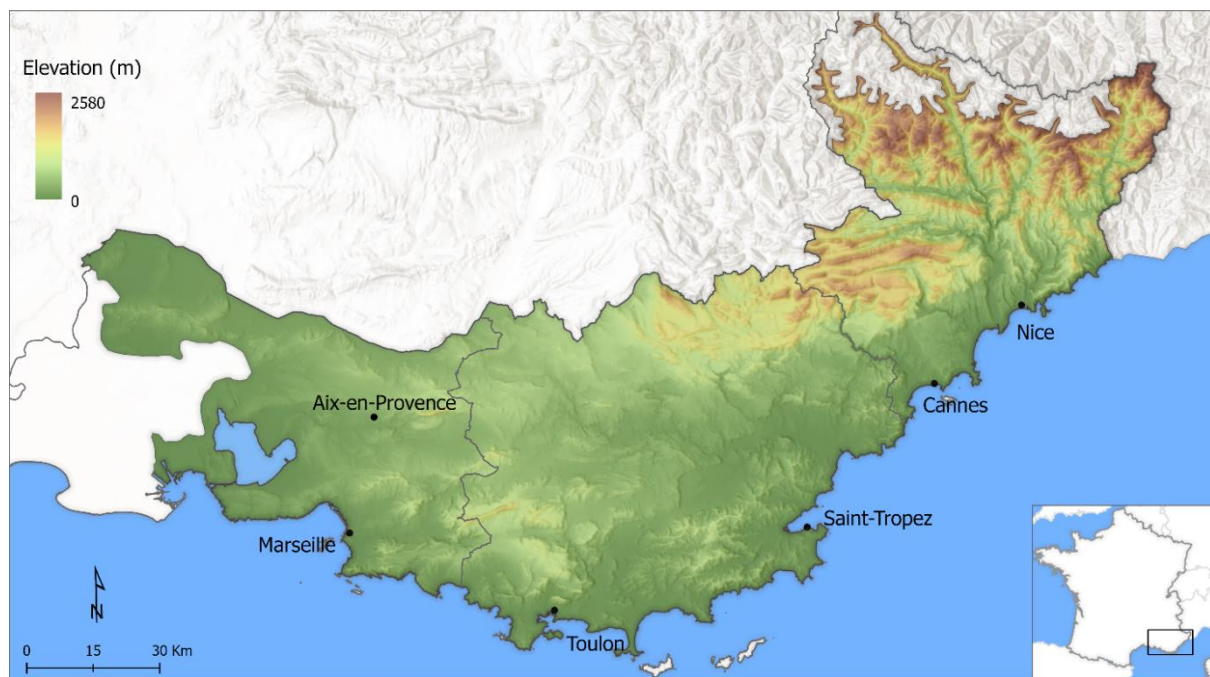
Figure 1: Map of south-eastern France showing the study area and the departmental limits overlaid on a 5 m Digital Elevation Model.

Table 1: Environmental characteristics of the study area per departmental unit

	Bouches-du-Rhônes	**Var**	**Alpes-Maritimes**
Total area (km²)	3456	6019	3495
Forested area (km²)	1530	4044	2727
Ratio forest/total (km²)	0.44	0.67	0.78
Mean slope (°)	8.8	11.9	24.3
Median slope (°)	5.7	9.6	25.2

Topography varies noticeably from West to East (Fig. 1). The gentlest slopes are found in the west (Bouches-du-Rhône) and both altitude and inclination increase towards the east. The steepest slope inclinations are found in the northeastern part of the study area where the French Alps are located. Topography influences population distribution since much of the built area is concentrated along the coast or on shallow to intermediate slopes in the WUI. In the Bouches-du-Rhône, the western portion of the department has particularly low population densities due to the presence of the national park and wetlands mentioned above. Similarly, much of the population in the Alpes-Maritimes is concentrated in the southern portion of the department. The 2010 population densities of 388.8, 167.5, and 252.0 persons/km² for the Bouches-du-Rhône, Var, and Alpes-Maritimes, respectively, are therefore only gross approximations as they simply divide population by total area without accounting for

geographic distributions. The order, however, is accurate and shows the greatest population density for Bouche-du-Rhône, and
the lowest for the Var. Based on the demographic and environmental characteristics described above, the westernmost section
(Bouche-du-Rhône) of the study area has low potential for fire ignition and propagation but increases when moving towards
the eastern half of department. The central part of the study area (Var department) has a high potential for fire ignition and the
greatest potential for fire propagation since it has a high forested area and a large continuous WUI area. Finally, the eastern
section (Alpes-Maritimes department) has high ignition and propagation potentials in the southern portion of the department
and low ignition / high propagation at higher altitudes.

2.2 Fire database

Forest fire research in France is usually based on the national database for forest fires in France (www.promethee.com) where
fire location is described by municipality where ignition occured. For this study, we used a fire Geographic Information
Systems (GIS) database provided by the National Forestry Office (Office National des Forêts, ONF). The dataset includes
more than 3,000 digitized burn scar polygons for fires that occurred between 1970 and 2019. Due to the long temporal extent
of the database, the level of accuracy as well as the method used to define burn scars varied over time. In the 1970s, burn scars
were mapped using field measurements with GPS devices, and the technique progressively evolved to integrate remote sensing
data (satellite imagery, orthophotos). Although the description of how BA was defined is not recorded in the database, earlier
polygons are clearly less accurate (coarse shapes with little detail) than burn scars after the advent of satellite imagery (Fig.
2).
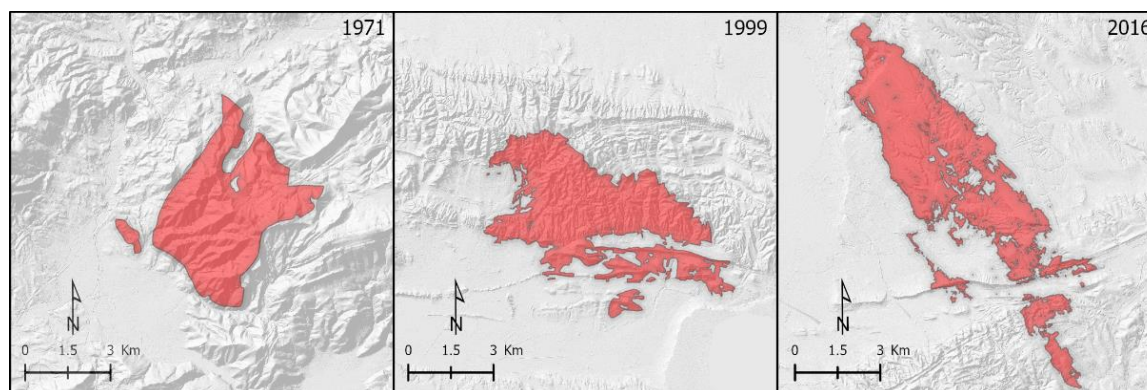
Figure 2: Evolution of digizited burn scar accuracy over the past decades.

