Role of land-cover and WUI types on spatio-temporal dynamics of fires in the French Mediterranean area

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ORIGINAL ARTICLE

Role of land-cover and WUI types on spatio-temporal dynamics of fires in the French Mediterranean area

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Abstract
This work aims at assessing, in the French Mediterranean area, the spatio-temporal trends of fires, including their causes, at fine scale (communities), comparing different periods between 1993 and 2017. These trends were compared to those of land-cover and wildland-urban interface (WUI) which were coupled with a spatial analysis of the ignitions in order to highlight the main drivers and preferential areas. Fire density was highly variable among communities, hotspots being located mostly close to big cities but spatially varying in time in contrast to fire occurrence and burned area. A decrease in the unknown cause proportion and a variation of the cause frequency were highlighted among periods, criminal fires being the most frequent and deleterious, especially before 2009, as well as those due to negligence during private activities, mostly after 2009. Land cover classes significantly varied among periods, artificialized and natural areas presenting a reversed trend compared with agricultural areas. Natural areas were the most affected by ignitions (60%), regardless of the period; this trend is slowly decreasing. WUI represented ~30% of the study area, the different types varying spatially (denser clustered types mostly located in the South-East) and showed an increase over time, especially for both clustered types but with high variability among communities. Half of the ignitions occurred in WUI, with "very dense clustered" and "scattered" types being the most affected, especially in 2009. Better understanding the spatio-temporal evolution of fires and of their causes should allow refining the fire policies in terms of awareness raising, firefighting means, and land management.

KEYWORDS
fire causes, fire ignition, French Mediterranean area, land cover, Wildland-Urban Interface

1 | INTRODUCTION

At the global scale, wildfires have become one of the main disturbances for the socio-ecosystems (Bowman et al. 2009). In the five most impacted countries of Europe (i.e., Portugal, Spain, France, Italy, and Greece, representing more than 87% of the area burned in the EU), on average, 48,910 fires burned 460,182 ha of vegetation every year, between 1980 and 2018 (San-Miguel-Ayanz et al., 2019). Along these countries, wildfires also take a heavy toll on Turkey as well as the coastal area of the Balkans (De Rigo et al., 2017). The analysis of the fire trends in Europe can provide an important insight into the spatial distribution and temporal evolution of fires, a crucial step to investigate the underlying causes and impacts of fire occurrence in this region (Rodrigues et al., 2013). In some of these countries, mega-fires regularly destroy large areas entailing huge economic impacts, for example, 47,000 ha in Portugal in 2017 (Viegas et al., 2017) or 85,000 ha in Greece in 2019 (Efthimiou et al., 2019). In France, however, the magnitude of fire events is much lesser as, for the past couple of decades, the largest fire size was 6744 ha in 2003 and 2600 ha in 2016 (Ganteaume & Barbero, 2019; Rigolot et al., 2020). Most burned area and fire occurrences are concentrated in the French Mediterranean region (58% of the burned area on average, between 2010 and 2018, and up to 80% in 2003 (San-Miguel-Ayanz et al., 2019) where large fires (≥100 ha), representing only 1% of the occurrence, are responsible for more than 70% of the burned area (Ganteaume & Guerra, 2018). However, the spatial variability of the fire activity in this area is high, with the south-easternmost part concentrating more than 68% of the fire occurrence and 73% of the burned area, mainly in summer (Ganteaume &

Guerra, 2018). Several factors can explain such a sensitivity to fire, among the most important being climate and weather conditions (warm, dry, and windy in summer) that are exacerbated by the climatic change leading to an increase in the drought and heat wave frequency (Abatzoglou et al., 2019; Jolly et al., 2015). There is already emerging evidence of an increasing frequency of compounded heat waves and drought episodes across Mediterranean regions in the observational record (Russo et al., 2019). Ecological factors, such as high vegetation cover resulting from land abandonment since the mid-20th century and by the systematic fire suppression policy, provide abundant fuel biomass for the fire (Moreira et al., 2011). Accurate and updated mapping of land use and land cover (LULC) changes are essential for understanding past and future trends in wildfire occurrence, by providing key data to understand spatial distribution of fuel types and a proxy of socioeconomic factors related with human activities that can be considered as potential ignition sources. However, there is only limited research that analyzes the patterns of change in the land use on a pan-European level (Naranjo-Gómez et al., 2018; Vilar, Camia, San-Miguel-Ayanz, & Pilar-Martín, 2016). Human factors, such as population density, drive numerous fire ignitions; 95% of the total number of fires are human caused, among them, 32% being criminal (Ganteaume & Guerra, 2018; Ganteaume & Jappiot, 2013). The forest dynamic established for a century, and more recently, the increase in coastal urbanization, industrial development, and tourist activity have resulted in an increase in the human pressure on the wildland area (Ganteaume & Jappiot, 2013). This trend is continuing into the 2000s with an intensification of the urban growth and infrastructure development adjoining wildland areas (Vilar, Camia, San-Miguel-Ayanz, & Martín, 2016), increasing the proportions of areas called "Wildland-Urban Interfaces" (WUI) (Greg Winter, 2000; Lampin-Maillet et al., 2011; Stewart et al., 2007; Xanthopoulos et al., 2012). In southeastern France (as in other Mediterranean regions throughout the world), WUIs are a serious issue in terms of land and fire management, since they often are the source of a large part of fire ignitions and are the most vulnerable (high stake areas) (Lampin-Maillet, 2009). The WUI rate of increase is often high, especially in tourist areas, along with that of the population density (Pellizzaro et al., 2012). In the horizon 2030, the population in some parts of southeastern France (2,050,000 dwellers in the district Bouches du Rhône in 2020) could have a 9% increase (www.insee.fr) that could raise the fire occurrence at the WUI. It is therefore of the upmost importance to better take into account the WUI in the current and future fire risk assessment. Different WUI mapping approaches in Europe, at national, regional or community level, implement different distance buffers and classify the WUI areas from a combination of urban and vegetation features in the landscape (e.g. Chas-Amil et al., 2013; D'Este et al., 2021; Herrero-Corral et al., 2012; Lampin-Maillet et al., 2010; Pereira et al., 2018. However, it is difficult to produce a cartographic map of fires in WUI areas across all European regions because of the lack of a common legal framework to define WUI areas for practical fire risk management and spatial planning. However, Modugno et al. (2016) considered the mapping of the proportion of WUI (national and per region) at European scale and identified the relationships between WUI areas and occurrences of large fires.

Highlighting WUI as a factor also influencing the fire activity in Mediterranean areas has been developed in previous studies (Bar Massada et al., 2009; Ganteaume & Long-Fournel, 2015; Lampin-Maillet, 2009; Moreira et al., 2020; Syphard et al., 2009; Syphard et al., 2012). In contrast, only a few tackle this issue, especially the spatio-temporal evolution of WUI, at a finer scale (i.e., community scale), but they need to be updated (e.g., Ganteaume & Long-Fournel, 2015). The information on the fire causes responsible for the ignitions is also something needed to improve fire prevention. However, this information is rarely provided (Ganteaume & Jappiot, 2013; Ganteaume & Guerra, 2018).

The aim of the current work was (i) to define what the spatio-temporal dynamics of fires (in terms of occurrence, burned area, as well as level of certainty and nature of fire causes) were at fine scale during the period 1993–2017 in the French Mediterranean area and (ii) to compare these trends to those of land-cover and WUI. More specifically, the objectives also included highlighting the main fire drivers and preferential areas among land cover and WUI types and understanding the temporal variation of fire causes, in attempting to link this evolution to that of land cover/WUI. This would allow an updated view of the current situation in this area in terms of fire activity and, ultimately, this work should help refine the fire policies in terms of awareness raising, firefighting means, and land management.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area, the Bouche-du-Rhône district (Figure 1A), is one of the 15 administrative districts (NUTS 3) of southeastern France (coordinates: north-west: 43.6558N, 5.4958E; south-east: 43.8328N, 5.6728E, surface area: 5087 km^2). It is also one of the most fire-prone region in terms of fire occurrence (i.e. number of fires) and burned area, especially in summer (Ganteaume & Barbero, 2019; Ganteaume & Guerra, 2018; Ganteaume, & Jappiot, 2013). This high sensitivity to fire is due to specific physiographic conditions given that this area is characterized by high population density (394 inhabitants km^{-2}, https://www.geoportail.gouv.fr), especially in its eastern part, and by an extensive WUI, which is among the main drivers of fire density in the study area (Ganteaume, & Long-Fournel, 2015). The on-going urban sprawling mostly occurs in watersheds and valleys adjoining the numerous forest massifs (Figure 1A) in this part of the district. The attractiveness of the study area to tourism is high, especially in summer on the coast. The main fuel types, located mostly on limestone-derived soils,

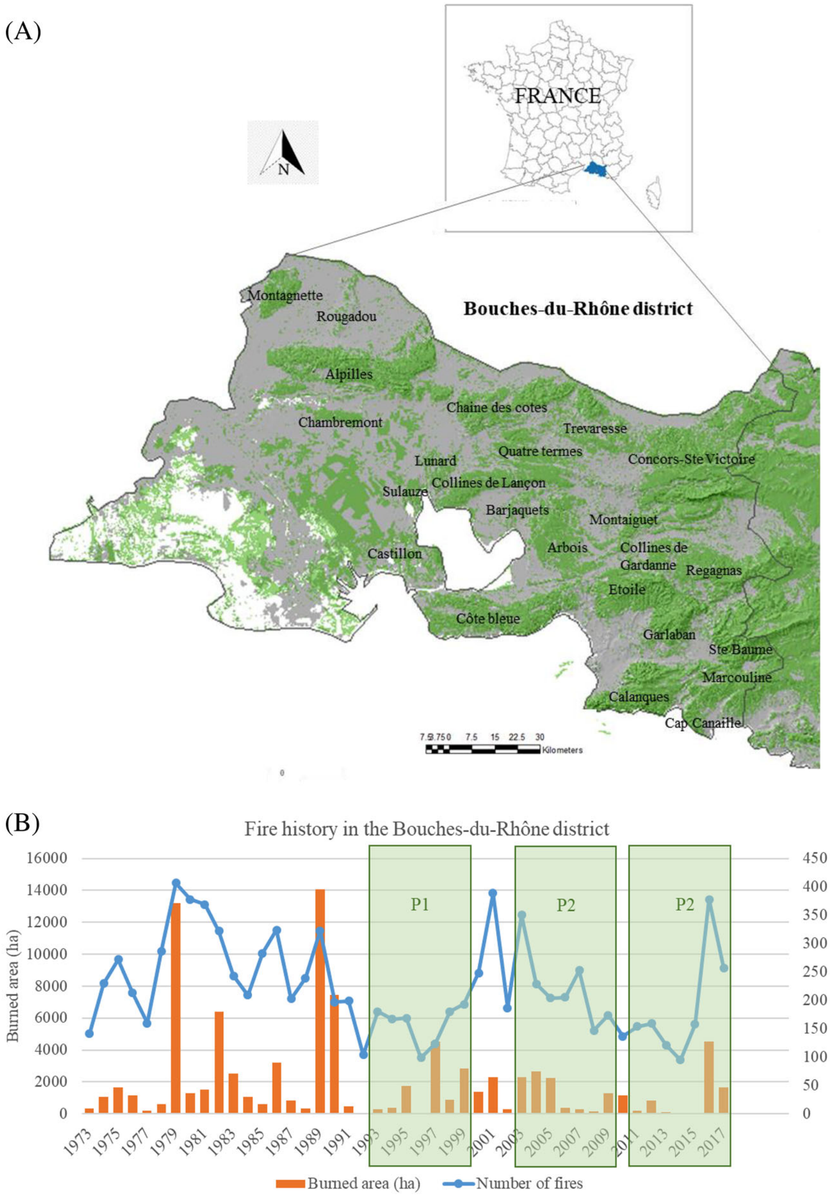

FIGURE 1 Map of the study area (BDTOPO IGN version 2 Lambert 93). Forested systems in green were extracted from the "BD Forêt 2014" of the National Geographic Institute (https://www.geoportail.gouv.fr) and 1:25000 digital terrain model from the National Geographic Institute (IGN)

are *Pinus halepensis* stands (Quézel, 2000) and mixed pine-oak (*Quercus ilex* and *Q. pubescens*) stands (respectively 42% and 18% of the forest stands; database of Inventaire National Forestier), often the preforest vegetation type before oak forests (Quézel & Barbero, 1992). Shrublands, called "garrigues," are another dominant fuel type (43% of the natural vegetation; database of Inventaire National Forestier) that corresponds to the predominant successional stage after woodland degradation (Barbéro et al., 1998). Forest fires occur frequently in the whole area, making the landscape a mosaic of all the previously mentioned types of natural vegetation and agricultural areas. The Mediterranean vegetation is very flammable, affecting fire spread and ultimately, the distribution of large fires. In contrast, the southwestern part of the Bouches-du-Rhône district, characterized by the lowest population density, is occupied by a large wetland area and by irrigated crops, such as rice paddies, corresponding to the Rhône's delta, and is therefore less susceptible to fire.

