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ABSTRACT

This spatio-temporal dynamic of fires was analyzed at the community scale in one of the most fire-prone areas of southeastern France. Three periods between 1993 and 2017 were compared in order to highlight a temporal variation of fires, land cover, and Wildland-Urban Interface (WUI). Fire density were highly variable among communities, hotspots being located mostly in the South-East, close to big cities but spatially varying in time. Fire occurrence and burned area did not significantly differ among periods, mostly due to high inter-annual variability. The proportion of fires with unknown cause decreased over time while criminal fires were the most frequent and deleterious, especially before 2009, followed by negligence during private activities, mostly after 2009. WUI represents ~30% of the study area, the different types varying spatially (denser clustered types mostly located in the South-East in contrast to “scattered” and “isolated”). There was an increase in WUI area over time, especially for both clustered types while the “isolated” decreasedbut this was highly heterogeneous among communities. Half of the ignitions occurred in WUI, “very dense clustered” and “scattered” types being the most affected, especially in 2009. Land cover classes significantly varied among periods, with a decrease in “agricultural areas” during the two first periods that increased again afterwards, which was reversed for” artificialized” and “natural areas”, to a lesser extent. The latter was the most impacted by ignitions (60%), regardless of the period, but showed a decreasing trend over time in contrast to the former.

KEY-WORDS

Fire ignition, WUI, land cover, fire causes, French Mediterranean area

1. INTRODUCTION

At the global scale, wildfires have become one of the main disturbances for the socio-ecosystems (1). In Europe, on average, 68,000 fires burn every year 450,000 ha of vegetation, 85% affecting the Mediterranean basin (2). Along the top five of the most affected European countries (Portugal, Spain, France, Italy, and Greece), wildfires also take a heavy toll on Turkey as well as on the coastal area of the Balkans (3). In some of these countries, megafires regularly destroy large areas entailing huge economic impacts, e.g. 47,000 ha in Portugal in 2017 or 85,000 ha in Greece in 2019 (4; 5). In France, however, the magnitude of fire events is much lesser as, for the past couple of decades, the largest fire size was 6,744 ha in 2003 and 2,600 ha in 2016 (6;7). The French Mediterranean region concentrates most fire occurrence and burned area (58% of the burned area on average, between 2010 and 2018, and up to 80% in 2003 (2)) where large fires (≥ 100 ha), representing only 1% of the occurrence, are responsible for more than 70% of the burned area (8). However, the spatial variability of the fire activity in this area is high, the southeasternmost part concentrating more than 68% of the fire occurrence and 73% of the burned area, mainly in summer (8). Several factors 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 (9; 10). There is already emerging evidence of an increasing frequency of compounded heat waves and drought episodes across Mediterranean regions in the observational record (11). Ecological factors, such as high vegetation cover resulting from the land abandonment since the mid-XXth century and by the systematic fire suppression policy, provide abundant fuel biomass for the fire (12). 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 (8 ;13). 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 (13). This trend is continuing into the 2000s with an intensification of the urban growth and infrastructure development adjoining wildland areas (14), increasing the proportions of areas called « Wildland-Urban Interfaces » (WUI) (15; 16; 17; 18). 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) (19). The WUI rate of increase is often high, especially in tourist areas, along with that of the population density (20). 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.

Highlighting WUI as a factor also influencing the fire activity in Mediterranean areas has been developped in previous studies (19; 21; 22; 23; 24; 25). 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. 24). The information on the fire causes responsible for the ignitions is also something needed to improve fire prevention, which is rarely provided (8; 13).

The aim of the current work was 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 last 25 years (1993-2017) in the French Mediterranean area. This would allow an updated view of the current situation in this area in terms of fire activity. Moreover, a better knowledge of the fire causes, coupled with a spatial analysis of the ignition points, will highlight the main factors and the preferential areas of these fire ignitions. Ultimatley, this work should allow refining the fire policies in terms of awareness raising, firefighting means, and land management.