2.3 Spatiotemporal analysis of burned area 1970-2019

A 500x500 m grid was created and overlaid on the study area in order to measure the percentage of the area that was burned
inside every 25 m cell for each year (Fig. 3). Subsequently, the percent values were summarized to produce the cumulative
percentage of BA for each cell. This approach facilitated the effort to identify clusters of cells/areas that have been burned
multiple times through time. To better illustrate the spatial and temporal trends in the study area, the aforementioned

methodology was applied into two 25-year subsets of the fire dataset i) 1970-1994, and ii) 1995-2019. The distinction between the earlier and later intervals of the time frame were made to highlight the impact of suppression strategies on fire occurrence.

130   Subsequently, all the data were analysed at the decadal temporal scale in order to obtain a finer resolution of temporal trends.

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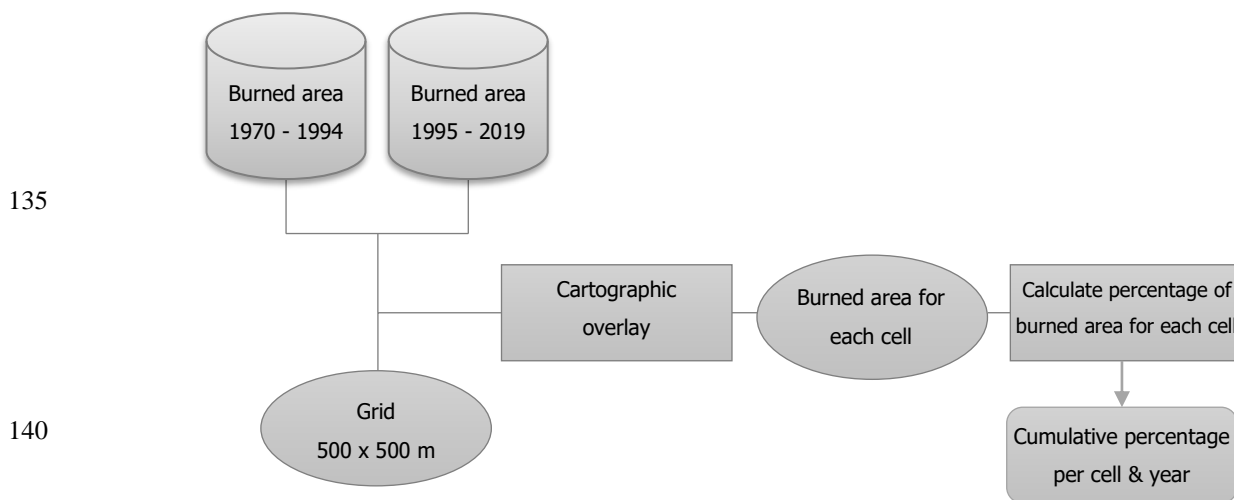
Figure 3: Flow chart depicting the processing steps to generate the cumulative percentage of forested burned area per cell.

2.4 Topography

Burn scar polygons were rasterized and overlain on a 5 m Digital Elevation Model (DEM) extracted from RGE-ALTI©, the
145   official National Geographic Institute (Institut Géographique National, IGN) database. The DEM was used to calculate aspect and slope inclination (Fig. 5). In the conversion of vector polygons to raster cells, BA smaller than half the cell size (25 m²) were not defined as burned during rasterization, so BA for the aspect and slope inclination analyses represent approximately 96% of actual BA in the study area. Both aspect and slope inclination were analyzed at decadal time intervals (1970-1979, 1980-1989, 1990-1999, 2000-2009, 2010-2019). Aspect was divided into intervals of 22.5°, so 8 categories were used: NW,
150   N, NE, E, SE, S, SW, and W. Total BA per aspect and BA per forested aspect were extracted from the data, but only BA per forested aspect will be shown here since the trends are nearly identical. Slope was divided into 5 categories: 0-10°, 10-20°, 20-30°, 30-40°, 40-50°, 50-60° and 60-90°. Results for slope inclination and aspect will be presented according to the distribution of BA among forested slope categories and the percentage of a forested slope category burned.

2.5 Forested areas

155   For the computation of the forested BA and the identification of fire-prone vegetation categories, GIS forest layers were extracted from the European CORINE land cover (CLC) database. The database includes five reference years 1990, 2000, 2006, 2012 and 2018. BA by vegetation type used the CLC layer closest to the BA data (see Table 1). In addition to the CLC reference layers, it was considered best to backwards forecast two additional forest cover layers for 1972 and 1980 to account

for any transitions of forested surfaces to non-forested ones or the opposite, for the two decades preceding the creation of the

160 CLC database. The methodology followed for the projection process is addressed in Subsection 2.5.1.

Table 2: Corine land cover layers and their respective fire periods.

Corine land cover	Fire period
1972 (Projected)	1970 – 1974
1980 (Projected)	1975 – 1984
1990	1985 – 1994
2000	1995 – 2002
2006	2003 – 2009
2012	2010 – 2014
2018	2015 – 2019

The vegetation types that were used in the current study follow the CLC nomenclature: Broad-leaved forest, Coniferous forest, Mixed forest, Natural grassland and Sclerophyllous vegetation (Fig. 4). Although Natural grassland and Sclerophyllous

165 vegetation are not forests, the categories will be referred to collectively as wildland or forested areas indiscriminately for the sake of brevity.
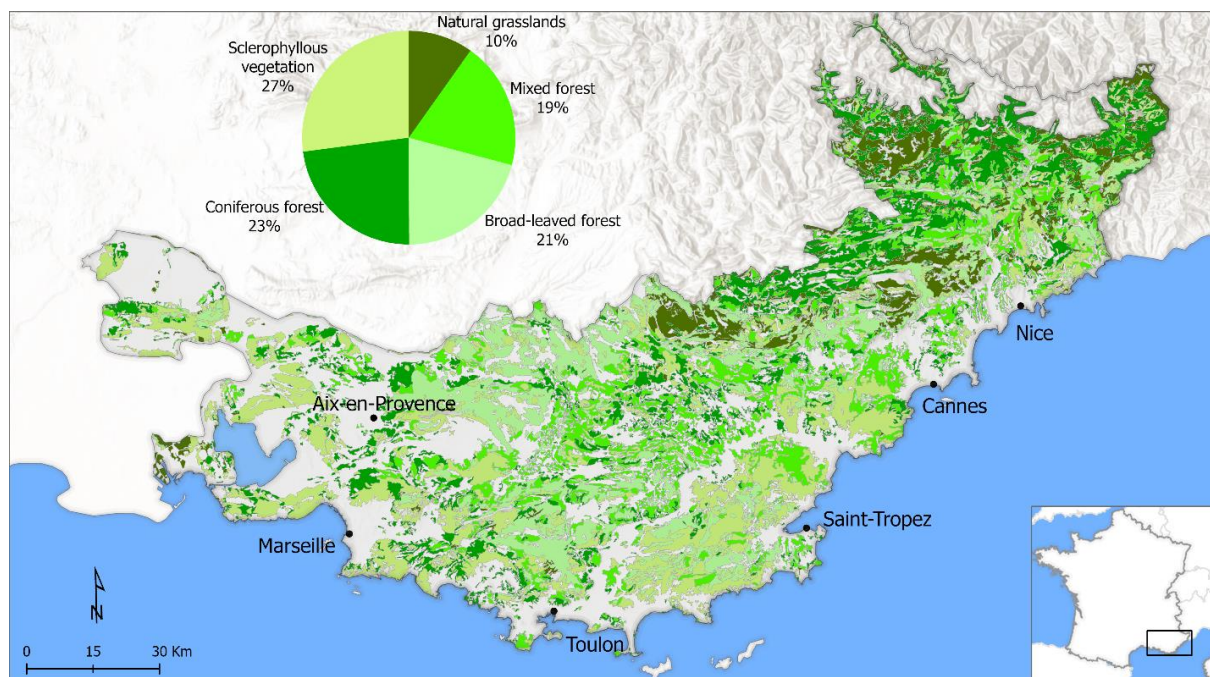
Figure 4: Distribution of forest types based on CLC 2018.