The Mediterranean climate prevailing in the study area is characterized by short and wet winters and by prolonged hot and dry summers, with strong drying wind (called Mistral), which favors fire propagation (Ruffault et al., 2017). The mean maximum temperature ranged from 9.8 to 13.2°C in winter and from 27.9 to 30.6°C in summer. Mean annual precipitation ranged from 472 to 820 mm (Météo France database). In general, topography is not very rough and the altitude ranges from sea level up to 1038 m in the East.

2.2 | Fire data

We compiled the data provided by the regional fire database Prométhée (number, burned area, certainty and nature of

TABLE 1 List of the fire causes and motives recorded in the study area according to the regional fire database prométhée (Definitions in San Miguel-Ayanz et al. 2018)

Class code	Fire cause/motive
Natural	Definition: Wildfire caused by natural origin, with no human involvement in any way
1	Lightning
Accidental	Definition: Wildfires unintentionally and indirectly caused by humans, without use of fire, connected neither to will nor to negligence, rather to fatality, and which included fires due to structures
2	Undetermined accidents
21	Power lines
22	Railways
23	Vehicles
24	Garbage dumps (legal–illegal)
Deliberate (intentional/criminal)	Definition: Wildfire intentionally caused by humans with the use of fire for different motives (e.g., conflict, interest, pyromania)
3	Undetermined arson
31	Deliberate - conflict (real estate, hunting)
32	Deliberate - interest (real estate, hunting, shepherds)
33	Deliberate - Pyromania
Negligence in professional works	Definition: Wildfire unintentionally caused by humans using fire or glowing objects during professional activities, not connected to fatality
4	Undetermined professional works
41	Forestry works
42	Agricultural works
43	Industrial works
44	Rekindle
Negligence in private activities	Definition: Wildfire unintentionally caused by humans using fire or glowing objects during recreation, not connected to fatality
5	Undetermined leisure activities
51	Private works
52	Recreation activities (children's games, fireworks, BBQ/bonfire)
53	Glowing items (cigarettes, distress rocket, hot ashes)

causes), which has been recording the fires in southeastern France since 1973, according to three periods (1993–1999, 2003–2009, and 2011–2017) in order to highlight the temporal variation of fires in the study area (Figure 1B). We used different periods and not a continuous time span to match the data availability on land-cover and WUI, which were not available every year (each period corresponding to a year of availability of these data). Some spatial analyses (spatial distribution of the number of fires and burned area according to the community) were performed on the entire period (1993–2017) or only on the last two periods when data were not exhaustive in the first one (e.g., for fire hotspots).

The level of certainty of fire causes was divided into two classes: unknown and known (the latter corresponding to the merging of the three classes "certain," "likely," and "supposed" used to qualify the level of certainty in the prométhée database). Among the nature of the known causes given in this database, five classes were taken into account, according to the definitions given by the Joint Research Centre (Camia et al., 2013): (i) natural, (ii) accidental, (iii) deliberate/criminal/intentional, (iv) negligence during professional works, and (v) negligence during private activities. Using 3-digits codes, the fire database Prométhée allows for more accuracy regarding the nature of causes (e.g., 311: deliberate with the motive of conflict regarding real estate). However, only the most recent period studied (2011–2017) was implemented with such an accuracy. To be consistent over the three periods studied, we chose to work on the one or two-digit code causes (see Table 1).

As the ignition spatial coordinates provided by the fire database prométhée are not accurate (fire ignitions located using a 2 km × 2 km grid reference developed by the firefighting services for approximating the location of the fire event), this georeferencing method makes it difficult to work at a fine scale, especially with land cover or WUI data. Therefore, we used the georeferenced ignitions compiled by the Office National des Forêts (ONF) and Direction Départementale des Territoires et de la Mer of Bouches-du-Rhône (DDTM13) available from 1961 to 2017, even though they were less exhaustive than the fire database Prométhée (especially in the beginning of the period). Indeed, the fire perimeters are defined using satellite images (implying a lack of data for the fires whose size is lower than 10 ha, with 22% of the fires recorded vs. 37% in 2003–3009, and 91% in 2011–2017).

2.3 | Land cover data

Contrary to the fire data, land cover and WUI data are not available every year, therefore we took into account a year belonging to each time period (1993–1999, 2003–2009, and 2011–2017) used for the fire data: 1994, 2006, and 2014 for the main land cover data and 1999, 2009, and 2017 for WUI data.

2.3.1 | Main land cover data

Data (projection Lambert 93) were extracted from the BD OCSOL PACA database (CRIGE PACA: Centre Régional d'Information Géographique Provence-Alpes-Côte d'Azur). The basic nomenclature of land covers remains mostly the same as for Corine Land Cover (CLC) (1 = artificialized, 2 = agricultural, 3 = natural (forests and other wildland), 4 = wetland, and 5 = water bodies) with subclasses increasing the accuracy of the land cover (e.g., code 111 = urban areas). In the current work, the two last classes have been merged into a class "Others."

The land cover analysis aims to identify the global evolutionary dynamic of the land cover classes over time in the study area. Moreover, crossing land covers and ignition points allows highlighting the fire ignition preferential areas in space and time.

2.3.2 | Wildland-urban interface

For the three periods studied, WUI data was extracted using the software *WUImap* developed by INRAE (ex IRSTEA). WUI vectorial data were obtained by crossing vectorial layers of "buildings" at the different periods, the study area's administrative boundary, and the mandatory brush-clearing area in WUI (regional regulation for buildings located at the WUI, i.e., at less than 200 m from wildland). Contrary to the work of Ganteaume & Long-Fournel (2015) who calculated a global WUI surface area corresponding to a 100 m buffer around each building located at the WUI, we used a more accurate WUI characterization and mapping (Lampin-Maillet et al., 2010) based on the four types of housing density (i.e. WUI types): "isolated," "scattered," "dense clustered," and "very dense clustered," as defined in Lampin-Maillet et al. (2009). This latter analysis was not performed in 2017 due to a computing problem in generating the different layers of housing density (too much data compiled requiring too much computational resources). Data on housing came from a vector layer made by the French National Geographical Institute (BD TOPO®) and was updated using a Spot 5 multispectral 2.5-m pan-sharpened image. The analysis was carried out in two steps, on the one hand, studying the WUI surface area changes between periods, and on the other hand, determining the part of explanation of fire ignitions by WUI and its temporal trend. This required the crossing between layers of fire ignitions and WUI using geographical information systems (ArcGIS 10).

2.4 | Data analyses

Spatial analysis of fires at the community level (fire occurrence and density) was based on the total number of fires during the 1993–2017 period, using ArcGis software, to assess the spatio-temporal variability of fires in the study area. Representing wildfire incidents as points on a map made it difficult to distinguish "clusters" of ignitions, because of the overlapping ignitions. To address this limitation, we used the Kernel density method to highlight the hotpots of ignitions (and of large fire ignitions) throughout the study area. This method is a nonparametric statistical technique that was aimed at producing a smooth density surface; therefore, accounting for the uncertainty regarding the accuracy of the original ignition location. In assigning a buffer area around each spatial fire ignition, a normal distribution of density surfaces (based on the number of ignitions per point) was created over each point. When multiple buffers overlapped, the kernel density values were combined to derive the ignition density surface. This provided a much clearer illustration of where the ignitions were the most frequent (hotspot) and allowed the use of a straightforward and quantitative value (number of ignitions per square kilometer). For this analysis, we used the Spatial Analyst Extension of ArcGIS 10.2 whose kernel function was based on Silverman's quartic kernel function (as in Ganteaume & Guerra 2018). However, Spatial Analyst provides a search radius algorithm based on the distance between ignitions giving a too smooth result. In order to obtain sharper density changes, we empirically chose a shorter search radius (6000 m radius, including 28 possible locations) according to the initial grid of the Prométhée database. A 50 m resolution was chosen for the output raster. This analysis was performed only for the most recent periods (2003–2009 and 2011–2017), given the lack of data for the period 1993–1999 in the ONF/DDTM13 database.

Afterwards, a global analysis of the fire occurrence and burned area was performed according to the period, followed by an interannual analysis, to determine the temporal variation within the same period that could not be highlighted using only the global analysis. The analysis of fire causes consisted of different steps. The first step studied the proportion of known versus unknown fire causes in the three periods in order to apprehend the improvement of the certainty of the causes over time and to determine when their analysis could be reliably attempted. Next, the fire occurrence and burned area were analyzed according to the nature of the cause in order to find out which were the most frequent and deleterious causes. The chi-square (χ^2) test was

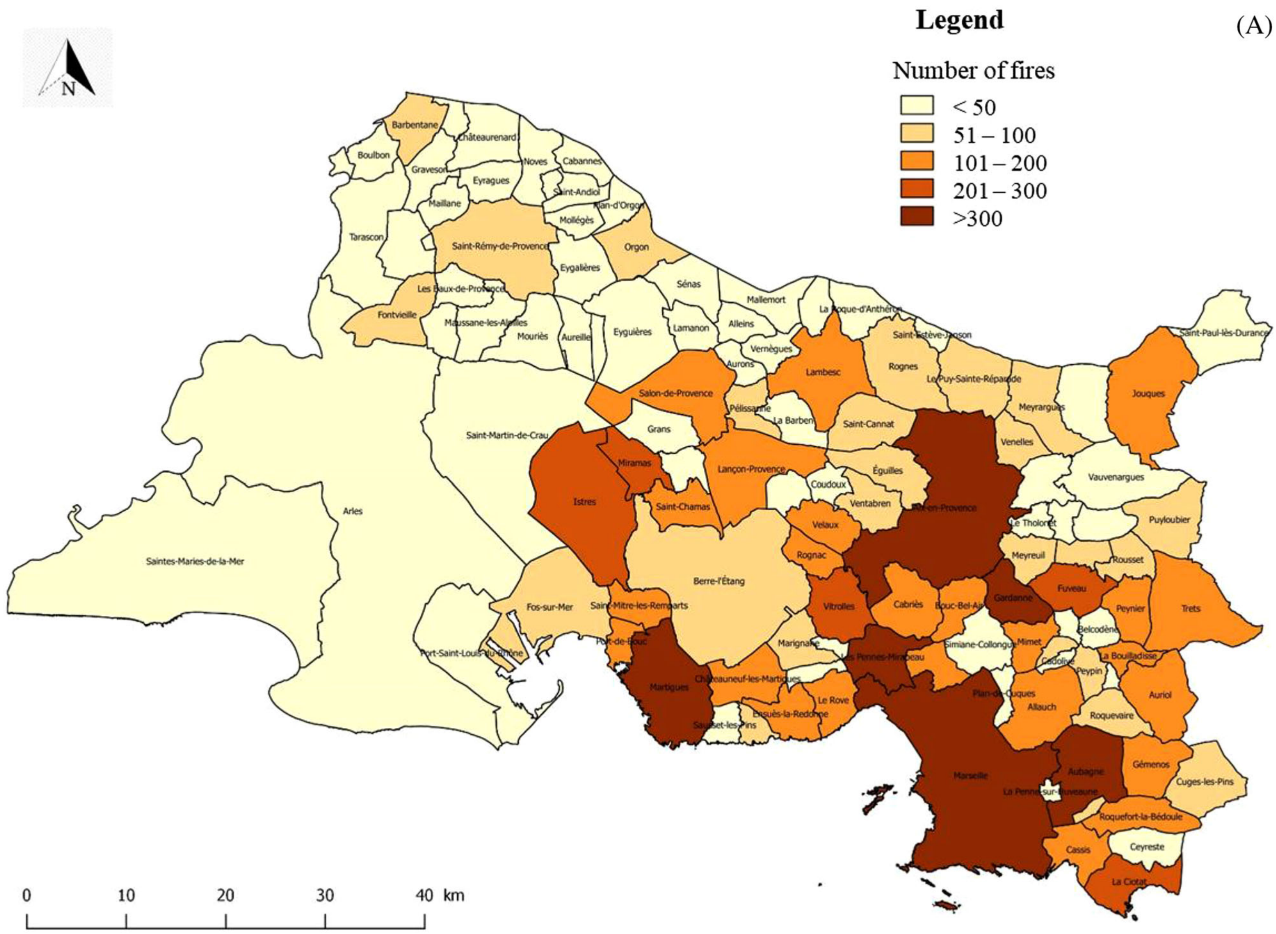

FIGURE 2 Fire number (a) and density (b) according to communities of the Bouches-du-Rhône district during the period 1973-2017 (Source - www.promethee.com)

used to test the difference in number of fires, burned area, certainty and nature of fire causes among periods and ANOVAs (Kruskal–Wallis test) were used to compare the different periods (Statgraphics® 19-X64; Statgraphics Technologies, Inc, USA). The same analyses were carried out to assess the temporal variation of land cover and WUI, at the scale of the study area and of the community.