2. MATERIAL AND METHODS

2.1. Study area

The study area, the Bouche du Rhône district (Fig. 1a), is one of the 15 administrative districts 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 (6; 8; 13). 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 (24). The on-going urban sprawling mostly occurs in watersheds and valleys adjoining the numerous forest massifs (Fig. 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, are *Pinus halepensis* stands (26) 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 pre-forest vegetation type before oak forests (27). 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 (28). Wildfires occur frequently in the whole area, making of the landscape a mosaic of all the previously mentioned types of natural vegetation and of 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 district Bouches du Rhône, 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, 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 favours fire propagation (29). The mean maximum temperature ranged from 9.8°C to 13.2°C in winter and from 27.9°C to 30.6°C in summer. Mean annual precipitation ranged from 472 mm 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

2.2.1. Fire occurrence, burned area, level of certainty and nature of fire causes

We compiled the data provided by the regional fire database Prométhée (number, burned area, certainty and nature of 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 (Fig. 1b).

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 of one-digit codes were taken into account, according to the definitions given by the Joint Research Centre (30): (i) natural (any wildfire caused by natural origin, with no human involvement in any way; only lightning in the study area), (ii) accidental (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 such as power lines, railways, vehicles, or garbage dumps), (iii) deliberate/criminal (wildfire intentionally caused by humans with the use of fire for different motives such as conflict, interest, or pyromania), (iv) negligence during professional works (wildfire unintentionally caused by humans using fire or glowing objects during professional activities, not connected to fatality), and (v) negligence during private activities (wildfire unintentionally caused by humans using fire or glowing objects during recreation, not connected to fatality). 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 more 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-digit code causes.

2.2.2. Georeferenced Ignitions

The ignition spatial coordinates provided by the fire database Prométhée are not accurate because the fire ignitions are located using a 2 km*2 km grid reference (developed by the firefighting services for approximating the location of the fire event). The considerable imprecision arising from this georeferencing method makes it difficult working at 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, although less exhaustive than the Prométhée fire database (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

2.3.1. Main Land Cover Data

Data was extracted from the BD OCSOL PACA database (CRIGE PACA : Centre Régional d'Information Géographique Provence-Alpes- Côte d'Azur). This data (projection Lambert 93) is an improvement of the Corinne Land Cover (CLC) version, and has allowed, since 1988, an updated regional land cover with good geometrical quality and maximum semantic confidence. The basic nomenclature of land covers remains mostly the same as for CLC (1 = artificialized, 2 = agricultural, 3 = natural (forests and other wildland), 4 = wetland, and 5 = water bodies) with sub-classes 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 CRIGE PACA land cover is available in 1999, 2006, and 2014 corresponding to the three periods studied (1993-1999, 2003-2009, and 2011-2017).

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 IRSTEA (which has become INRAE since January 1st, 2020). WUI vectorial data was obtained 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 in WUI, i.e. at least than 200 m from wildland). Contrary to the work of (24) who calculated a global WUI surface area corresponding to a 100 m-buffer around each building located in WUI, we used a more accurate WUI characterization and mapping (31) based on the four types of housing density (i.e. WUI types): "isolated", "scattered", "dense clustered", and "very dense clustered", as defined in (32). This latter analysis was only performed for 1999 and 2009 due to a computing problem in generating the different layers of housing density for 2017 (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 multi-spectral 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 with known causes 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 non-parametric 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 (8)). However, spatial analyst provides a search radius algorithm based on the distance between ignitions giving a too smoothed 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 50m-resolution was chosen for the output raster. This analysis was carried out at two different periods (1999 and 2009) in order to highlight how the fire hotspots would vary spatially in the study area over time.

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 *vs* 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^2 test was 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. Spatial variation of fires

During the period 1973-2017, there was a high variability of the number of fires among communities (Fig. 2a), which was well defined spatially (most affected areas in the centre and in the East of the study area). The major cities, Marseille and Aix-en-Provence, their neighbouring communities, as well as those around the Etang de Berre, were the most sensitive to fire. Taking into account the community surface area, the community's 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 the most at risk were located in the southeastern part of the study area (Fig. 2b). Using the georeferenced fire ignitions, we performed the analysis 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. A temporal variation of the fire ignition hot-spots was highlighted between the two periods considered (Fig. 3). During the period 2003-2009, 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). In contrast, for the period 2011-2017, the hot-spots 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. In general, the northern part of the district presented a lower fire density than the southeastern part, regardless of the period. This result agreed with the previous analysis performed using the data of the Prométhée database, although less accurate in terms of georeferencing.