2.5.1 Forest layer projection

170 Although most urban growth occurred on agricultural land (Roy et al., 2015) and forest cover changed little, the Land Change Modeler (LCM) module of Terrset (Eastman 2020) was used to predict vegetation cover in 1972 and 1980. LCM is programmed to forecast change from an earlier to a later date, so going back in time required the temporal inversion of filenames for the 1990 (renamed to 200) and 2000 (renamed to 1990) CLC layers; in this way, land cover was predicted for 2010 (1980) and 2018 (1972). Land cover categories were simplified from the original CLC categories to the following: Built,

175 Broad-leaved forest (Broad), Coniferous forest (Conifer), Mixed forest, Natural grassland (Grass), Sclerophyllous (Bush), Other, and Water. Only transitions greater than 0.05% of the landscape (14.3 km²) were modeled, and these included the following (From-To): Bush-Grass, Bush-Other, Built-Other, Grass-Other, Broad-Bush, Other-Grass, Bush-Conifer, Other-Bush, Bush-Broad, Bush-Mixed, Mixed-Bush, Other-Conifer, Mixed-Broad, Mixed-Other, Other-Broad, Other-Mixed, Broad-Other, Grass-Bush, Mixed-Conifer, Built-Mixed, Built-Bush, Conifer-Mixed. Note that these are the inverse of historical

180 trends, so the Built-Mixed transition actually back forecasts the historical transition of Mixed forest to Built area.

Explanatory variables used to predict land cover change were the following: Altitude, Slope inclination, Distance from Built area, Distance from Broad, Distance from Conifer, Distance from Mixed, Distance from Grass, Distance from Bush, Distance from Other and Distance from Water. According to Eastman (2020), Cramer's V values of ≥0.15 for explanatory variables are useful and should be kept in the model, and all explanatory variables used here met those criteria. Accuracy rates to model

185 transitions ranged from 65% to 90% with mean and median values of 78 and 80%, respectively.

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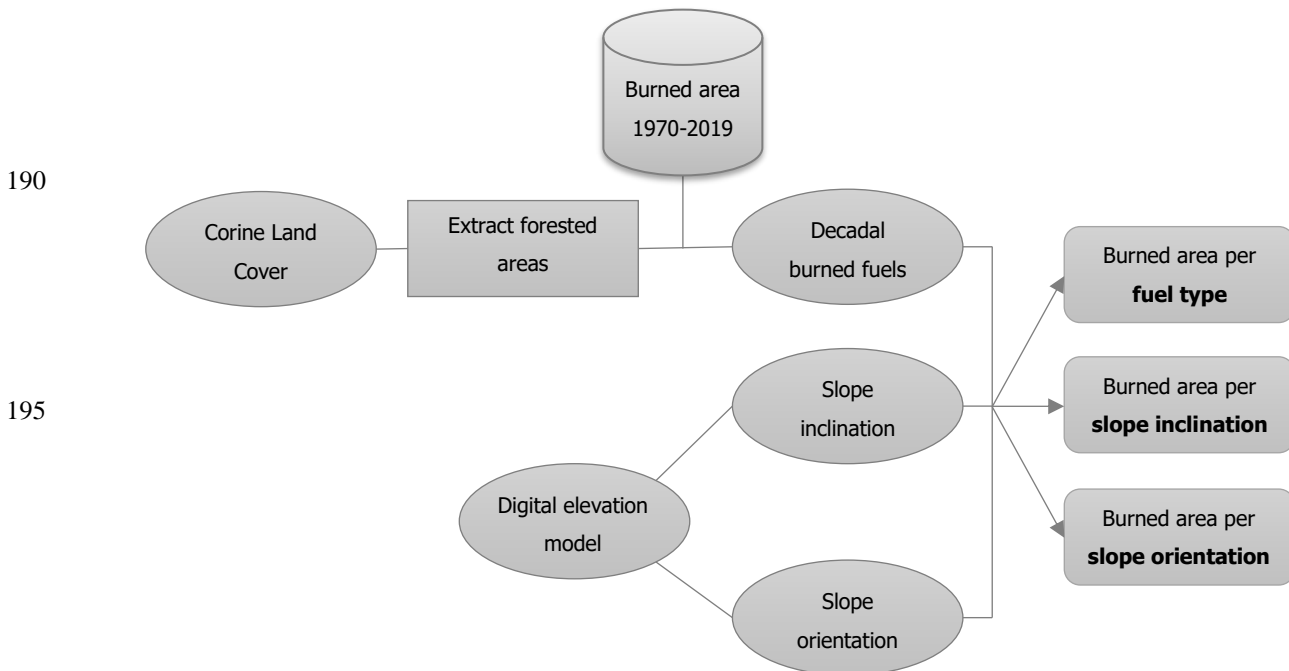


Figure 5: Flow chart depicting the processing steps and data used to relate BA to fuel type, slope orientation and inclination.

3 Results

Results presented below will first describe the fire history for the 1970-2019 interval, subsequently analyze the spatio-temporal evolution of BA split in two 25-year periods and finally explore the relationship of BA to topography (slope orientation and inclination) and fuel type. Factor-specific results will be discussed as they are presented in the following results sections while broader considerations will be explained in the Discussion section.

3.1 Fire history 1970-2019

In total, 3,382 fires occurred between 1970 to 2019 that burned 296,820 ha. The average size of burned scars is 87.7 ha and the median value is 4.2 ha. The number of fires equal to or greater than 100 ha, 500 ha, and 1,000 ha is 378, 123 and 65 respectively. Regarding the fires that occurred on forested landscapes, the total number of fires for the same period is 2,424 that burned 263,645 ha, which corresponds approximately to 88.2% of the total BA. The average size of BA in forested landscapes is 111.7 ha and the median value is 6.5 ha. The number of fires equal to or greater than 100 ha, 500 ha, and 1,000 ha is 314, 106 and 60 respectively. As stated above, the results exclusively deal with the BA that was occupied by one of the forest types mentioned in section 2.5 since the trends with respect to vegetation and topography are almost identical.