3 | RESULTS

3.1 | Spatio-temporal variation of fires

3.1.1 | Variation of fire metrics

During the period 1993–2017, there was a high variability of the number of fires among communities (Figure 2A), which was well defined spatially (the most affected areas located in the center and the East of the study area, the major cities, Marseille and Aix-en-Provence, their neighboring communities, as well as those around the Etang de Berre, being the most fire-prone). Taking into account the community surface area, the fire density could be derived from the data provided by the fire database Prométhée, refining the results of the previous analysis, and highlighting that the communities most at risk were located in the southeastern part of the study area (Figure 2B). However, a temporal variation of the fire ignition hotspots was highlighted between the 2003–2009 and 2011–2017 (Figure 3). During the first period, the fire ignition density was higher in the communities located North and East of Marseille (the most impacted forest massifs being around Gardanne, western Regagnas massif, eastern Garlaban and the eastern part of the Calanques National park close to Marseille). Then, during the second period, the hotspots were more concentrated in the communities West of Etang de Berre (Castillon and Lunard forest massifs). Overall, most communities in the Bouches-du-Rhône district were impacted by wildfires, except the wetter western part corresponding to the Rhône's delta with a decreasing trend from the South to the North of the area, regardless of the period.

The comparison of the fire occurrence among periods showed higher values during the period 2003–2009 with 1562 fire events (Figure 4A) contrary to the burned area that revealed a constant decreasing trend, from 10664 to 7402.7 ha since 1993–1999 (Figure 4B). However, both variations were not significant (Kruskal–Wallis test, $P_{\text{occurence}} = 0.175$;

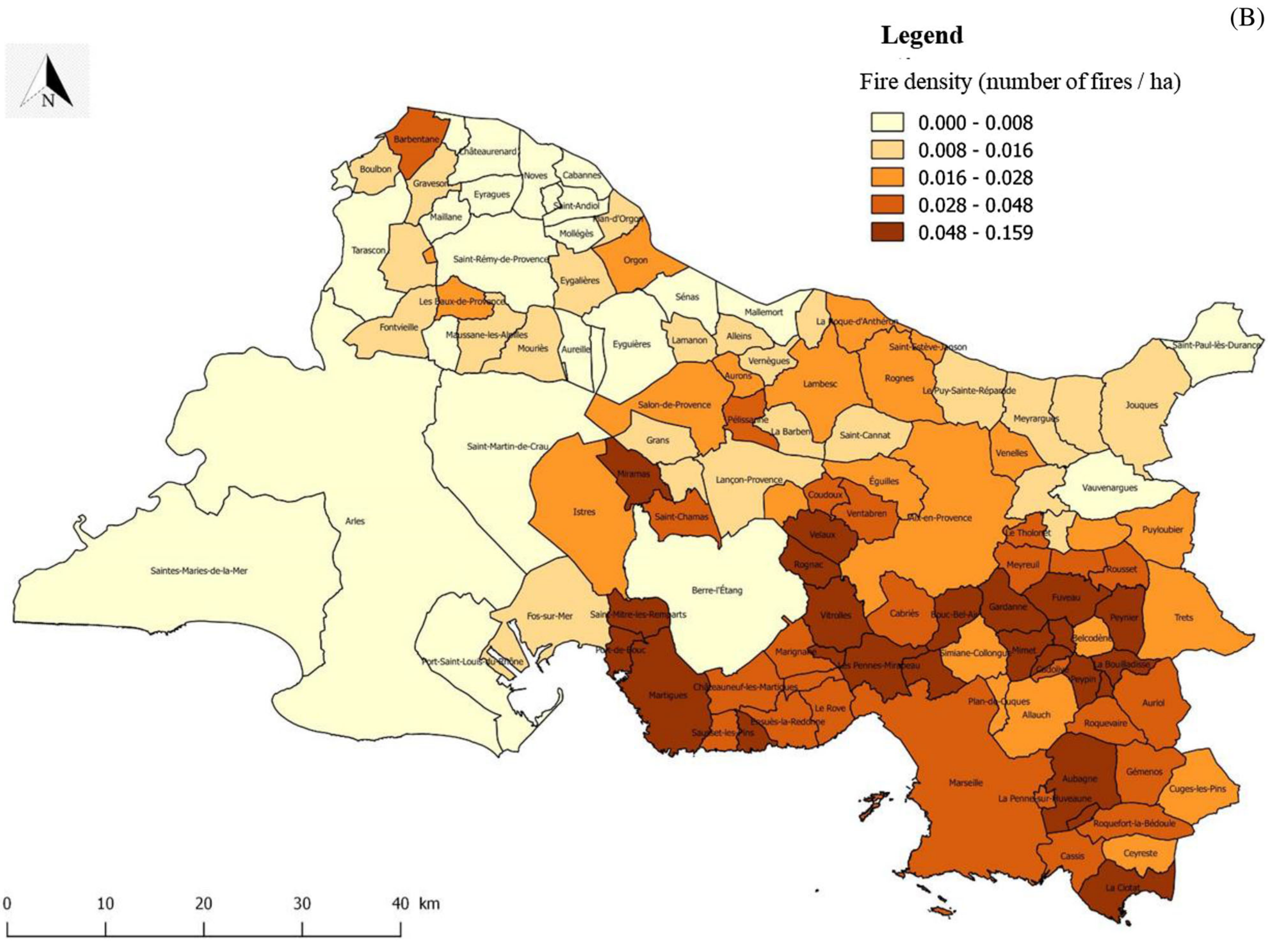

FIGURE 2 Continued

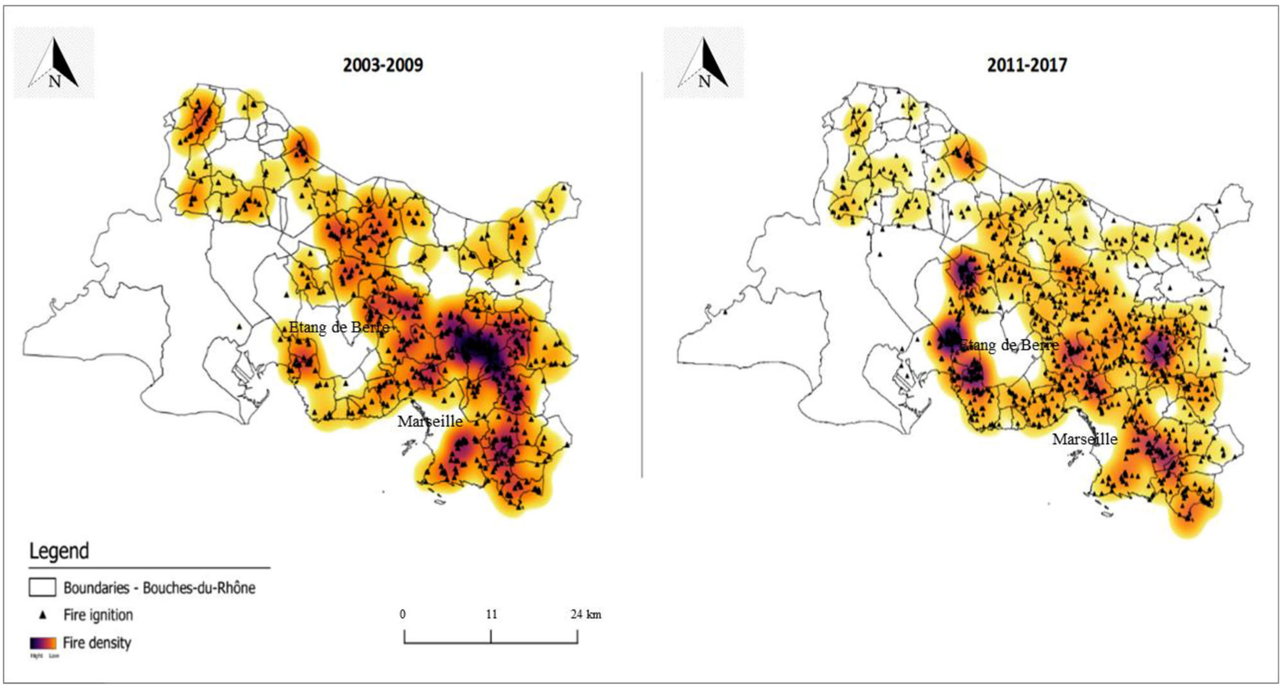

FIGURE 3 Fire hot-spots in 2003–2009 and 2011–2017 in the Bouches-du-Rhône district (*Source*: ONF/DDTM13)

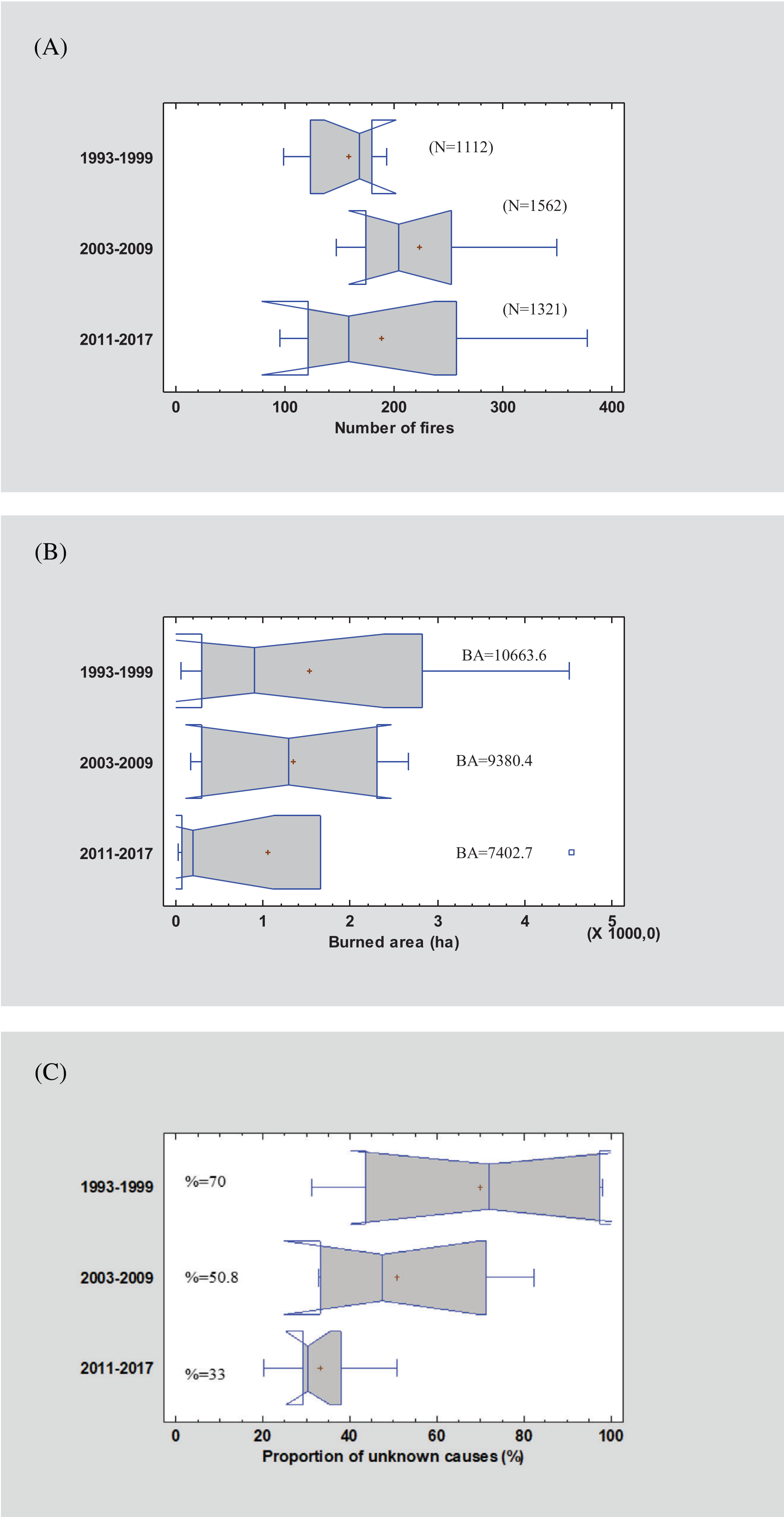

FIGURE 4 Variation of fire occurrence (A), burned area (B), and proportion of unknown causes (C) according to the time period (*Source*: www.promethee.com)