3.1.2. Temporal variation of fires

The comparison of the fire occurrence among periods showed a maximum of fire occurrence during the period 2003-2009 with 1562 fire events (Fig. 4a). In contrast, the burned area revealed a constant decreasing trend, from 10664 to 7402.7 ha since 1993-1999 (Fig. 4b). However, both variations were not significant (Kruskal Wallis test, $P_{occurence} = 0.175$; $P_{BurnedArea} = 0.443$), mostly due to a high variability within periods. The interannual analysis of occurrence and burned area highlighted important discrepancies among and within periods (Fig. 4 and Suppl. Mat. 1, 2). Regarding the fire occurrence (Fig. 4a), between 1993 and 1999, there is a low scattering of data around the annual mean (158.9 ± 34.2 fires) meaning that the interannual variability was low. In contrast, this variability strongly increased for the two other periods (2003-2009 and 2011-2017), displaying higher standard deviations (223.1±65.7 and 188.9±97.3, respectively). Besides the global increase in the number of fires, there was also an increase in the interannual variability (e.g. the most recent period gathered the two highest values among 21 values studied in the three periods : 95 fires in 2014 and 378 fires in 2016 ; Suppl. Mat. 1). Regarding the burned area, the internannual variability was strong for the periods 1993-1999 (1523.3±1637.4 ha*)* and 2011-2017 (1057.5±1642.9 ha) as well as, to a lesser extent, for 2003-2009 (1340.1±1076.4), meaning that the annual burned area has been more homogeneous during this latter period (Fig. 4b). As previously experienced, the most recent period presented the two highest values (22.3 ha in 2014 and 4533.2 ha in 2016 mostly due to the Rognac fire that burned burned more than 2600 ha (Suppl. Mat. 2).

3.1.3. Temporal variation of the level of certainty and nature of fire causes

The difference in the proportion of unknown causes among periods was significant (Kruskal Wallis test, p=0.012). Indeed, the elucidation rate of fire causes considerably improved between 1993-1999 and 2011-2017 (Fig. 4c), entailing a decrease in the proportion of unknown causes from 70% down to 33%. 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. For instance, the period 1993-1999 encompassed, at the same time, the year with the highest proportion of unknown causes (98% in 1999) and among the lowest (31% in 1998). In this latter period, there was a radical change occurring between 1996 and 1997 regarding the proportion of unknown causes (decreasing from 72% to 52%) (Suppl. Mat. 3). The most recent period (2011-2017), besides the fact that it was 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 ($SD_{2011\text{-}2017}=$ 9.5%).

Regarding the nature of the causes in terms of occurrence, most fires were criminal (>40%) showing an increasing trend from 1993-1999 to 2011-2017, followed by those due to negligence during private activities (>20%), the other causes being less frequent, regardless of the period (Fig. 5a). Regarding the burned area, the criminal fires were the most destructive (up to 78% of the total burned area, more frequently due to large fires, i.e. ≥100 ha, than for other causes) during the two first periods. Fires due to negligence during private activities burned the most during the last period (59% *vs* 30% for criminal fires) (Fig. 5b). This was mostly the result of one fire event that occurred in 2016 and burned more than 2600 ha burned. It is also 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. This lack of significativity could be due to the high variability, both in terms of number of fires and burned area, within each period (Suppl. Mat. 4).

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 displaying the lowest rate (5.56%) and those due to negligence during private activities displaying the highest (129.8%) (Fig. 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 (Fig. 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, the class « agricultural areas» strongly decreased from 1999 to 2006 (except olive groves; Suppl. Mat. 5 and 6) benefiting to the classes « dense vegetation » (mixed forests and deciduous stands; Suppl. Mat. 5 and 6) and « artificialized areas » (except for discontinuous urban areas; Suppl. Mat. 5 and 6), to a lower extent (Fig. 7). Between 2006 and 2014, there was a general decrease in the land cover areas except for the class « artificialized areas » (but with a slowing increase, from 21.1% to 1.9%). The decrease in « agricultural areas » was also slowed down. Overall, the evolution between 2006 and 2014 was slight (Table 1). The statistical analyses (Khi^2) showed that the land cover classes and periods were not independent ($p<0.0001$).

Over the period studied (up to 2009), WUI repesented on average 28.6% of the district surface area, with a 2.33%-increase between 1999 and 2009 (Table 2). 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, so was the northern part, to a lesser extent (e.g. Fig. 8).

The analysis of the rate of change in the surface area of the different types of WUI between 1999 and 2009 revealed an increase in the global surface area (+ 8,5%) 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 2). The statistical analyses (Khi^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% (Fig. 9a). The « dense clustered» type was characterized by a stronger evolution than the previous one (on average + 25.8%) but with a 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 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% (Fig. 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% (Fig. 9d).