Annual forested BA varies significantly from year to year (Fig. 6) although there are clear differences between the first two decades (1970-1990) and the last three (1991-2019). Most of the big fires occurred in the 1970s and especially in the 1980s followed by a sharp decrease in the beginning of 1990s. Similarly to the rest of the southern Mediterranean Europe, the majority of the forested BA is related to a small number of large fires (Turco et al., 2016). Only 5 of the 50-year record account for approximately half of the total forested BA (125,000 ha) (1979, 1986, 1989, 1990 and 2003). The recorded forested BA in these years surpasses 20,000 ha with the highest one documented in 1989 with nearly 36,000 ha burned. Only a single year (2003) with such high total BA can be found after 1990. As described by Fox et al., (2015) for the Alpes-Maritimes, this corresponds to an improvement in fire-fighting strategy, and the same explanation appears to hold for the neighboring departments.

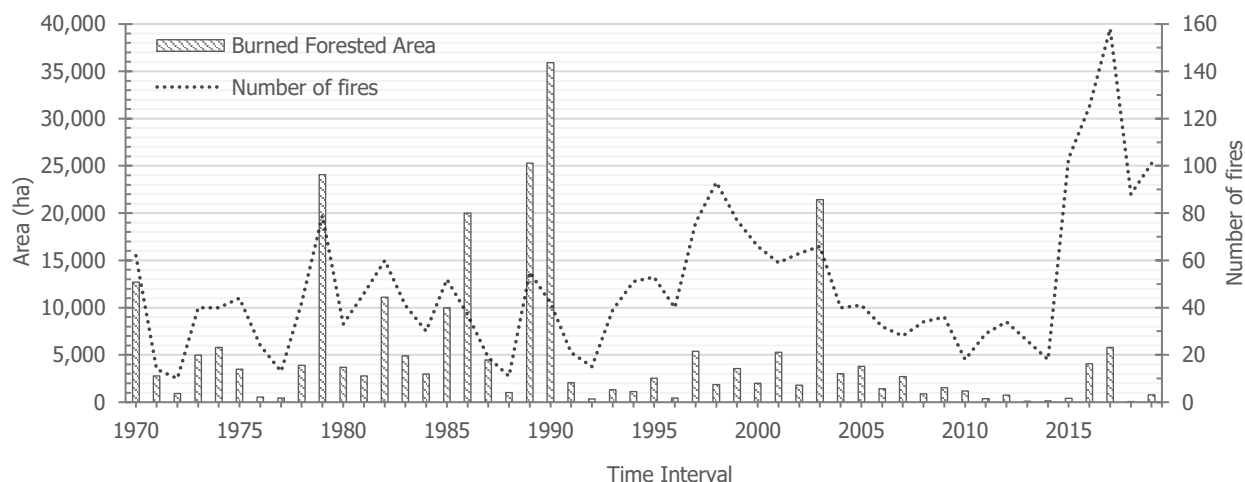
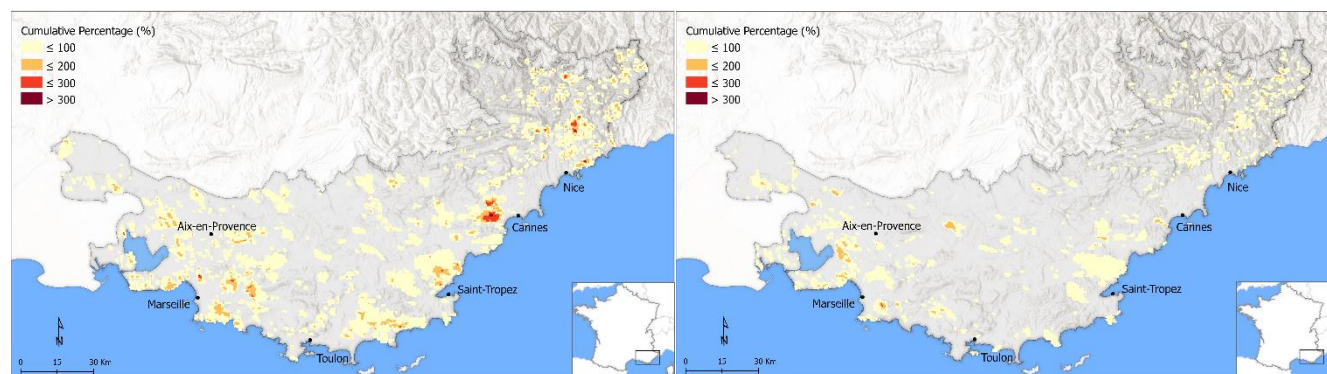



Figure 6: History of annual forested burned area and number of fires from 1970 to 2019.

Figure 7 maps cumulative percentage area burned inside each 25 ha cell, split into two 25-year periods, 1970-1994 and 1995-
225   2019. Generally, most fires occur in the WUI north of the large coastal cities since densely developed areas have too little
vegetation to burn, and relatively remote areas have too few ignition sources. Although we did not treat wind direction or
speed, BA shapes in both periods tend to align themselves with known wind patterns in the region: they have a NW-SE
orientation throughout most of the western and central sections (Bouches-du-Rhône and Var departments) but show little
preferential orientation in the eastern one (Alpes-Maritimes) where wind speeds are lower than in the Rhône valley subject to
230   the local "Mistral" winds. Overall, there is an explicit difference between the two periods with the second one having
significantly fewer burned cells, which are also slightly more spatially dispersed. In addition, cumulative percent values are
noticeably lower, with a small number of cells exceeding 100% and only a few reaching 300%. All major hotspots disappear
in the second interval apart from some located mainly in the western area of study zone near Aix-Marseille.

235   **Figure 7: Cumulative percentage of forested burned areas in the 1970-1994 interval (left) and in the 1995-2019 interval (right) over a 25x25m grid.**

The largest patches in both intervals are found in the central part of the study zone which combines continuous forest cover
and a lower population density that is distributed more evenly throughout the department (Var). Additionally, the two largest

continuous BA clusters are found here, one north of Saint-Tropez and one east of Toulon (near Hyères). In the second time

240   interval the first cluster shrunk whereas the second one completely disappeared. In the western section of the study area, burned patches are located in constrained areas between densely built zones (Aix-en Provence and Marseille) with several cells displaying high fire recurrence. In the latter period (1995 to 2019) frequently burned patches appear to have shifted from inland towards the coast; fire recurrence remains relatively high, especially considering that in the second period the total BA in forested landscapes is considerably lower than in 1970-1994. In the eastern section of the study area, population is particularly

245   dense along the coast (Cannes-Nice), BA cells are concentrated inland along the periphery of the coastal built-up area. A major hotspot is found just west of Cannes that exhibits the highest cumulative percent values, which however almost disappears in the second period. In comparison to the rest of the study area, patches are smaller and more numerous with high to very high recurrence, even at high altitudes (particularly close to the French-Italian border). A noteworthy difference between the first and the second interval over both the western and the eastern segments of the study zone, is that even though the number of

250   burned cells appears to be similar the clusters of cells are smaller, which potentially indicates that even though a fire was lit it was quickly contained.