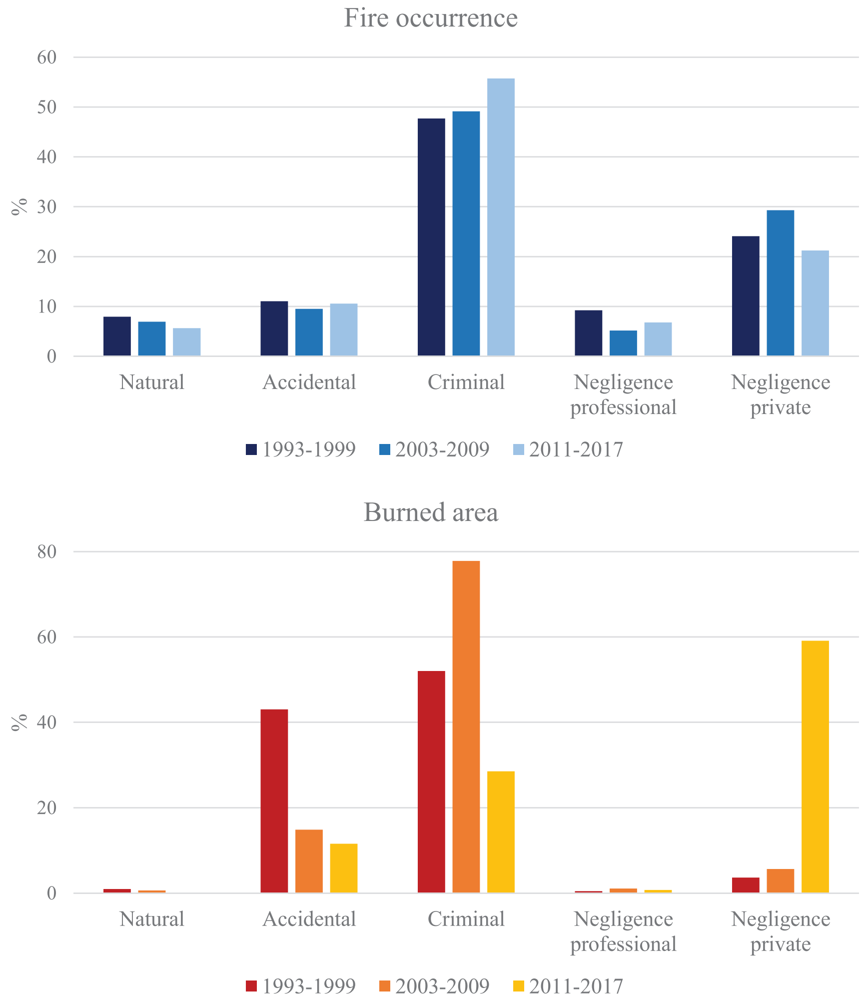

FIGURE 5 Fire occurrence and area burned according to the fire cause during the three periods studied in the Bouches-du-Rhône district (*Source*: www.promethee.com)

$P_{\text{BurnedArea}} = 0.443$), mostly due to high data variability. Indeed, the interannual analysis of these metrics highlighted important discrepancies among and within periods; for example, low interannual variability of fire occurrence during the period 1993–1999 and of burned area during 2003–2009, in contrast to the other periods (e.g. the most recent period gathered the two highest values, for both occurrence and burned area; Figure 4 and Tables A1 and A2).

3.1.2 | Temporal variation of the level of certainty and nature of fire causes

The proportion of unknown cause significantly decreased over time (Kruskal–Wallis test, $p = 0.012$; Figure 4C), from 70% down to 33% during the last period. However, for the first period, the interannual variability turned out to be rather high ($SD_{1993–1999} = 28\%$), meaning that the elucidation of the nature of fire causes was heterogeneous within the years studied (e.g., this period encompassed 98% of unknown causes in 1999 and 31% in 1998) and a sharper decrease occurred between 1996 and 1997 (from 72% to 52%) (Table A3). The most recent period (2011–2017), besides being the best in terms of level of certainty, was characterized by a very low interannual variability meaning that the elucidation rate of the fire causes was homogeneous throughout the period ($SD_{2011–2017} = 9.5\%$).

Regarding the nature of the causes, in terms of occurrence, most fires were criminal (>40%; Figure 5a) and were the most destructive, in terms of burned area, during the first two periods (up to 78% of the total burned area, more frequently due to large fires, i.e., ≥100 ha; Figure 5b). Moreover, these fires showed an increasing trend from 1993–1999 to 2011–2017, followed by those due to negligence during private activities (overall, > 20%). These latter fires burned the most during the last period (59% vs. 30% for criminal fires), mostly due to one fire event that occurred in 2016, the other causes being less frequent and less severe, regardless of the period (Figure 5A and B). It is worth noting that the area burned by accidental fires was exceptionally high during the first period (43%) for only 11% of occurrence. Despite these contrasted trends, the statistical analyses revealed that neither the occurrence nor the area burned significantly varied among the periods, regardless of the cause, likely due to the high variability of the fire metrics within each period (Table A4).

The rate of change in the number of fires increased between 1993–1999 and 2003–2009, regardless of the cause, with the fires due to negligence during professional activities

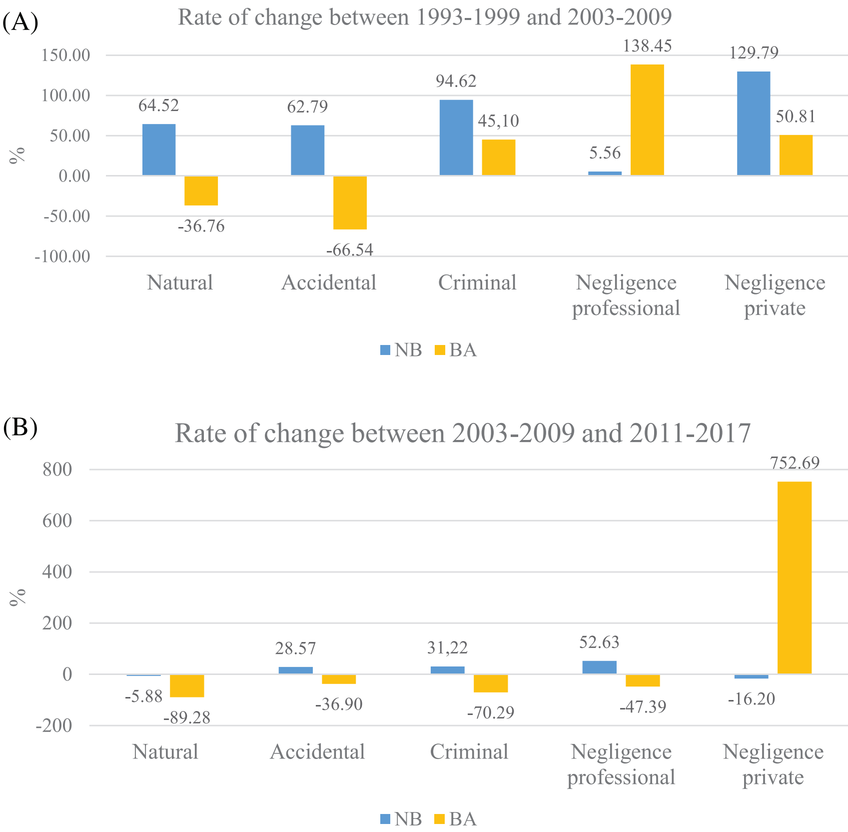

FIGURE 6 Variation of fire occurrence (NB) and burned area (BA) according to the fire cause from 1993–1999 to 2003–2009 and from 2003–2009 to 2011–2017 in the Bouches-du-Rhône district (Source – www.promethee.com)

displaying the lowest rate (5.56%) and those due to negligence during private activities displaying the highest (129.8%) (Figure 6A). Regarding these periods, a decreasing rate of change in the area burned by natural and accidental fires was highlighted in contrast to the other causes (increasing rate up to 138% for the area burned by fires due to negligence during professional activities). Between 2003–2009 and 2011–2017 (Figure 6B), only the number of natural fires and of those due to negligence during private activities showed a decreasing rate while this trend was general for the burned area except for negligence during private activities (strong increase of 753%).

3.2 | Spatio-temporal variation of land cover and WUI

Regarding the land cover, agricultural areas are more represented to the West of the study area, in contrast to natural and artificialized areas. The former class strongly decreased between 1999 (first period) and 2006 (second period), except for olive groves (Tables A5 and A6), benefiting to the classes "dense vegetation" areas (mixed forests and deciduous stands; Tables A5 and A6) and artificialized areas (except for discontinuous urban areas; Tables A5 and A6), to a lower extent (Figure 7). Between the second and the third period (2006 and 2014), there was a general slight decrease in the land cover areas except for the artificialized areas (but with a slowing increase, from 21.1% to 1.9%) (Table 2). The statistical analyses (χ^2) showed that the land cover classes and periods were not independent ($p < 0.0001$).

Over the period studied, WUI represented on average 28.6% of the district surface area, with a 2.33% rate of change between 1999 and 2009 (Table 3). The WUI types spatially varied throughout the territory, "very dense clustered" and "dense clustered" being mostly concentrated around the big cities (Marseille and Aix-en-Provence) and around the Etang de Berre, to a lesser extent. In contrast, the southwestern part of the study area was mostly characterized by the "scattered" and "isolated" types, as well as the northern part, to a lesser extent (e.g., Figure 8).

The analysis of the rate of change of the total WUI surface area revealed an increase in the global surface area (+8.5%) between 1999 and 2009 benefiting the "dense clustered" and "very dense clustered" types (+155% and +15%, respectively). The "scattered" type also increased in this time span, but to a lesser extent (+7%) in contrast to the "isolated" type (−3.8%) (Table 3). The statistical analyses (χ^2) showed that the WUI classes and periods were not independent ($p < 0.0001$).

This temporal variation was combined with a strong heterogeneity among communities, regardless of the WUI type. Regarding the "very dense clustered" type, this variability spanned from −3.6% in Vauvenargues to +135.9% in Saint-Marc-Jaumegarde, and the most represented rates of change encompassed 5% to 30% (Figure 9A). The "dense clustered" type was characterized by a stronger evolution than the previous one (on average +25.8%) but with a

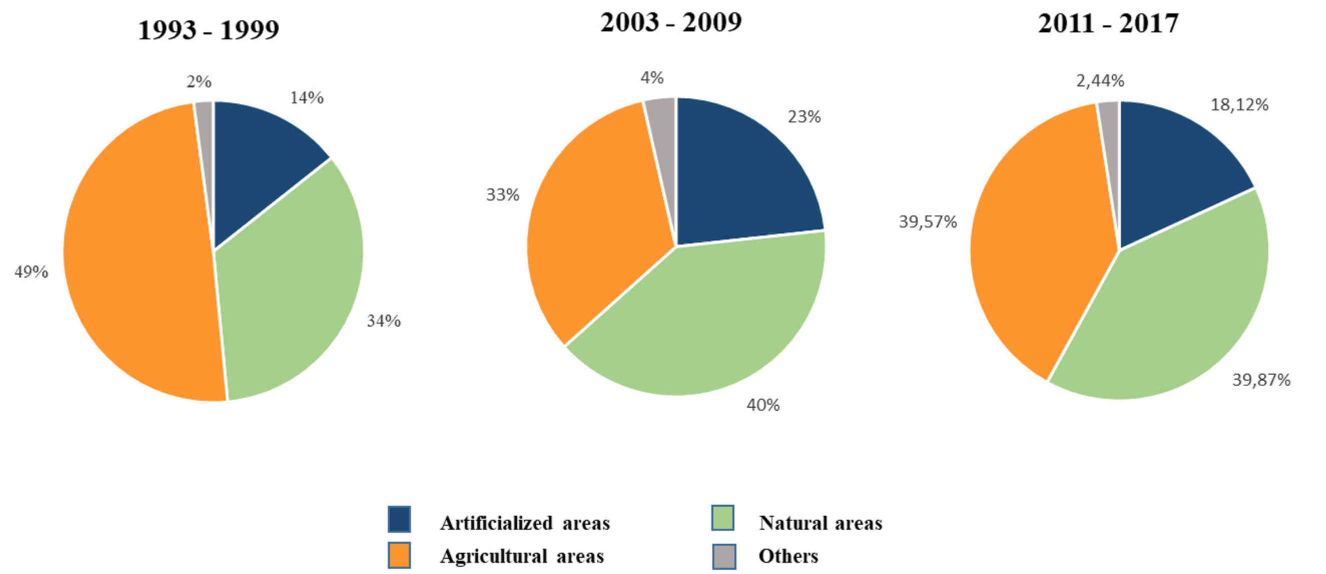

FIGURE 7 Proportions of the different classes of land cover according to the different periods studied in the Bouches-du-Rhône district (Source – CRIGE PACA)