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

The land cover the most impacted by wildfires was « natural areas » (around 60% of the ignitions), regardless of the period, followed by « artificialized areas » (25-30%). The class « agricultural areas » was submitted to only 10% of ignitions, on average. Except for the class « natural areas », the proportion of ignitions increased from 1999 to 2006 (Table 3).

The burned area was the highest in “natural areas” and “artificialized areas” presented a smaller burned area than “agricultural areas”, regardless of the period. While the burned area did not change over time for the class « agricultural areas », the class « natural areas » presented a decreasing trend in contrast to the class « artificialized areas » (Table 3).

Very few ignition points occurred in agricultural areas which could be explained by the small proportion of fires due to negligence during professional work (see fig. 5a), among which even a few were due to agricultural work (1.3% during the period 2011-2017 according to the Prométhée database). Regardless of the period, most ignitions occurring in agricultural areas were located in farmlands out of the irrigation perimeter (dry lands), vineyards, and orchards (Suppl. Mat. 5, 6, 7). On the contrary, in natural areas, the fuel amount available for fire ignition and propagation was high (more or less dense vegetation) and these areas represented 45% of the total land cover (around 2200 km²), increasing the probability of fire ignition. Most ignitions were located in mixed conifers-deciduous (except during the first period) as well as in conifers stands and in shrublands (Suppl. Mat. 5, 6, 7). These ignitions 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).

Artificialized areas represented around 1000 km² corresponding to 23% of the land cover and gathered between 24% and 29% of the ignitions according to the period studied (Table 3). Moreover, 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 Fig. 5a), especially during private work (11.8 % during the period 2011-2017 according to the Prométhée database). Areas corresponding to WUI in the class

« Artificialized area » (“Discontinuous urban area” and “Scattered dwellings”) gathered most ignitions (Suppl. Mat. 5, 6, 7).

Taking into account the accurately georeferenced ignitions from the DDTM13/ONF database, we found that WUI were impacted by 49.3% of the ignitions and those occurring in « natural areas » were mainly located very close to the « artificialized areas » (Fig. 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 and that the WUI « very dense clustered» and « scattered » types were the most affected (32% and 29%, respectively) (Table 4). When the analysis was carried out at the level of each period, the trend previously highlighted changed. In 1999, 248 ignitions occurred in the Bouches-du-Rhône district. Almost 39% (96 ignitions) of these ignitions were located within WUI area despite this area represented only 27.5% of the district’s total area (1 ignition for 1456 ha). In contrast, the ignitions located outside WUI area (152 representing 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). The most affected WUI types were « isolated » and « scattered » (35% and 28%, respectively) (Table 4). 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 area (1 ignition for 525 ha while there was 1 ignition for 1244 ha outside WUI area, therefore less than two times). The most affected WUI types partially changed compared to the previous period (« very dense clustered » : 36% and « scattered » : 29%), showing the same pattern as during the global period (Table 4).

4. DISCUSSION

4.1. Fire metric temporal variation

Overall, most communities in the Bouches-du-Rhône district were impacted by wildfires, except the wetter and less populated part corresponding to the Rhône's delta. The northern part of the district was also less fire prone than the South-East, mainly due to lower population density (24).There was a large variability in both occurrence and burned area among communities, the most impacted ones being close to big cities. This agreed with the work of (24) that showed that housing density, as a proxy of population density, was one of the main drivers of fire density. However, the temporal variations of occurrence and burned area were not significant, mostly due to the high variability within periods. There was also a temporal variation of the fire hotspots, which is an additional result to the work of (24) who tackled the fire issue in the study area at the spatial scale only. Indeed, during the period 2003-2009, the fire ignition density was higher in the communities located North and East of Marseille while for the period 2011-2017, the hot-spots were concentrated in the communities West of Etang de Berre. This temporal variation of fire hotspots has also been highlighted in other regions in the world, such as in California (33). This result is important in terms of fire management strategy showing the the fire hotspots can change over time.