Overall, the patterns described here are coherent with known interactions between fire ignition, vegetation continuity, and wind speed: fire ignition occurs most frequently in proximity to human activities (Badia et al., 2011; Chas-Amil et al., 2013; Jiménez-Ruano et al., 2017; Lampin-Maillet et al., 2011) and BA depends on fuel continuity and wind speed (Dueane et al.,

255   2015; Fernandes et al., 2016).

3.2 Burned area distribution and topography

Topographic effects studied here include both aspect and slope inclination. For each of these, data will be presented firstly as the distribution of BA according to slope category (the sum of all bars equals 100%), and secondly as a percentage of the slope category.

260   ### 3.2.1 Burned area according to slope aspect

Figure 10 shows the distribution of BA according to slope aspect, evidently BA distribution favors mainly S-facing slopes (including SE and SW) in all five decades (Fig. 10), and NW and NE slopes tend to have the lowest occurrence. Furthermore, values for S-facing slopes tend to increase with time, indicating that their susceptibility to burn has increased over the 50-year study period. The opposite can be observed for the other slopes, except for E-facing which have remained constant. However,

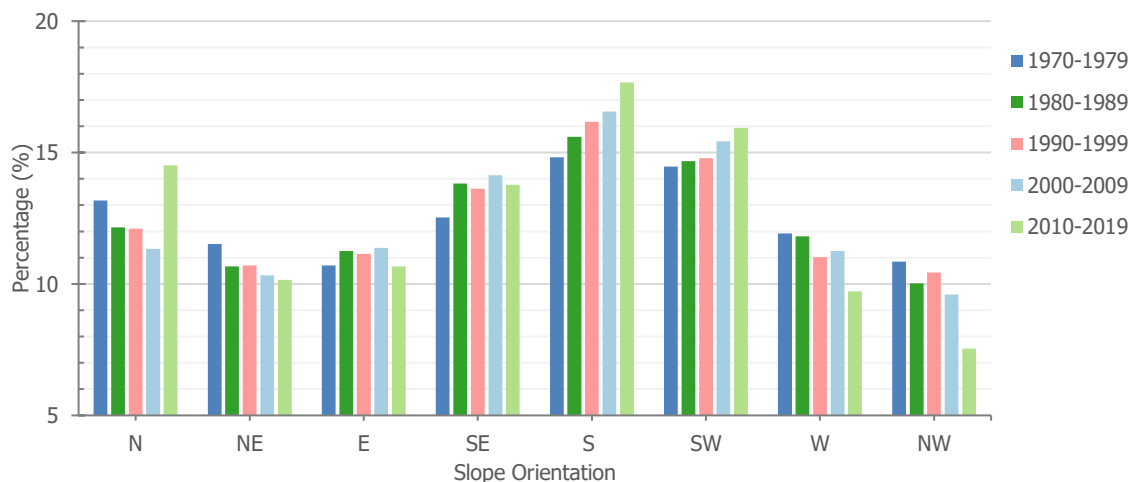
265   on the northern shore of the Mediterranean, there are generally more S-facing (sum of SW, S, SE) than N-facing (sum of NW, N, NE) slopes, and BA distribution may therefore be a simple reflection of area rather than susceptibility to burn. In the study zone, forested N-facing slopes account for about 10.2% of all slopes, while S-facing forested slopes cover 14.4%. These values equal 33.4% and 39.9%, respectively, when generally N-facing (N, NW, NE) and generally S-facing (S, SW, SE) slopes are summed. In order to compensate for this, BA is plotted as a percentage of the burned forested slopes in Figure 9.

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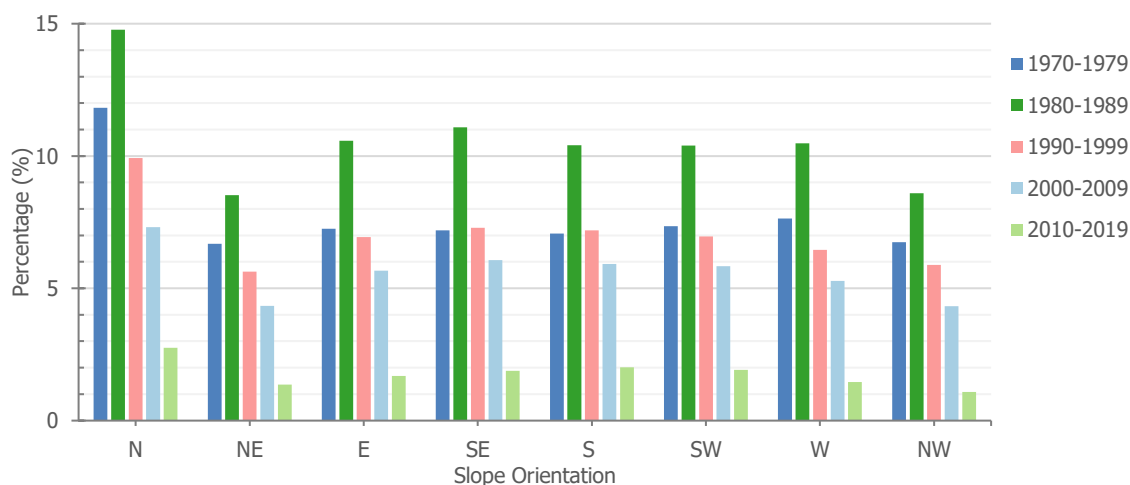
Figure 8: Distribution of BA according to slope orientation by decade (the sum of each decade equals 100%)

Since the size of BA is reflected in Figure 9, bar height peaks in 1980-1989 and decreases sharply afterwards. It is therefore necessary to compare slope aspect trends within a decade to determine slope susceptibility. Contrary to expectations, N-facing slopes burn proportionally more every decade. NE and NW aspects are the ones that proportionally burn the least, so when N-facing (N, NW, NE) and S-facing (S, SW, SE) slopes are summed, proportion values favor N-facing in 1970-1979 (N: 25.2%, S: 21.6%); are perfectly balanced in 1980-1989 (N: 31.9%, S: 31.9%) and 1990-1999 (N: 21.4, S: 21.4); favor S-facing in 2000-2009 (N: 15.9, S: 17.8%) and in 2010-2019 (N: 5.2, S: 5.8%). Overall, it appears that proportion values in all S-facing slopes (S, SW, SE) tend to balance out and even surpass the N-facing ones over the course of time.

280 **Figure 9: Percentage of forested slopes burned according to slope orientation by decade.**

3.2.2 Burned area according to slope inclination

As for slope aspect, Figure 10 shows the distribution of BA according to slope inclination where the sum of all bars within a decade equals 100%. Distributions vary greatly between slopes less than and greater than 30°. Below 30°, there are no clear differences between slope inclination categories. Above 30°, the percentage BA drops abruptly. Temporal fluctuations of the
285 distributions show a general shift from high inclination slopes (40° or greater) to lower inclination slopes (≤20°).