TABLE 2 Temporal evolution of the main land cover classes (ha) among the periods studied (Source: CRIGE PACA)

	1999	2006	Rate of change	2006	2014	Rate of change
Artificialized areas	63329.82	106391.31	68.00%	106391.31	87163.17	−18.07%
Natural areas	150796.70	183383.75	21.61%	183383.75	191748,19	456%
Agricultural areas	218261.75	151129.22	−30.76%	151129.22	190342.99	25.95%
Others	9224.49	16270.39	76.38%	16270.39	11723.26	−27.95%

TABLE 3 Rate of change of the WUI type surface areas (ha) between 1999 and 2009 in the Bouches-du-Rhône district. WUI types are based on the housing density (Source: WUIMap)

Type of WUI	Surface area 1999	Surface area 2009	Rate of change (%)
Very dense	42877	49506	+15.5
Dense	24736	28448	+15.0
Scattered	38440	41126	+7.0
Isolated	33743	32469	-3.8
Total WUI surface area	139796	151639	+8.5
Proportion of the study area occupied by WUI	27.48%	29.81%	+2.33

decrease in 41% of the communities (Fig. 9b). The "scattered" type also showed an increasing trend between 1999 and 2009, but to a lesser extent than the two previous types (on average +9.3%), with a strong variability among communities ranging from −100% in Carry-le-Rouet to +88.3% in Maussane-les-Alpilles. In total, 31% of the communities were characterized by a decrease in this type of WUI, the variation mainly ranged between −5% and +30% (Figure 9C). The "isolated" WUI type was special as it was the only one characterized by a global decrease in the study area (–1.6%). Indeed, 59% of the communities presented a decrease in this type of WUI, values ranging from −55.1% to +107.9% (Saint Savournin and Carnoux-en-Provence, respectively), the most represented rates of change encompassed −15% to +10% (Figure 9D).

3.3 | Spatio-temporal variation of fires according to land cover and WUI

The land cover the most impacted by wildfires was the natural areas (around 60% of the ignitions and most of the

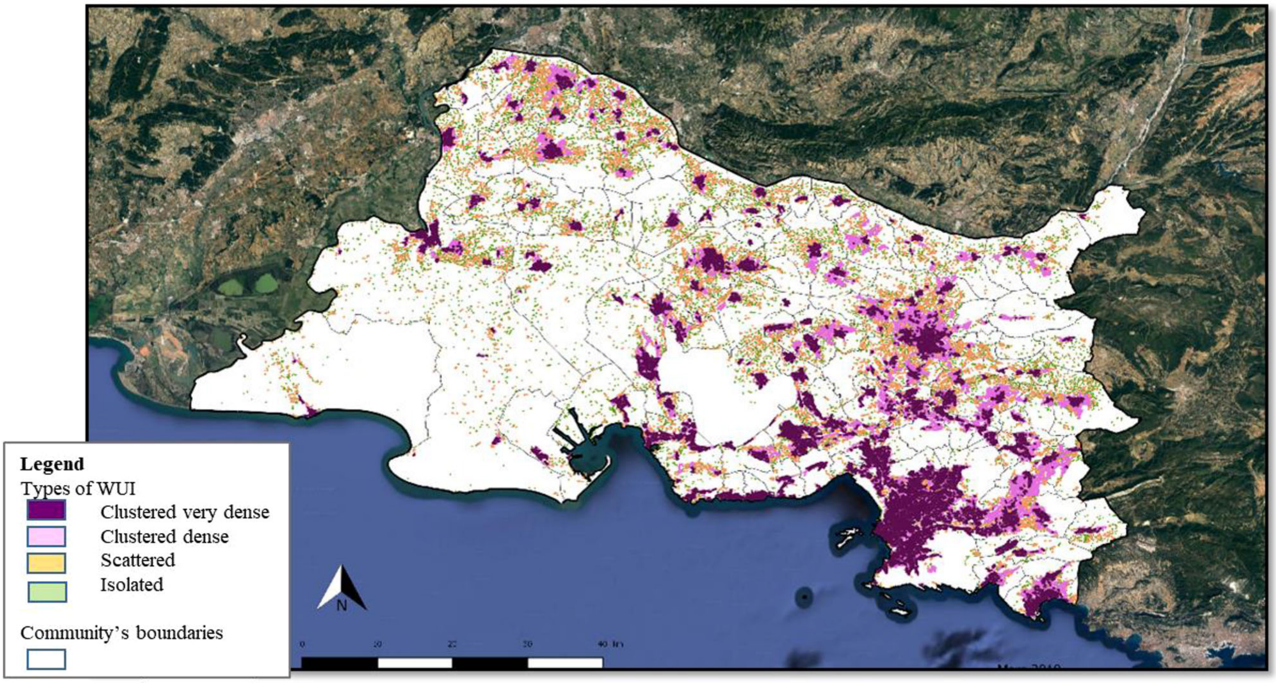

FIGURE 8 Spatial distribution of the different types of WUI (based on housing density) in the Bouches-du-Rhône district in 2009

(A)

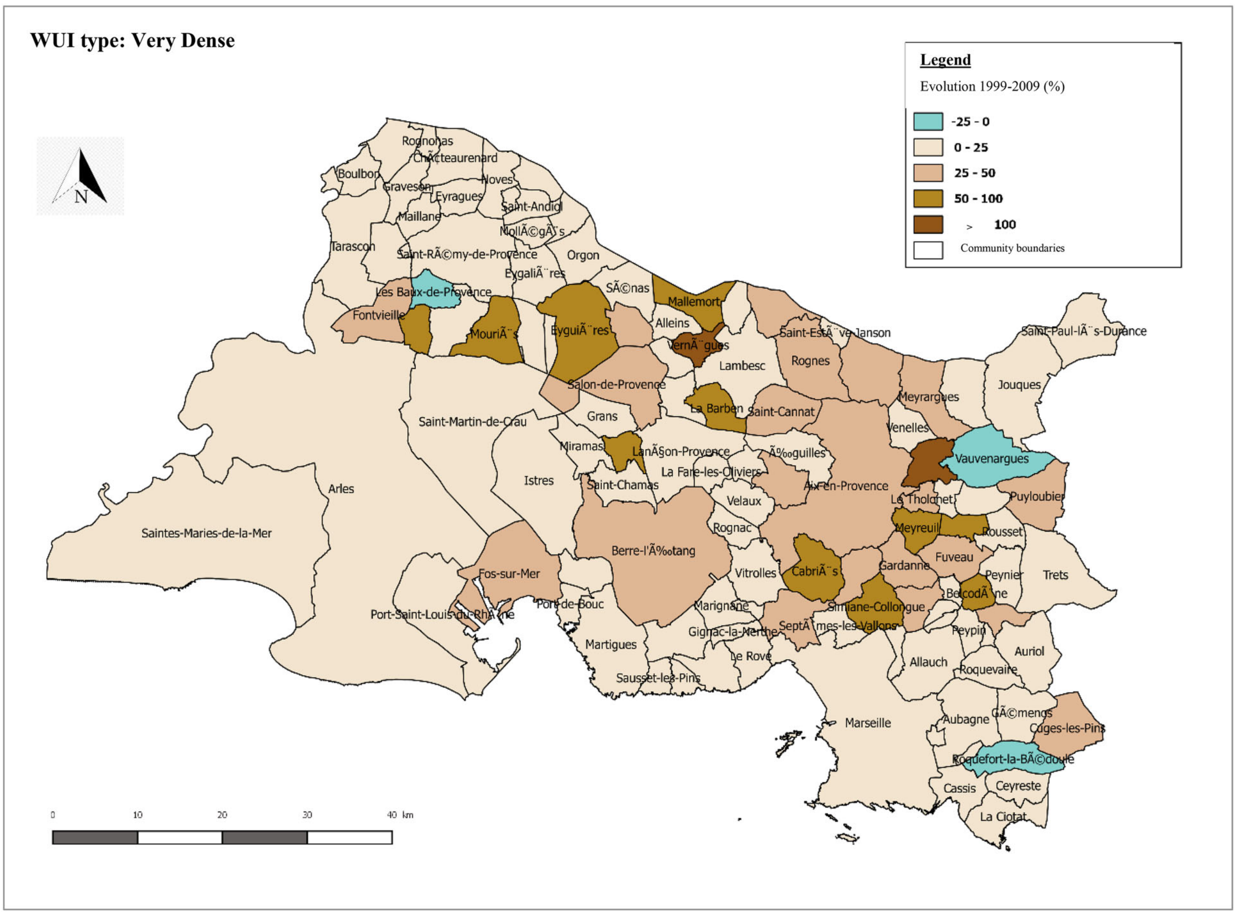

FIGURE 9 Evolution of the WUI "clustered very dense" (A), "clustered dense" (B), "scattered" (C), and "isolated" (D) types according to the community in the Bouches-du-Rhône district between 1999 and 2009

(B)

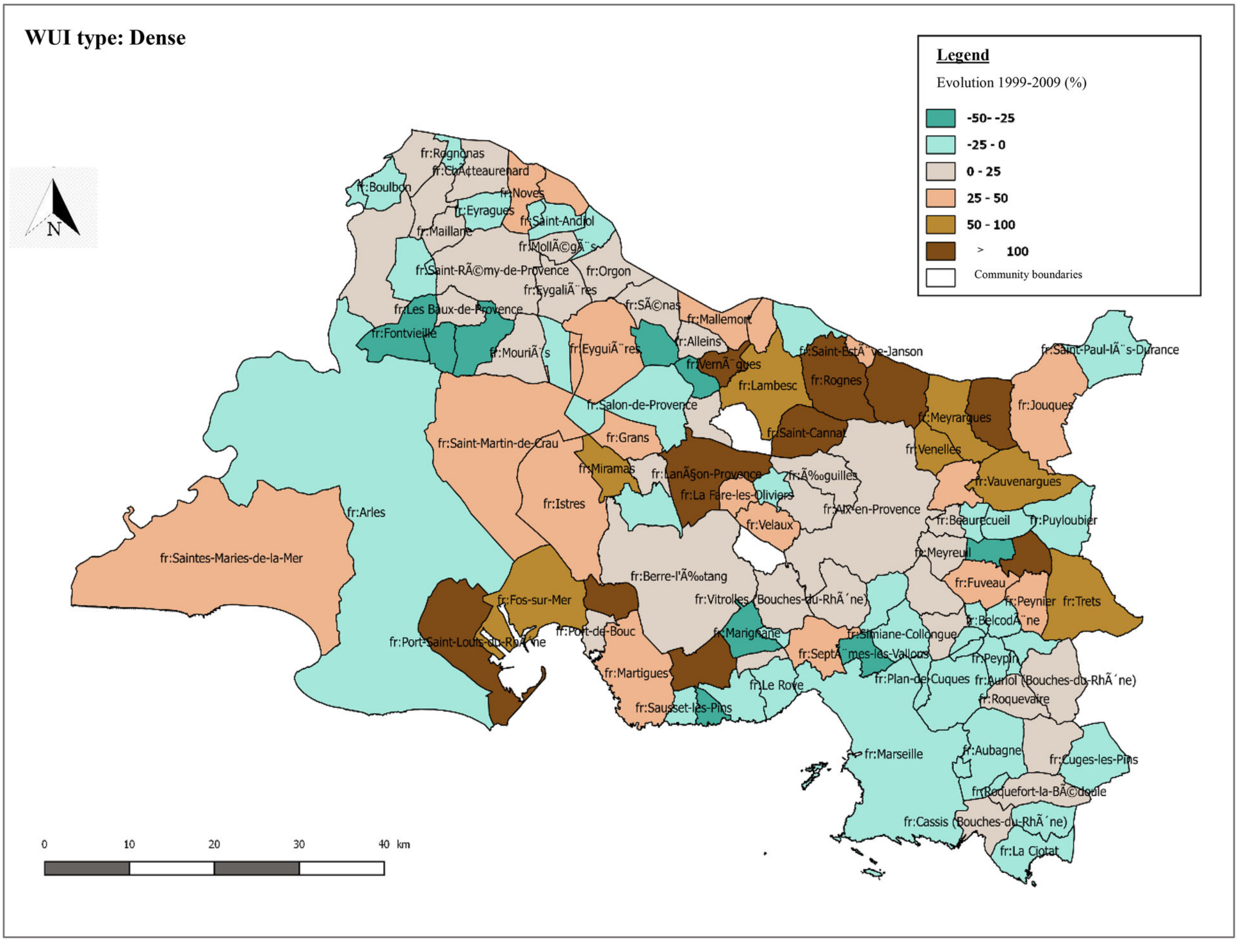

FIGURE 9 Continued

TABLE 4 Proportion of fire occurrence and burned area in the main land covers in 2006 and 2014 in the Bouches-du-Rhône district (No results for the period 1993–1999 due to the inaccuracy of the data records during this period)