Among human practices known to alter the fire regime, fire suppression has been suggested to be one of the the most explicative factors in the reduction of the total burned area during the XX century (34). The decreasing trend of burned area in the Bouches-du-Rhône has been highlighted in the end of the 80s (Fig. 1b), when a new fire policy brought new fire suppression and prevention practices in southeastern France. In this new strategy, anticipation and massive attack on the fire within 10 minutes after ignition could act in decreasing the probability that a fire would burn large areas (34). In our work, the decreasing trend of the burned area shows the efficiency of such a policy. However, the persistance of large fire events during extreme weather conditions (e.g. 2003, 2016) reveals that these events can outweigh by far terrestrial and aerial fire-fighting strategies (7; 25). For instance, this was the case during the fire in Rognac (August 2016) that burned more than 2600 ha, out of which 2000 ha were located at the WUI and in urban areas. These areas are as yet among the best defended due to their high stake (35). Despites favourable fire statistics in the French Mediterranean region, the burned area could be tripled considering on the horizon 2100 for the worst climatic scenario (36), at a rate between +15% and +25% per decade (37). Some even stated that the « success » of a fire management policy based on systematic fire suppression is doomed in the long term since the large or mega-fires will only be delayed (7). Indeed, the massive accumulation of fuel will lead to unstoppable fires due to the massive intensity released once ignited. Altough the context differs, this situation is also on-going in South Africa or Australia (7; 25).

Regarding the fire occurrence, the situation was less clear-cut in the Bouches-du-Rhône district for the past 25 years but showed a trend differing from that of the entire region (38). Indeed, the socio-environmental characteristics of the district make it more vulnerable to fire ignitions than other parts of southeastern France (8). Even though 2003 remains the most catastrophic year in terms of fire occurrence and burned area in most European countries, it was not the same in our study area ; indeed 2016 was more destructive (378 fires and 4533.2 ha burned *vs* 350 fires and 2308.1 ha burned in 2003; www.prométhée.com). It is worth noting that the impact of 2003 differed spatially in this region, with the neighbouring district (Var) among the most impacted by the 2003 fires (6). In other countries of southern Europe, such as Portugal, the situation differed with a regular increase in fire occurrence since the 80s, especially that of large fires (39; 40).

We highlighted an improvement of the level of certainty of fire causes from 1993-1999 to 2011-2017 but with a rather high variability, especially in 1993-1999. This heterogeneity (i.e. high interannual variability of fire causes) during this first period was mostly due to the creation of official teams (one team for each district of southeastern France, composed of a firefighter, a forest manager and a police officer) in 1997. These teams have to investigate, if possible, the cause of each fire occuring in this region, therefore increasing the proportion of known causes since then (8). The same trend has been observed in Portugal since 1988 (74% of unknown cause to 47-53% in 2015-2017 (41 ; 42)).

The nature of the fire cause is quite diverse and the fire ignition is generally not a random phenomenon (43; 44) because most fires result from motivated human actions (42). The fire cause analysis revealed that, in the study area, most fires were criminal and were more and more frequent between 1993 and 2017, followed by those due to negligence from private activities, natural fires being the least frequent, regardless of the period. Regarding the burned area, the strongest temporal variation was displayed by accidental causes (only during the first period despite a low occurrence), criminal causes (the most destructive, especially during the two first periods), and negligence during private activities (especially during the last period). It is worth noting that except for this latter cause, the burned area showed a decrease between 2003-2009 and 2011-2017, while both occurrence and burned area mostly increased between 1993-1999 and 2003-2009, due to the general increase in these fire metrics. 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 (8). It is worth noting that the relatively large areas burned by accidental fires for each period (>10%) as well as by fires due to negligence during private activities during the last period were due to only one destructive event (for instance, during the last period, an accidental fire due to a vehicle burned 711 ha in 1997). Between 1993-1999 and 2003-2009, despite an increasing rate of the fire occurrence, regardless of the cause, the opposite trend was found for the area burned by the natural and accidental causes. This showed 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 for the burned area, except for the latter (due to one large fire event in 2016 and in 2017).

In the study area, natural fires were mostly small fires (< 1 ha) and the highest proportion of large fires were criminal. Indeed, generally, the criminal fires are set when the weather conditions are favourable to the fire propagation (i.e. when the wind is strong and the relative humidity low). It would be also interesting to check if the ignitions located in the forest areas would be really related to the criminal causes that represents almost half of the ignitions in the study area. Indeed, the motives of the criminals are to deliberately set a fire, which is favoured in natural areas due to the high amount of fuels available for the fire. Several studies also showed that, in southeastern France, when the population density is higher in summer, fires due to negligence (especially due to private activities close to housing or infrastructures) are smaller but more frequent that criminal fires but with a high spatial variability (8; 45). The situation in the study area is comparable to Spain (55% of criminal fires burning 59% of the total area between 2001 and 2010) (46).