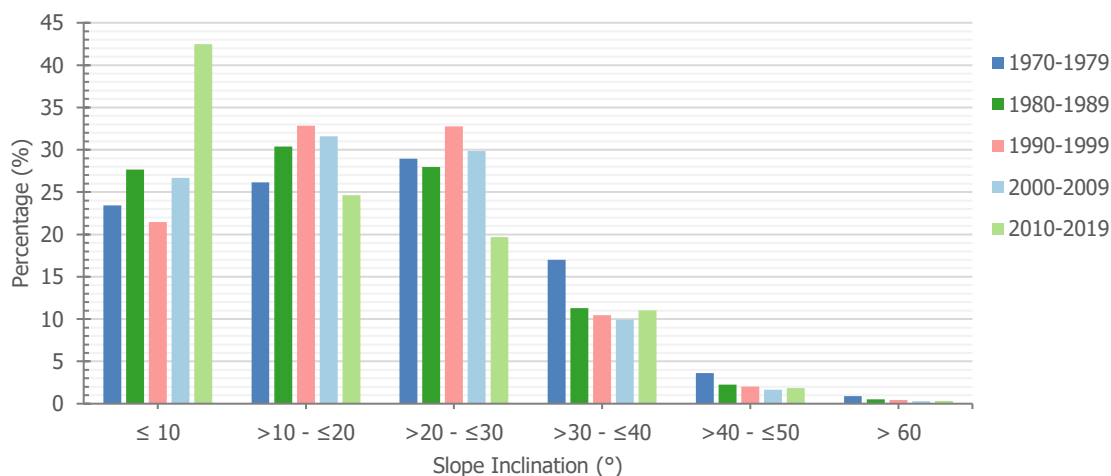



Figure 10: Distribution of BA according to slope orientation by decade (the sum of each decade equals 100%).

Forested slope distributions correspond to the following values: ≤10°, 30%; 10°≤20°, 28%; 20°≤30°, 24%; 30°≤40°, 14%; 40°≤50°, 3%; 50 and greater, 1%. When BA is plotted as a percentage of forested slope inclination area (Fig. 11), a slightly
290 different pattern emerges. As for slope aspect, the absolute area burned dominates bar height in Figure 11, so comparisons must be made within decades to identify spatial patterns. Very steep forested slopes (generally located in the Eastern portion of the study area as described above) burn proportionally more than shallow slopes, but since these slopes represent a negligible proportion of the forested area, we will focus on spatial patterns within the 0-40° range. Within this range, the greatest proportion of burned area is on intermediate slopes of 20°≤30° for all decades except 2010-2019, where differences may be
295 due more to one or a few large fires than to a general trend because of the relatively low burned area. Depending on the decade, the second highest burned slopes can be either just below or above the 20°≤30° range, but the overall tendency is for a slight shift to lower (10°≤20°) slope inclinations over time as described above. Low inclination forested slopes which account for a high percentage of BA in the western (Bouches-du-Rhône) and central (Var) parts of the study area have the lowest percentage burned area values. Over time, steeper slopes are less attained by wildfires.

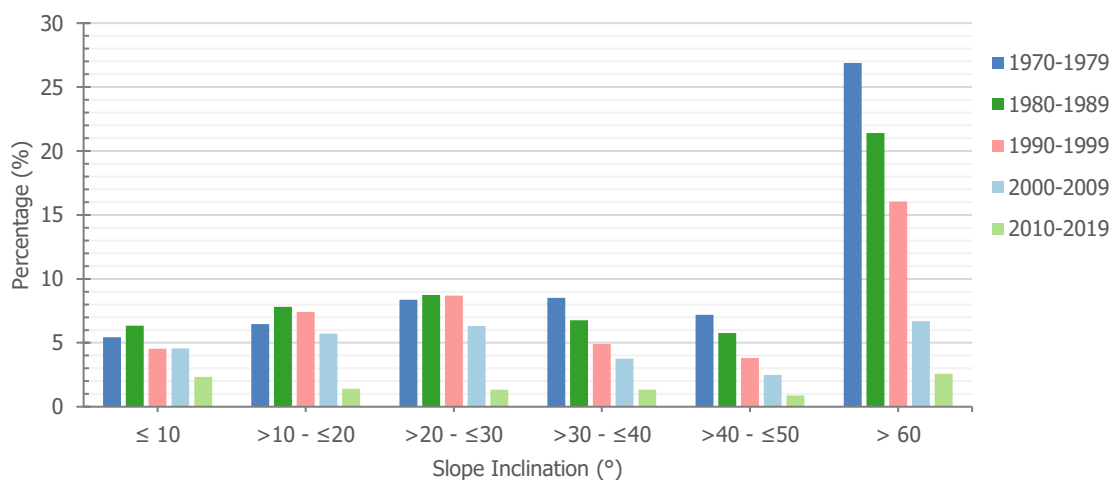



Figure 11: Percentage of forested slopes burned according to slope orientation by decade.

3.3 Burned area according to forest type

Forested and semi natural vegetation is distributed between 5 categories of which grasslands and sclerophyllous vegetation have the lowest and the highest 50-year average covers respectively: Broad-leaved forest, 20.6%; Coniferous forest, 24.1%: Mixed forest, 19.2%; Grasslands, 11.2%, and Sclerophyllous, 24.9%. Through the last 5 decades, mixed forest and broadleaves remained roughly the same in terms of coverage, whereas Conifers present a slight but decreasing trend. Sclerophyllous vegetation is expanding in the area (≈6% increase), becoming the most common type in the last 3 decades. Finally, natural grasslands is by far the least common type and has shrunk slightly (≈3,5% decrease) over the course of the last 50 years.

Table 3 Average and relative forested areas according to vegetation type between 1970 to 2019.

Type	Area (ha)	%
Broad-leaved forest	172,547	20.6
Coniferous forest	201,262	24.1
Mixed forest	160,973	19.2
Natural grassland	93,322	11.2
Sclerophyllous vegetation	208,057	24.9
Total	836,161	

BA by fuel type analysis was also conducted at a decadal time scale in order to better illustrate the distribution of BA and fire susceptibility of the various fuel types over time. Figure 12 depicts the decadal distribution of BA per fuel type from to 1970 to 2019 where the sum of all bars within a decade equals 100%. Sclerophyllous vegetation dominates the distribution,

consistently representing the largest portion of BA in all 5 decades. In addition, its proportion among the fuel types consistently

increases each decade, with the exception of the last one (2010-2019) where a slight decrease is noted. The proportion of

burned sclerophyllous vegetation nearly doubled between 1970-1979 to 2000-2009 from 35% to 68% respectively. BA is more

or less evenly distributed among the other vegetation types. Mixed forest follows a declining trend after 1990-1999, whereas

coniferous forest displays a slow increasing trend after the same period. Broad-leaved forest BA distributions present no

significant change after 1970-1979.