	2006		2014	
	Occurrence	**Burned area**	**Occurrence**	**Burned area**
Artificialized areas	24.39%	17.91%	28.82%	23.74%
Agricultural areas	9.23%	31.13%	12.21%	31.61%
Natural areas	66.38%	50.95%	58.97%	44.65%

burned area), regardless of the period, with most ignitions being located in mixed conifers-deciduous (except during the first period) as well as in conifers stands and in shrublands (Tables A5–A7). Indeed, these areas represented 45% of the total land cover (around 2200 km^2), increasing the probability of fire ignition, and providing higher fuel amount available for fire ignition and propagation. Artificialized areas represented around 1000 km^2 corresponding to 23% of the land cover and gathered between 24% and 29% of the ignitions according to the period studied (Table 4) but the burned area was the lowest in this class, given the lower amount of vegetation, regardless of the period. Areas corresponding to WUI in the class "Artificialized area" ("Discontinuous urban area" and "Scattered dwellings") gathered most ignitions (Tables A5–A7). In contrast, the agricultural areas were submitted to only 10% of ignitions, on average, mostly located in farmlands out of the irrigation perimeter (dry lands), vineyards, and orchards (Tables A5, A6, and A7), regardless of the period. Except for the natural areas, the proportion of ignitions increased from 1999 to 2006 and, while the area burned in agricultural areas did not change over time, the area burned in natural areas presented a decreasing trend in contrast to the artificialized areas (Table 4).

Taking into account the accurately georeferenced ignitions of the DDTM13/ONF database, we found that WUIs were impacted by 49.3% of the ignitions and those occurring in natural areas were mainly located very close to the artificialized areas (Figure 10). In contrast, the number of fires occurring within the forest area (i.e., far from human settlements) was low. Regarding the temporal variation of the fire ignitions according to the WUI types, we found that half of the ignitions occurred within WUI area during the period 1993–2009, mostly in the "very dense clustered" and "scattered" types (32% and 29%, respectively) (Table 5). When the analysis was carried out for each period, the trend previously highlighted changed. Indeed, in 1999, corresponding to the

(C)

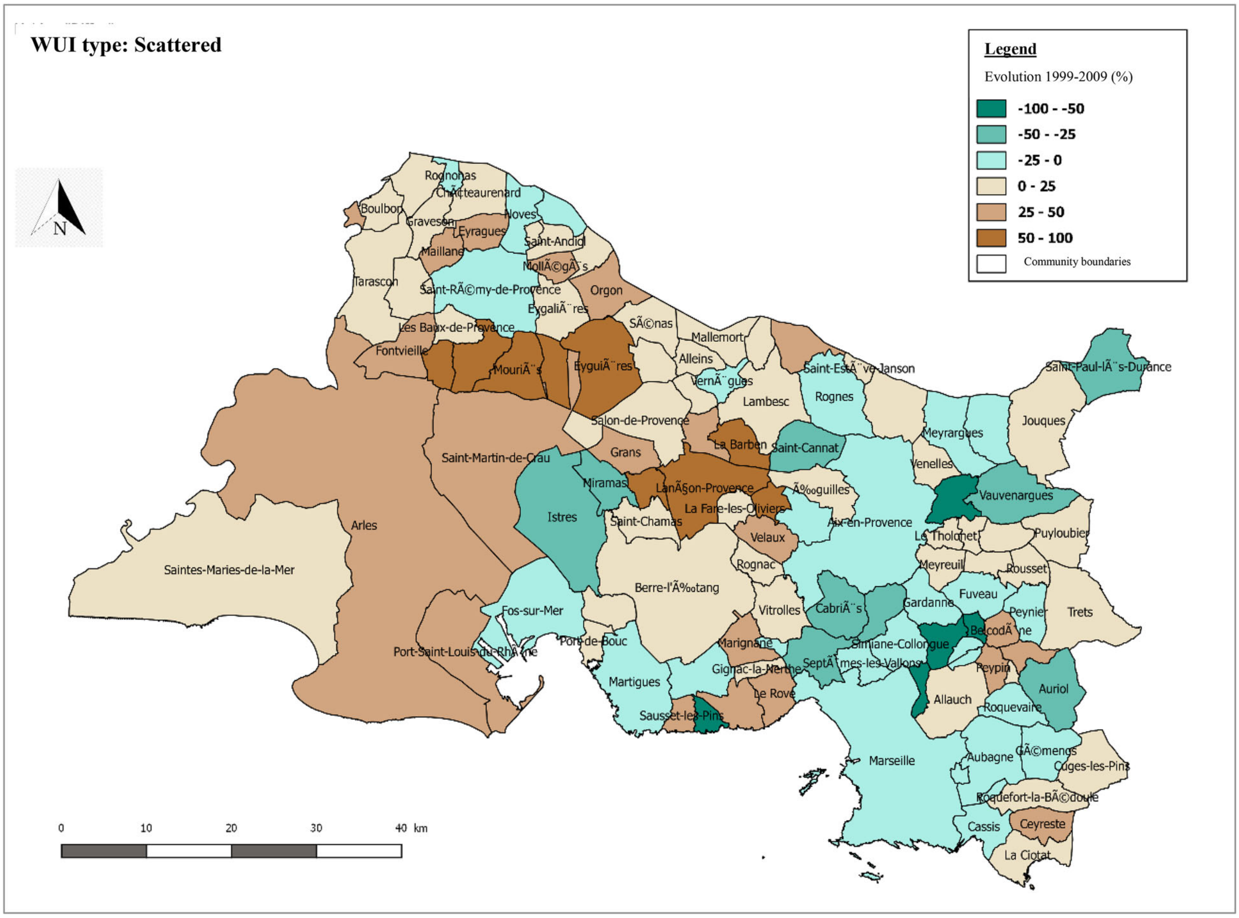

FIGURE 9 Continued

first period, 248 ignitions occurred in the Bouches-du-Rhône district, with almost 39% of these ignitions (96 ignitions) located within WUI areas, mostly in the types "isolated" and "scattered" (35% and 28%, respectively; Table 4), despite WUIs represented only 27.5% of the district's total area (1 ignition for 1456 ha). In contrast, the ignitions located outside WUI areas (62% of the total number of ignitions) were distributed over a larger surface area (1 ignition for 2427 ha, therefore less than those in WUI). In 2009, the number of ignitions increased up to 576 (more than twice the number of the previous period) with more than 50% within WUI areas (1 ignition for 525 ha while there was 1 ignition for 1244 ha outside WUI areas, therefore less than two times), mostly affecting the types "very dense clustered" (36%) and "scattered" (29%) (Table 5).

4 | DISCUSSION

4.1 | Fire metric variation

Overall, most communities in the Bouches-du-Rhône district were impacted by wildfires, with a large variability in both occurrence and burned area, the most impacted communities being close to big cities. The wetter part corresponding to the Rhône's delta and the northern part of the district were less fire-prone than the South-East, mainly due to lower population density (Ganteaume & Long-Fournel, 2015). This agreed with the work of Ganteaume and Long-Fournel (2015) that showed that housing density, as a proxy of population density, was one of the main drivers of fire density. Results also showed that temporal variations of occurrence and burned area were not significant, mostly due to the high variability within periods and that there was also a temporal variation of the fire hotspots between 2003–2009 and 2011–2017, which is an additional result to the study of Ganteaume and Long-Fournel (2015) who worked at the spatial scale only. This latter result is of interest for fire management strategy showing the the fire hotspots can change over time, trend also highlighted in other regions in the world, such as in California (Li & Banerjee, 2021).

The decreasing trend of burned area highlighted in the study area begun in the late 1980s (Figure 1B), when a new fire policy brought new fire suppression (anticipation and massive attack on the fire within 10 min after ignition) and prevention practices in southeastern France, decreasing the probability that a fire would burn large areas (Ruffault & Mouillot, 2015). However, despite this decrease, the persistence of large fire events during extreme weather conditions (e.g. 2003, 2016 in SE France) reveals that these events can

(D)

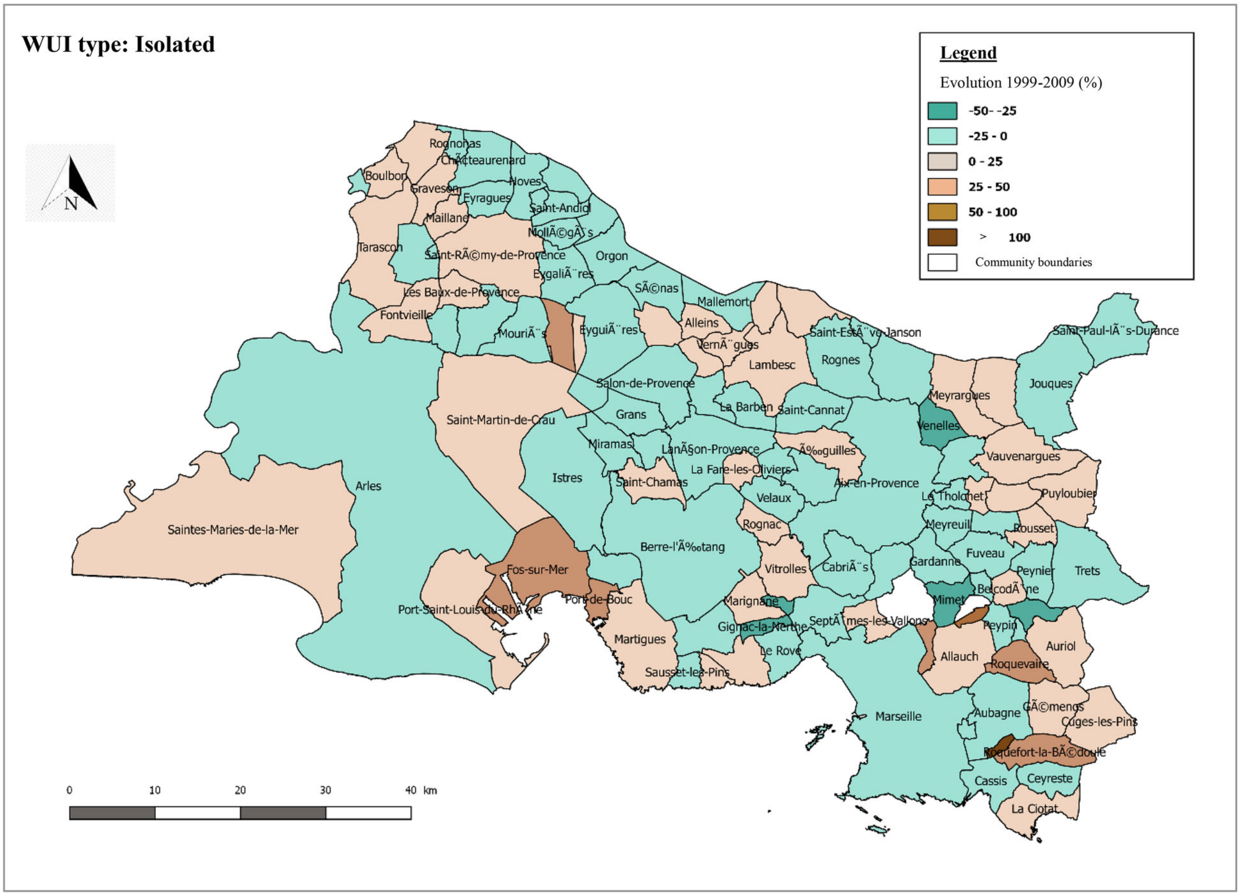

FIGURE 9 Continued

outweigh, by far, terrestrial and aerial fire-fighting strategies (Moreira et al., 2020; Rigolot et al., 2020) and therefore can sometimes strongly impact WUIs (although among the best defended areas due to their high stake), as during the Rognac fire in 2016 (Ganteaume et al., 2021). However, despite these lower fire statistics in the French Mediterranean region, the burned area could be tripled considering on the horizon 2100 for the worst climatic scenario (Fargeon et al., 2020), at a rate between +15% and +25% per decade (Dupuy et al., 2020). Some even stated that the "success" of a fire management policy based on systematic fire suppression (leading to massive fuel accumulation) is doomed in the long term since the large or mega-fires will only be delayed (Rigolot et al., 2020). Although the context differs, this situation is also on-going in South Africa or Australia (Moreira et al., 2020; Rigolot et al., 2020).