4.2 Land Cover and WUI Temporal Variation

Land cover significantly varied over time, with a decrease in “agricultural areas” during the two first periods benefiting to “natural areas” and “”artificialized areas”, however the trend reversed between 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 (47), the Appenines (48), and Sicily (49)), often due to the intensification of silvicultural activities and to a gradual agricultural abandonment (47). The same occurred in Greece (50), Spain (51), but also in the French Pyrenean region (52). The Mediterranean area is one of the most significantly altered hotspots on Earth (53); indeed, agricultural lands, evergreen woodlands and shrublands, so widespread in the whole Mediterranean basin, are the result of anthropogenic disturbances that have been occurring over centuries or even millennia (54). 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: urban sprawling, agricultural intensification in the most suitable areas 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 (20; 55 ; 56).

As for land cover, WUI can also be easily mapped everywhere in the world using land cover and housing data when available so that their extent and dynamic can be quantified (57). For instance, WUI covered 9.5% of the conterminous United States in 2010 and had a 41% growth in the number of houses since 1990 (58). Similar trends have been reported across southern Europe (59). 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 interface, mainly represented by tourist villages and resorts on the coast, increasing at a faster rate than the scattered and isolated types (20). In the study area, over the period 1993-2017, WUI repesented on average 28.6% of the district surface area, with a 2.3%-increase between 1999 and 2009. There was a well-marked spatial distribution of the different WUI types within the study area : 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. There was also a temporal variation of these types between 1999 and 2009. 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 heteroneneity among communities, regardless of the WUI type. In the continental USA, results also showed that the extent and rate of expansion differed between WUI types (58).

4.3 Fires according to Land Cover and WUI

« Natural areas » were the most affected by fire ignitions (mainly located very close from the « artificialized areas », mostly urban areas) in the study area during the periods studied in contrast to « agricultural areas ». 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 "artificialized areas", which could be correlated with the increase in this land cover's surface area (+234.1 km²) between 2006 and 2014, therefore resulting in more human-caused ignitions. 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, with more large fires where the forests are dense and less developed by human habitats and where the population density is relatively low. In contrast, frequent fires with greater social and economic impact on human lives and society were concentrated in areas where shrubland was the dominant land cover, associated with a higher level of human activity (33).

WUI was impacted by, on average, 49.3% of the ignitions while located in a smaller surface area than "natural areas" (only 28.6% of the study area). In Spain, (60) found that WUI corresponding to dispersed housing in a forested area, characterizing people moving from cities to natural areas, had more fire risk than WUI 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 (17)) during the first period (1999), with 39% of ignitions within WUI, 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 WUI.

It is now well-known that the fire risk is higher in WUI in the northern part of the Mediterranean basin (14; 61; 62). As shown in a previous work, the pattern of ignition risk among land covers differed between WUI and non-WUI areas in Galicia (Spain), forestry plantation showing the highest increase in ignition risk in WUI compared to non-WUI areas in contrast to native forests and agricultural areas (62). Another study (63), carried out in Catalonia (Spain), determined how WUI's vulnerability to wildfires spatially varied among three major WUI types (metropolitan, agroforest, and mountain agrosilvopastoral), each showing significant temporal changes in Land Use and Land Cover but with vulnerability depending on their own fire dynamics (63). These authors showed that the abandonment of traditional activities negatively affected WUI vulnerability, regardless of the type (63).

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. 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 (44; 64; 65). The current study showed that, between 2003-2009 and 2011-2017, mostly 50% of the fires were located at WUI, even if these areas represent less than 25% of the district area, which is a trend also observed in other Mediterranean areas (56; 66; 67; 68; 69). However, if the change in the firefighting strategy in the late 80s 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 (70).

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, 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 class "natural areas" was the most impacted by ignitions and underwent the largest burned area, regardless of the period, in contrast to the class "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 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. Land use planning and landscape management, through urban planning policies, have to be considered to regulate existing WUI and their surrounding (71, 72) and better plan their extension taking into account the current fire risk (22) in order to reduce it in the future (73). There is more and more evidence that policy makers should focus more on land use patterns in wildfire protection plans. For instance, (74) showed that as the spatial configuration of development patterns in WUI (infill, radial, and outlying) influenced wildfire ignition, this should be used to direct land use planning to reduce fire risk in densifying area, which could also reduce overall suppression costs.