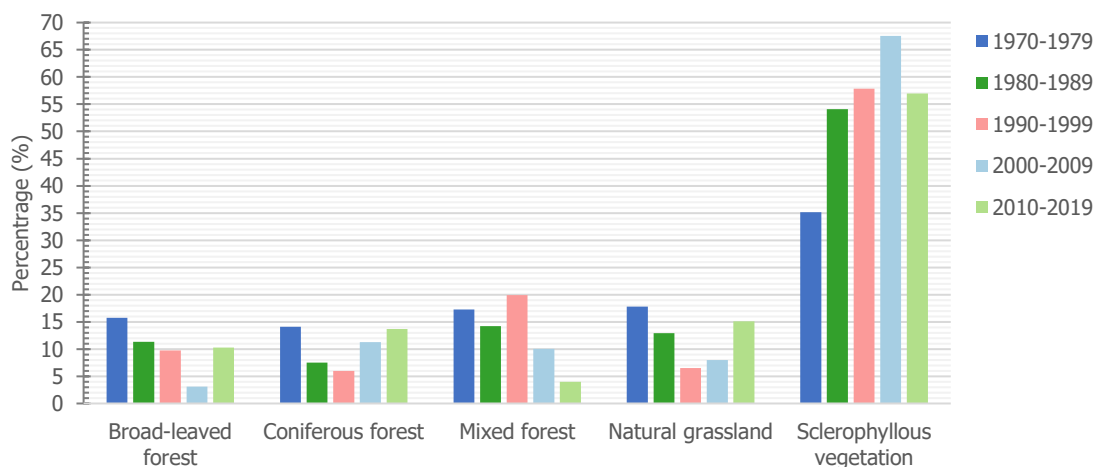



Figure 12: Distribution of burned area according to vegetation category by decade (the sum of each decade equals 100%).

To account for the size and the changes in total area of each vegetation type, the decadal percentage that was burned from the

total area of each category is a presented in Figure 13. Vegetation distributions vary little over the decades where Broad-leaved

forest covers about 21%; Coniferous, 24%, Mixed Forest, 19%; Grassland, 11%, and Sclerophyllous, 25%. This last category

evolved from 21% in 1970-1979 to 27% in 2010-2019, and these gains were made mostly from Grassland (loss of 3%) and

Coniferous (loss of 2%). As for slope aspect and inclination, the general trend follows the rapid decrease of BA after the 1980-

1989 interval, so bar heights generally decrease over time after the 1980-1989 peak. The greatest percentage BA for all decades

is for Sclerophyllous vegetation, where values range from about 2 to 8 times greater than any other cover. In addition, the

susceptibility of sclerophyllous vegetation increases over time despite a small drop in relative importance in 2010-2019.

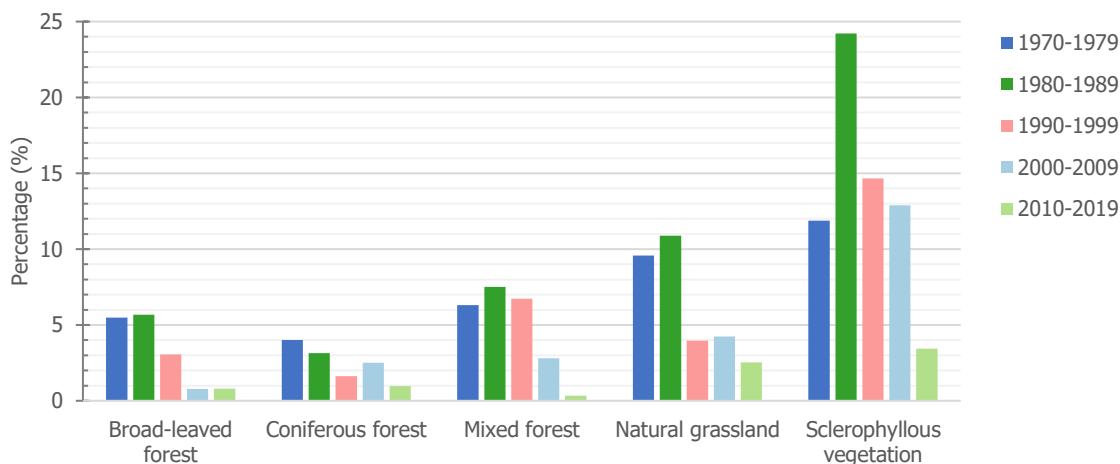



Figure 13 Percentage of vegetation categories burned by decade.

Even though natural grassland represents the least frequent type, and its total coverage decreases slightly over time in the study area, its proportion of BA is similar to or greater than other fuel types after sclerophyllous. Mixed forest tends to have greater percentage burned areas than Broad-leaved and Coniferous and lower than Grassland, except for 1990-1999. On the other hand, conifers exhibit very low proportions even in decades when big fires occurred and appear unaffected by the fire policy change in the 1990s and the amount of BA each decade. Finally, broad leaves are generally situated between Mixed and Coniferous.

4 Discussion

4.1 Fire history

BA in south-eastern France have undergone substantial changes over the last 50 years. Clear declining trends characterize every decade after 1990 and especially in the 2010-2019 interval, where BA represent only 5.3% (13,649 ha) of the total, which is a 68.9% decrease compared to the previous decade (2000-2009). Furthermore, around half of the total BA (125,000 ha) was recorded in 5 years: 1979, 1986, 1989, 1990 and 2003. Due to the catastrophic fires in the period between 1986 to 1990, a new fire policy ("Vulcain") was established that came fully into effect in 1994 (Direction de la Sécurité Civile, 1994). This new strategy focused on aggressively suppressing fire ignitions under any weather conditions in order to avoid the propagation of fire to the extent where suppression would become more difficult and expensive. Although Fire Weather Index values were not calculated here for the 3 administrative departments, Fox et al. (2015) noted a general increase in summer temperatures between about 1980 and 2010, so the fire-fighting policy had a major impact on the decrease in total BA after 1994, with the exception of 2003. This year was the hottest/driest year on record in the Alpes-Maritimes since at least 1973 (Fox et al., 2015), and although its BA was greater than any other year since 1991, it was not exceptional compared to the

1979-1990 time interval. Nonetheless, it raised doubts regarding the sustainability of the rapid extinction strategy and its ability to reduce fire risk in the long term since resources are spread thinly over a greater number of ignitions (Curt and Frejaville, 2018).

355 The effect of the new firefighting strategy can also be viewed spatially; fire patches are less large and are distributed over smaller geographic proximities with one another, and fire recurrence is lower and clustered mostly near populated zones. Despite the size of the study area and the physical proximity of the burned scars, there are different reasons that are contributing to determine the fire pattern before and after the policy change. In areas such as around Aix-en-Provence and Marseille where the low vegetation continuity affects the extent of the fire, the change of fire-fighting strategy had lesser effect, whereas in the

360 central part of the study area, where most of the big scars are located, the new fire policy was able to effectively limit the propagation of fire over the continuous forest cover that defines the region. In the eastern segment of the study area, which involves different environmental characteristics (high elevation, milder winds, high fuel continuity), many small and dispersed patches are found, which however, are mainly reduced in the low-altitude WUI near-coastal areas in the second period (1995-2019).