Regarding the fire occurrence, the situation was less clear-cut in the study area for the past 25 years but a trend differing from that of the entire region (Curt & Fréjaville, 2018) could be highlighted. Indeed, the socio-environmental characteristics of the district make it more vulnerable to fire ignitions than other parts of southeastern France (Ganteaume & Guerra, 2018). Even though 2003 remains one of the most catastrophic years in terms of fire occurrence and burned area in several European countries (San-Miguel-Ayanz et al., 2019), it was not the same in our study area for which 2016 was more destructive (378 fires and 4533.2 ha burned vs. 350 fires and 2308.1 ha burned in 2003; www.promethee.com). In other countries of southern Europe, such as Portugal, the situation differed with a regular increase in fire occurrence since the 1980s, especially that of large fires during the period 1981–2013 (Ferreira-Leite et al., 2016).

We highlighted an improvement of the level of certainty of fire causes from 1993–1999 to 2011–2017 but with a rather high interannual variability, especially in 1993–1999. The heterogeneity during this first period was mostly due to the creation, in 1997, of official teams (one team for each district of southeastern France, composed of a firefighter, a forest manager, and a police officer), investigating, if possible, the cause of each fire occurring in this region, therefore increasing the proportion of known causes since then (Ganteaume & Guerra, 2018). The same trend has been observed in Portugal since 1988 (74% of unknown cause to 47–53% in 2015–2017) (Ferreira de Almeida & Vilacae-Moura, 1992; Tedim et al., 2019).

The nature of the fire cause is quite diverse and the fire ignition is generally not a random phenomenon (Tedim et al., 2014, 2018) because most fires result from motivated human actions (Tedim et al., 2019). The fire cause analysis revealed that, in the study area, most fires were criminal and increased

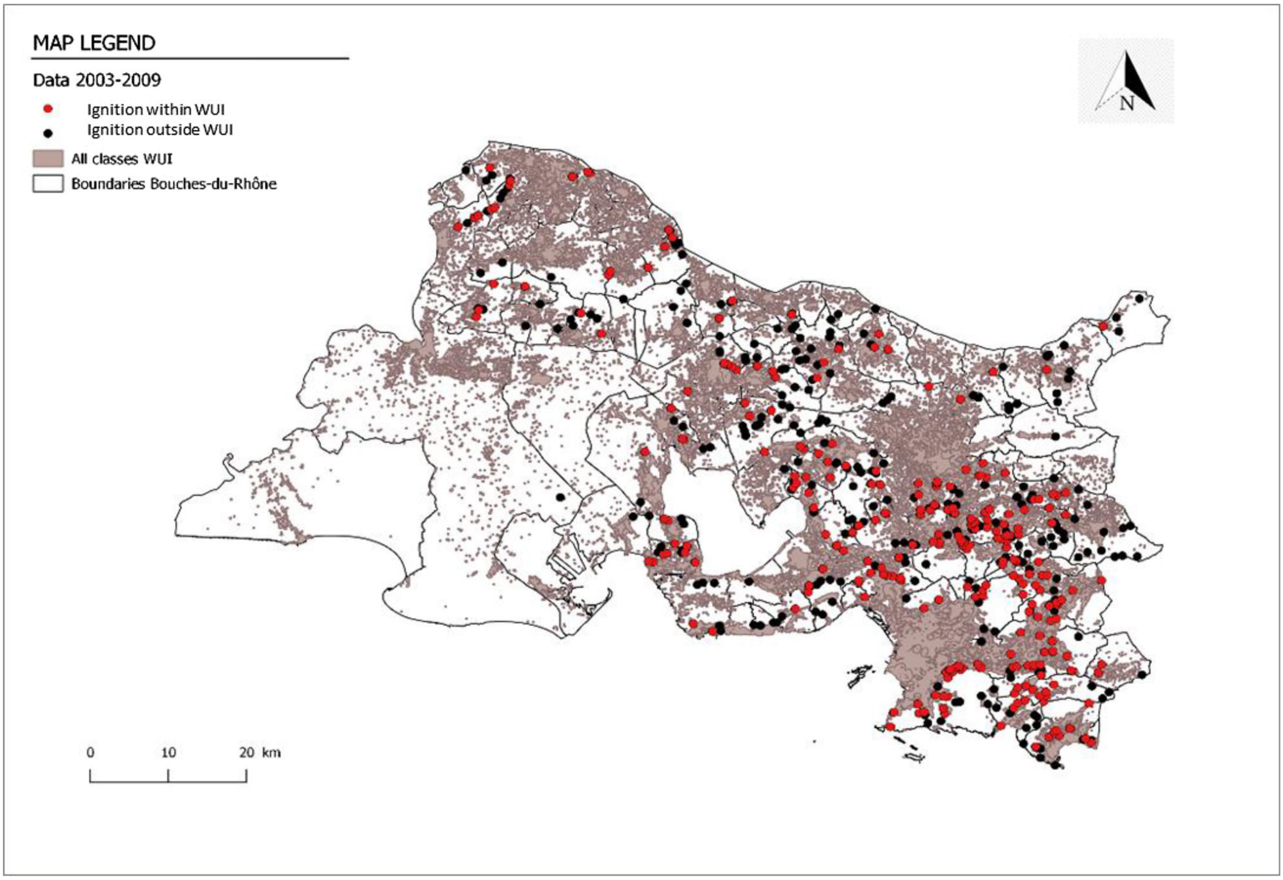

FIGURE 10 Distribution of fire ignitions according to WUI in the Bouches-du-Rhône district (*Source*: ONF/DDTM13)

TABLE 5 Temporal variation of the distribution of ignitions according to the WUI type (Source: ONF/DDTM13, WuiMap)

Type of WUI	Number of ignitions 1993–2009	%	Number of ignitions 1993–1999	%	Number of ignitions 2003–2009	%
Very dense clustered	124	32.2	19	19.8	105	36.3
Dense clustered	74	19.2	16	16.7	58	20.1
Scattered	110	28.6	27	28.1	83	28.7
Isolated	77	20,0	34	35.4	43	14.9
Total within WUI	385	50.2	96	38.7	289	50.2
Total outside WUI	439	49.8	152	61.3	287	49.8
Total	824	100	248	100	576	100

in frequency between 1993 and 2017. Regarding the burned area, the strongest temporal variation was displayed by criminal causes (the most destructive in terms of burned area, especially during the two first periods), accidental causes (only during the first period, despite a low occurrence), and negligence during private activities (especially during the last period). It is worth noting that these relatively large areas burned by the two latter causes were due to only one destructive event. When comparing accidental and natural fires, the former were more destructive in the study area, which is not the case in other districts of the region (Ganteaume & Guerra, 2018). However, the area burned by these fires decreased between 1993–1999 and 2003–2009, despite an increasing rate of fire occurrence, showing that the size of these fires decreased between the two periods. The increase in the rate of change in occurrence between the two last periods was slowing down for most causes, even decreasing for the natural cause and the negligence during private activities, which entailed a decreasing rate of the burned area, except for the latter (due to one large fire event in 2016 and in 2017). In the study area, the highest proportion of large fires were criminal as, generally, they are set when the weather conditions are favorable to fire propagation (i.e., when the wind is strong and the relative humidity low). Several studies also showed that, in southeastern France, when the population density is higher in summer (due to tourism), fires due to negligence (especially due to private activities close to housing or infrastructures) are smaller but more frequent than criminal fires and with a high spatial variability (Curt & Fréjaville, 2016; Ganteaume & Guerra, 2018). The situation in the study area is comparable to Spain (55% of criminal fires burning 59% of the total area between 2001 and 2010) (Gómez-Armisén & Úbeda, 2015).

4.2 | Land cover and WUI variation

Land cover significantly varied over time, with a decrease in agricultural areas during the two first periods benefiting to natural and artificialized areas, however the trend reversed between the two last periods (2006 and 2014). Previous studies also revealed a clear trend of forest expansion and the reduction of croplands and grasslands in some regions of Italy (Calabria: Di Fazio et al., 2011), the Appenines: Malandra et al., 2018, and Sicily: Donato et al., 2016), often due to the intensification of silvicultural activities and to a gradual agricultural abandonment (Di Fazio et al., 2011). The same occurred in Greece (Petanidou et al., 2008), Spain (Poyatos et al., 2003), but also in the French Pyrenean region (Roura-Pascual et al., 2005), highlighting that the Mediterranean basin is one of the most significantly altered hotspots on Earth (Myers et al., 2000). Indeed, agricultural lands, evergreen woodlands, and shrublands, so widespread in the whole region, are the result of anthropogenic disturbances that have been occurring over centuries or even millennia (Blondel, 2006). However, over the past decades, the most significant land cover/land use changes have occurred as a consequence of a series of widespread and often connected phenomena, including urban sprawling and agricultural abandonment in marginal areas, more frequent and more intense summer wildfires, and the rapid expansion of tourist activities and infrastructures, above all, along the coasts (Antrop, 2004; Kosmas et al., 2000; Pellizzaro et al., 2012).

As for land cover, WUIs can also be easily mapped everywhere in the world using land cover and housing data, when available, so that their extent and dynamics can be quantified (Bouillon et al., 2014). For instance, WUIs covered 9.5% of the conterminous United States in 2010 and had a 41% growth in the number of houses since 1990 (Radeloff et al., 2018). Similar trends have been reported across southern Europe (Galiana-Martin et al., 2011). For instance in Sardinia, the temporal trend of WUIs clearly showed the shift from a prevailing agro-pastoral economy to an economy based mainly on tourism, with an intensification of WUI clustered type, mainly represented by tourist villages and resorts on the coast, increasing at a faster rate than the scattered and isolated types (Pellizzaro et al., 2012). In the study area, over the period 1993–2017, WUIs represented on average 28.6% of the district surface area, with a 2.3%-increase in the rate of change between 1999 and 2009 and a well-marked spatial distribution of the different WUI types. Indeed, the "very dense clustered" and "dense clustered" types were mostly concentrated around cities and around the Etang-de-Berre while "scattered" and "isolated" types were mostly located in the southwestern and northern parts of the study area. According to an increase in the global WUI surface area (+8,5%), the "dense clustered" and "very dense clustered" types mostly increased as well as the "scattered" type, to a lesser extent, in contrast to the "isolated" type that decreased between 1999 and 2009. This temporal variation was also characterized by a strong heterogeneity among communities, regardless of the WUI type.

4.3 | Variation of fires according to land cover and WUI

The natural areas were the most affected by fire ignitions (mainly located very close to the artificialized areas, mostly urban areas) during the periods studied in contrast to agricultural areas. These ignitions in natural areas could mostly be due to arson given that this cause was the most frequent (50% of the total occurrence and 57% of the total burned area on average during the three periods studied) compared to negligence (according to the Prométhée database, only 1.6% of the fires were due to negligence during forestry work during the period 2011–2017, for instance). The low fire occurrence in agricultural areas could be explained by the small proportion of fires due to negligence during professional work (see Figure 5A), among which even a few were due to agricultural work (1.3% during the period 2011–2017). However, this trend was decreasing over time (fire ignitions dropping from 66% to 58%), which could also be related to a decrease in the surface area of the land cover classes related to wildland. In contrast, ignitions were increasing in the artificialized areas, which could be correlated with the increase in this land cover's surface area (+234.1 km^2) between 2006 and 2014, therefore resulting in more human-caused ignitions. These ignitions could be due to arson or related to the cause "negligence during private activities" (26% of the fires and 22% of the burned area, on average, during the three periods studied; see Figure 5A), especially during private work (11.8 % during the period 2011–2017). In California, the distribution of fires was also found to be related to the vegetation cover and land use, and therefore, varied spatially throughout the territory (Li & Banerjee, 2021).