365 Nonetheless, many of the aforementioned fire recurrent patches go beyond environmental factors. Arson is the first cause of large fires (> 100 ha) in southern France (Ganteaume and Jappiot, 2013), so these frequently BA may reflect greater than average arson activity, and this is currently under study.

4.2 Burned area and topography

4.2.1 Slope orientation

370 S-facing slopes have the greatest BA and are more exposed to forest fires than other slopes due to both environmental factors, such as greater insolation and therefore greater evapotranspiration, so vegetation is generally drier in summer, and to WUI patterns since S-facing slopes in southern France have more houses and therefore more potential ignition sources (Fox et al., 2018). S-facing (sum of SW, S, SE) slopes play an increasingly important role over time, which could be linked to a combination of hotter summers and an increasing number of human dwellings on these slopes. Surprisingly, the results show

375 a greater proportion of N-facing slopes are burned compared to S-facing aspects. Laboratory experiments and fire spread models have demonstrated that the rate of spread is fastest on steeper slopes aligned in the same direction as the wind (Boboulos and Purvis, 2009; Lopes et al., 2019). In our context, strong "Mistral" winds come from the N, NW, and W as we go from Bouches-du-Rhône towards the Alpes-Maritimes, and this clearly impacts fire occurrence. A finer study of wind speed and direction is underway to refine this relationship, but differences in fire susceptibility between N-facing and S-facing slopes

380 may not be that great in extreme conditions where wind direction and speed may play a greater role.

4.2.2 Slope inclination

Slope inclination favors fire propagation directly through more efficient radiative heat transfer (Rothermel, 1983) and increases the rate of spread and fire intensity (Csontos and Cseresnyés, 2015; Capra et al., 2018). Indirectly, slope inclination influences fire ignition and suppression through accessibility as well as through solar radiation variations fuel moisture, and fuel density which in turn influence flammability (Holden et al., 2009). In this study, intermediate slope inclinations were most susceptible to burn for several reasons: radiative heat transfer is more efficient, they are too steep for dense human occupation but well-suited to isolated or diffuse housing, and accessibility for suppression is difficult. The lowest inclinations had lower proportional BA (apart from the 2010-2019 interval); not only is radiative heat transfer less efficient on these slopes but flat areas are more densely inhabited and easily accessible, so the lower BA probably depends as much or more on early suppression as on physical processes. In addition, the results show a shift in BA from steeper to less steep slopes over time, and this suggests that the rapid suppression strategy put into place in the early 1990s reduced the propagation of fire from lower slopes where ignitions are expected to be greater to steeper wildland areas. Fire was contained more quickly and escaped to steeper wildland areas less frequently. Due to the complex interactions between physical processes, human activities and topography, topographic roughness is frequently recognized as a significant but secondary predictor of fire occurrence after WUI characteristics in Euro-Mediterranean zone (Ganteaume and Jappiot, 2013; Nunes, 2012)

4.3 Burned area and fuel type

The role of vegetation in fire frequency and BA patches located in the Bouches-du-Rhône and Var departments was studied by Curt et al., (2013). Their case study reflects patterns observed here at a larger scale, namely that vegetation flammability is secondary to landscape organization. Large open patches of continuous fuel, as are found in the Var department, favor larger fires with shorter return intervals than the small patchy wildland distribution in the Bouches-du-Rhône. Burned vegetation volume and patterns observed here highlight the frequently cited role of sclerophyllous vegetation (shrubland) (Ganteaume and Jappiot, 2013; Moreira et al., 2011; Oliveira et al., 2014; Tessler et al., 2016). Shrublands both favors fire propagation in dry conditions (Baeza et al., 2002) and result from recurrent fires (Tessler et al., 2016). As Mermoz et al., (2005) suggested, the fire proneness of sclerophyllous vegetation is connected to its ability to regenerate faster and allow for quicker fuel accumulation, which also applies in our case since sclerophyllous vegetation is the type burning the most while also growing within the region. Additionally, in Mediterranean environments, large fires tend to occur in landscapes with dense shrublands (Moreira et al., 2011; Ruffault and Mouillot, 2017) and that is also the case here, since in all 5 years with the highest BA, sclerophyllous vegetation was the one with the greatest burned proportion. The proportion of fires occurring in bushland increases over time and this may reflect the greater propagation velocities in this vegetation type. In a context, where initial suppression is crucial to fire extinction, bushlands may resist early suppression better than other covers where initial propagation is perhaps slower. Similarly, grasslands are also over-represented in BA and this may be due to faster initial

propagation or accessibility issues, as for example in certain mid to high-altitude areas over the eastern section of the study area, where burned clusters of this fuel type are found. As other studies have concluded (Oliveira et al., 2014), natural
415 grasslands display a high fire susceptibility, especially considering that their total coverage declines slightly here whilst the proportion of BA grows with time. On the other hand, conifers have low BA proportion even in years when big fire(s) occurred. Coniferous forest is a recognized pyrophyllic cover, but it is the least fire prone type in our results, possibly because most of the coniferous area is in high-altitude zones where there are fewer fire ignitions. This also confirms the importance of landscape organization described by Curt et al. (2013).

420 **5 Conclusion**

In this study, results provide a coherent picture of interactions between a long temporal fire geodatabase and environmental characteristics through the scope of changes in firefighting strategies. In areas of relatively high artificial densities, as in the Bouches-du-Rhone, BA patches are limited in size by fuel continuity, despite recurrent strong "Mistral" winds. Areas with large continuous vegetation and diffuse human occupation are most propitious to large frequent fires, as in the Var department.
425 Remote hinterlands with extensive continuous vegetation have fewer fires, as in the Alpes-Maritimes due to a lack of ignition sources.

S-facing aspects have an increasingly bigger impact over time, which may be linked to both environmental and increased human presence on those slopes. Slope inclination remains important throughout the 50-year study period during which intermediate inclinations (20-30°) are more susceptible to burn; this is probably due to both physical processes (radiative heat
430 transfer) and human considerations (accessibility…), though these were not quantified here. The general shift in BA from steeper to gentler slopes over time may reflect the impact of early suppression as described above.

Over half of the total BA in the last 50 years concerned sclerophyllous vegetation, thus confirming its strong association with high fire susceptibility and recurrence. Considering that sclerophyllous vegetation regenerates and expands faster than the rest of the fuel types in the region, this may lead to an increase in fire risk in the future. Natural grasslands, even though they cover
435 limited area and decline with time, were also preferred by fire.

Further ongoing exploitation of the fire GIS database in conjunction with WUI characteristics will likely further improve our understanding on the driving forces of BA and the impacts of fire-fighting strategies in the region.

Author contribution

CB established the fire geodatabase, carried out data processing, analyses, visualization and wrote the initial draft. DF
440 performed the land cover modelingz, contributed to the interpretation of the results, wrote, and reviewed the manuscript. EB provided expertise for data analyses and reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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