According to previous studies carried out in southern Europe (Bajocco et al., 2010; Etienne et al., 1998; Gonzalez-Olabarria et al., 2012; Modugno et al., 2016), we found that peri-urban and coastal tourist areas showed a strong co-occurrence of WUIs and fires. WUIs were impacted by, on average, 49.3% of the ignitions while located in a smaller surface area than the natural areas (only 28.6% of the study area), which is a trend also observed in other Mediterranean areas (Gude et al., 2008; Kosmas et al., 2000; Rodrigues et al., 2016; Rodrigues et al., 2018; Syphard et al., 2019). In Spain, Badia et al. (2011) found that WUIs corresponding to dispersed housing in forested area had more fire risk than those corresponding to settlements in an agro-forest mosaic, typical in farming areas. WUI types' susceptibility to fire also varied over time. Indeed, the "isolated" and "scattered" types were the most affected (as highlighted by Lampin-Maillet et al., 2011) during the first period (1999), with 39% of ignitions within WUIs, while it was "very dense clustered" and "scattered" that were the types (representing the highest proportion of WUI in 2009) mainly targeted in the second period (2009), with 50% of ignitions within WUIs.

It is now well-known that the fire risk is higher at the WUIs in the northern part of the Mediterranean basin (Calviño-Cancela et al., 2016; Modugno et al., 2016; Vilar et al., 2016). As shown in a previous work, the pattern of ignition risk among land covers differed between WUI and non-WUI areas in Galicia (Spain) (Calviño-Cancela et al., 2016) and WUI's vulnerability to wildfires spatially varied among three major WUI types (metropolitan, agroforest, and mountain agro-sylvopastoral in Catalonia (Spain), the abandonment of traditional activities negatively affecting WUI vulnerability, regardless of the type (Badia et al., 2019). A more in-depth analysis of the WUI areas (spatio-temporal evolution) should allow a better characterization of these areas for a better territorial fire risk management. Indeed, fire risk has been exacerbated by the rapid increase in the WUI area and this trend is supposed to worsen as simulations project a continued expansion in the future due to demographic trend, the attraction to areas with natural amenities, recreational activities, retirement to rural areas, and economic reasons (Galiana-Martin & Karlsson, 2011; Tedim et al., 2018; Theobald & Romme, 2007). However, if the change in the firefighting strategy in the late 1980s is taken into account, the increase in fire risk due to climatic (increasing summer temperature and drought period) and land use (increasing WUI areas) changes does not necessarily lead to more fires (Fox et al., 2015).

Land use planning and landscape management, through urban planning policies, have to be considered to regulate existing WUI and their surrounding (Ganteaume, 2018; Syphard et al., 2014) and better plan their extension taking into account the current fire risk (Bar Massada et al., 2009) in order to reduce the risk in the future (Hammer et al., 2009). Indeed, there is more and more evidence that policymakers should focus more on land use patterns in fire protection plans as the spatial configuration of development patterns at the WUIs have been shown to influence fire ignition (for instance, densifying area, which could also reduce overall suppression costs; Mobley, 2019).

5 | CONCLUSIONS

Most communities of the Bouche-du-Rhône district were impacted by fires (according to their occurrence, density, and burned area) with a high spatial (the most impacted communities being located close to big cities) but also temporal variability. The level of certainty of the fire causes has strongly improved since 1997, showing a decreasing interannual variability, especially in 2011–2017. The study area was also characterized by a high occurrence of criminal fires, regardless of the period. These fires were the most destructive, except in 2011–2017, when fires due to negligence during private activities burned the largest area, but mostly as a result of one large fire event.

The surface area of the main land cover classes varied among periods, with a decrease in agricultural areas between 1999 and 2006 benefiting to the other classes but the trend reversed between 2006 and 2014. The natural areas were the most impacted by ignitions and underwent the largest burned area, regardless of the period, in contrast to the agricultural areas. However, this trend was decreasing over time in contrast to that of artificialized areas. The proportion of WUI increased over time, especially the "dense clustered" and "very dense clustered" types (in contrast to the "isolated" type), and represent on average ∼29% of the district's area. There was also a spatial variation of the WUI types, "dense clustered" and "very dense clustered" types being located mostly around urban areas in the East while the other types were more frequent in the southwestern and the northern parts of the study area. The "very dense clustered" and "scattered" types were the most affected by fires in 2009 while it was "isolated" and "scattered" in 1999. There was a strong heterogeneity among communities in this temporal variation, regardless of the WUI type.

Housing development is one of the most important causes of landscape change throughout the world. The current work provided results at a fine scale (community) that are important to take into account, as we need to better plan the WUI to develop resilient communities along with fire-resilient landscapes.

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APPENDIX

TABLE A1 Annual fire occurrence according to the three periods studied in the Bouches-du-Rhône district (www.promethee.com). SD: Standard deviation

Time step	Number of fires 1993–1999	Number of fires 2003–2009	Number of fires 2011–2017
Year 1	180	350	154
Year 2	167	229	159
Year 3	169	204	121
Year 4	99	205	95
Year 5	124	253	158
Year 6	180	147	378
Year 7	193	174	257
Mean	159	223.1429	188.86
SD	34.2	65.7354	97.375

TABLE A2 Annual burned area according to the three periods studied in the Bouches-du-Rhône district (www.promethee.com). SD: Standard deviation

Time step	Burned area 1993–1999	Burned area 2003–2009	Burned area 2011–2017
Year 1	288.4	2308.1	196.5
Year 2	361.3	2674.1	831
Year 3	1736.7	2263.5	102
Year 4	47.12	390.5	22.3
Year 5	4507.6	293.7	65.8
Year 6	898.7	164.4	4533.2
Year 7	2823.6	1285.8	1651.6
Mean	1523.35	1340.01	1057.49
SD	1637.42	1076.35	1642.87

TABLE A3 Annual proportion of unknown and known causes according to the three periods studied in the Bouches-du-Rhône district (www.promethee.com). SD: Standard deviation

	% Unknown			% Known		
Time step	1993–1999	2003–2009	2011–2017	1993–1999	2003–2009	2011–2017
Year 1	98	71.4	20.1	2.339	28.57	79.9
Year 2	95	33.2	29.6	4.890	66.81	70.4
Year 3	98	40.7	33.1	2.028	59.31	66.9
Year 4	72	82.4	37.9	28.17	17.56	62.1
Year 5	52	47.4	30.4	47.83	52.57	69.6
Year 6	44	47.6	50.8	56.41	52.38	49.2
Year 7	31	32.8	29.2	68.92	67.24	70.8
Mean	70	50.8	33	30.08	49.21	67
SD	28	19.1	9.48	28.02	19.09	9.48

TABLE A4 Annual occurrence (a) and area burned (b) by the fires due to the main causes according to the three periods studied in the Bouches-du-Rhône district (www.promethee.com). P1: 1993–1999, P2: 2003–2009, P3: 2011–2017; SD: Standard deviation

a: Number of fires

	Natural			Accidental			Criminal			Negligence professional			Negligence private		
Causes	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Year 1	1	6	3	1	13	7	0	52	84	3	3	7	0	26	22
Year2	4	16	2	4	22	9	0	68	64	4	12	3	3	35	34
Year 3	0	4	13	3	9	8	0	62	27	0	7	5	2	39	27
Year 4	5	6	7	3	4	3	0	16	38	6	3	2	0	7	9
Year 5	3	4	12	8	13	8	27	60	60	9	5	9	13	51	21
Year 6	11	4	3	7	1	23	76	36	97	11	4	16	24	32	47
Year 7	7	11	8	17	8	32	83	68	105	3	4	16	52	26	21
Mean	4.43	7.29	6.86	6.14	10.00	12.86	26.57	51.71	67.86	5.14	5.43	8.29	13.43	30.86	25.86
SD	3.74	4.57	4.45	5.37	6.88	10.51	37.53	19.27	29.23	3.80	3.21	5.77	19.15	13.58	11.98

b: Burned area (ha)

	Natural			Accidental			Criminal			Negligence professional			Negligence private		
Causes	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Year 1	0.02	41.23	0.53	0.3	20.20	1.69	0	1331.05	9.07	282.63	3.3	0.85	0	11.51	12.67
Year2	6.55	1.51	0.02	7.3	66.99	2.28	0	2501.56	806.09	2.8	11.76	0.15	1.67	26.13	9.21
Year 3	0	0.32	0.86	3.5	10.86	7.57	0	1748.23	17.16	0	11.47	0.21	0.1	314.47	1.93
Year 4	0.66	0.36	0.29	1.4	1.2	0.38	0	223.35	7.07	7.32	0.62	0.42	0	8.50	0.46
Year 5	0.25	0.02	1.77	3463.84	6.38	0.26	968.52	181.27	23.82	9.82	53.17	0.31	5.33	17.48	5.07
Year 6	67.27	1.24	0.16	14.66	0.010	719.28	503.08	91.31	537.45	4.37	1.77	2.72	272.17	22.66	2686.03
Year 7	0.60	2.97	1.47	19.93	1068.80	9.64	2771.93	80.49	428.61	6.35	4	40.63	15.68	44.07	1077.46
Mean	10.76	6.81	0.73	501.56	167.78	105.87	606.22	879.61	261.33	44.76	12.30	6.47	42.14	63.55	541.83
SD	25.02	15.21	0.67	1306.26	397.98	270.51	1024.87	980.42	327.95	104.94	18.57	15.09	101.59	111.26	1026.39

TABLE A5 Distribution of fire ignitions according to the land cover classes in 1999 in the Bouches-du-Rhône district (Source: ONF/DDTM13, CRIGE PACA)

Land cover		**Number of ignitions**
	Discontinuous urban area	9
	Scattered dwellings	12
	Industrial and commercial areas	1
	Communication network (roads and railways)	7
"Artificialized areas"	Airports	0
	Mines	1
	Dumping areas	1
	Parks	0
	Sport and leisure areas	0
Total ignitions "Artificialized areas"		31
	Agricultural lands without irrigation	10
	Irrigated agricultural lands except rice paddies	0
	Rice paddies	0
	Areas with high density of greenhouses	0
"Agricultural areas"	Vineyards	2
	Orchards	0
	Olive groves	1
	Pastures	0
	Complex and parcel cropping systems	2
	Agricultural land with native vegetation	4
Total ignitions "Agricultural areas"		19
	Deciduous stands	6
	Conifer stands	79
	Mixed stands	1
	Shrublands	87
"Natural areas"	Changing forests and shrublands	2
	Sparse vegetation	14
	Prairies	4
	Moors and bushes	0
	Bare ground	5
Total ignitions "Natural areas"		198
Total		248

TABLE A6 Distribution of fire ignitions according to the land cover classes in 2006 in the Bouches-du-Rhône district (Source: ONF/DDTM13, CRIGE PACA)

Land cover		Number of ignitions
	Discontinuous urban area	36
	Scattered dwellings	52
	Industrial and commercial areas	26
	Communication network (roads and railways)	11
"Artificialized areas"	Airports	1
	Mines	4
	Dumping areas	1
	Parks	4
	Sport and leisure areas	5
Total ignitions "Artificialized areas"		140
	Agricultural lands without irrigation	18
	Irrigated agricultural lands except rice paddies	2
	Rice paddies	
	Areas with high density of greenhouses	1
"Agricultural areas"	Vineyards	6
	Orchards	10
	Olive groves	1
	Pastures	15
	Complex and parcel cropping systems	
	Agricultural land with native vegetation	
Total ignitions "Agricultural areas"		53
	Deciduous stands	16
	Conifer stands	89
	Mixed stands	139
	Shrublands	84
"Natural areas"	Changing forests and shrublands	33
	Sparse vegetation	12
	Prairies	3
	Moors and bushes	2
	Bare ground	3
Total ignitions "Natural areas"		381
Total		574

TABLE A7 Distribution of fire ignitions according to the land cover classes in 2014 in the Bouches-du-Rhône district (Source: ONF/DDTM13, CRIGE PACA)

Land cover		Number of ignitions
" Artificialized areas "	Discontinuous urban area	82
	Scattered dwellings	127
	Industrial and commercial areas	46
	Communication network (roads and railways)	44
	Airports	6
	Mines	2
	Dumping areas	40
	Parks	
Total ignitions "Artificialized areas"		347
"Agricultural areas"	Agricultural lands without irrigation	41
	Irrigated agricultural lands except rice paddies	13
	Rice paddies	2
	Areas with high density of greenhouses	29
	Vineyards	21
	Orchards	5
	Olive groves	33
	Pastures	3
	Complex and parcel cropping systems	
	Agricultural lands with native vegetation	
Total ignitions "Agricultural areas"		147
"Natural areas"	Deciduous stands	33
	Conifer stands	166
	Mixed stands	325
	Shrublands	128
	Changing forests and shrublands	31
	Sparse vegetation	9
	Prairies	12
	Moors and bushes	5
	Bare ground	1
Total ignitions "Natural areas"		710
Total		1204