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FIGURE CAPTIONS

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 Geograhic Institute (https://www.geoportail.gouv.fr) and 1:25 000 digital terrain model from the National Geographic Institute (IGN).

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

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.prométhée.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.prométhée.com).

Figure 6 : Variation of fire occurrence and burned area 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.prométhée.com).

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).

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

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.

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

TABLES

Table 1 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	4,56%
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 2 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 (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

Table 3 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%

653 Table 4 Temporal variation of the distribution of ignitions according to the WUI type (Source:
654 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

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FIGURES

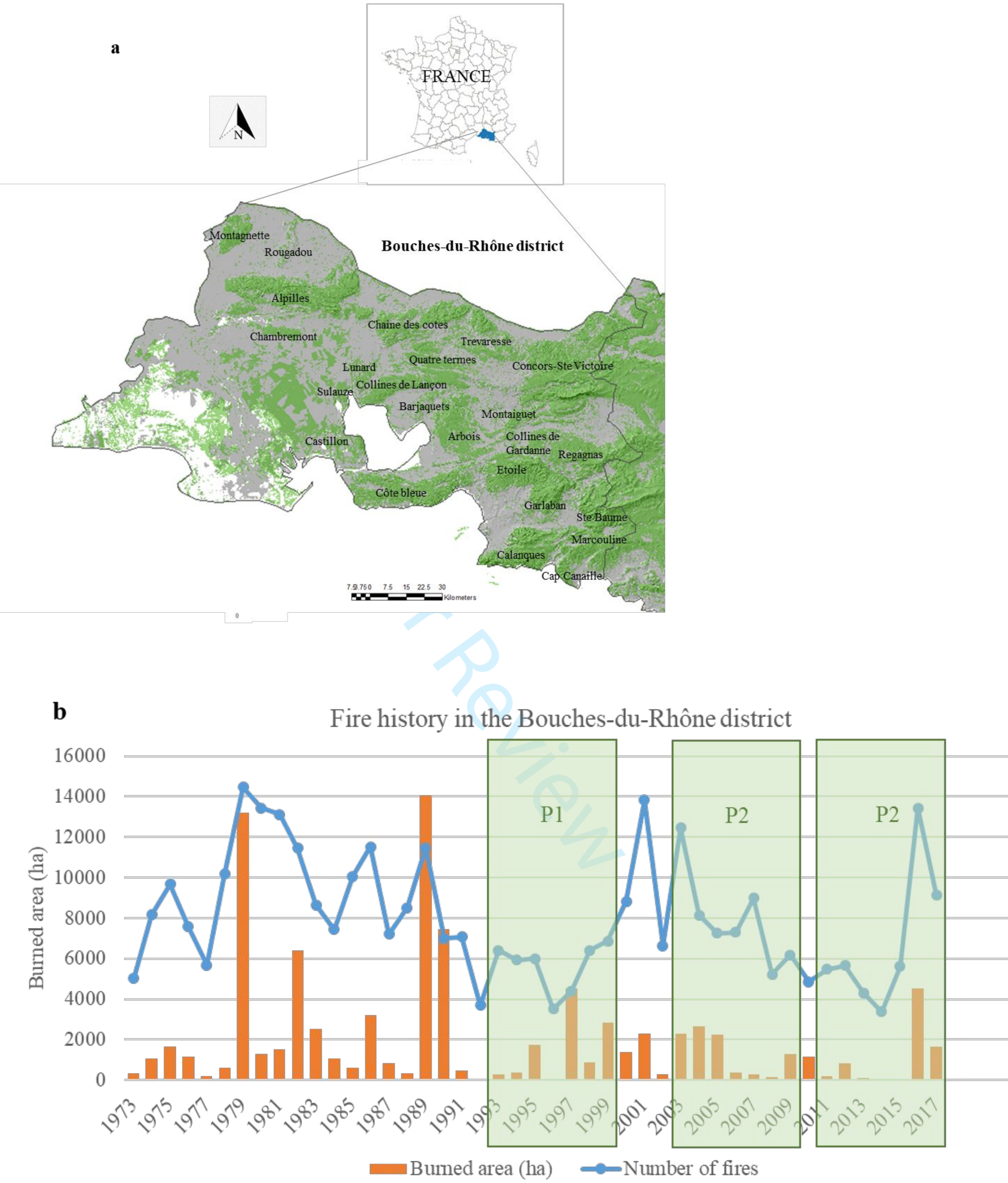


Fig. 1

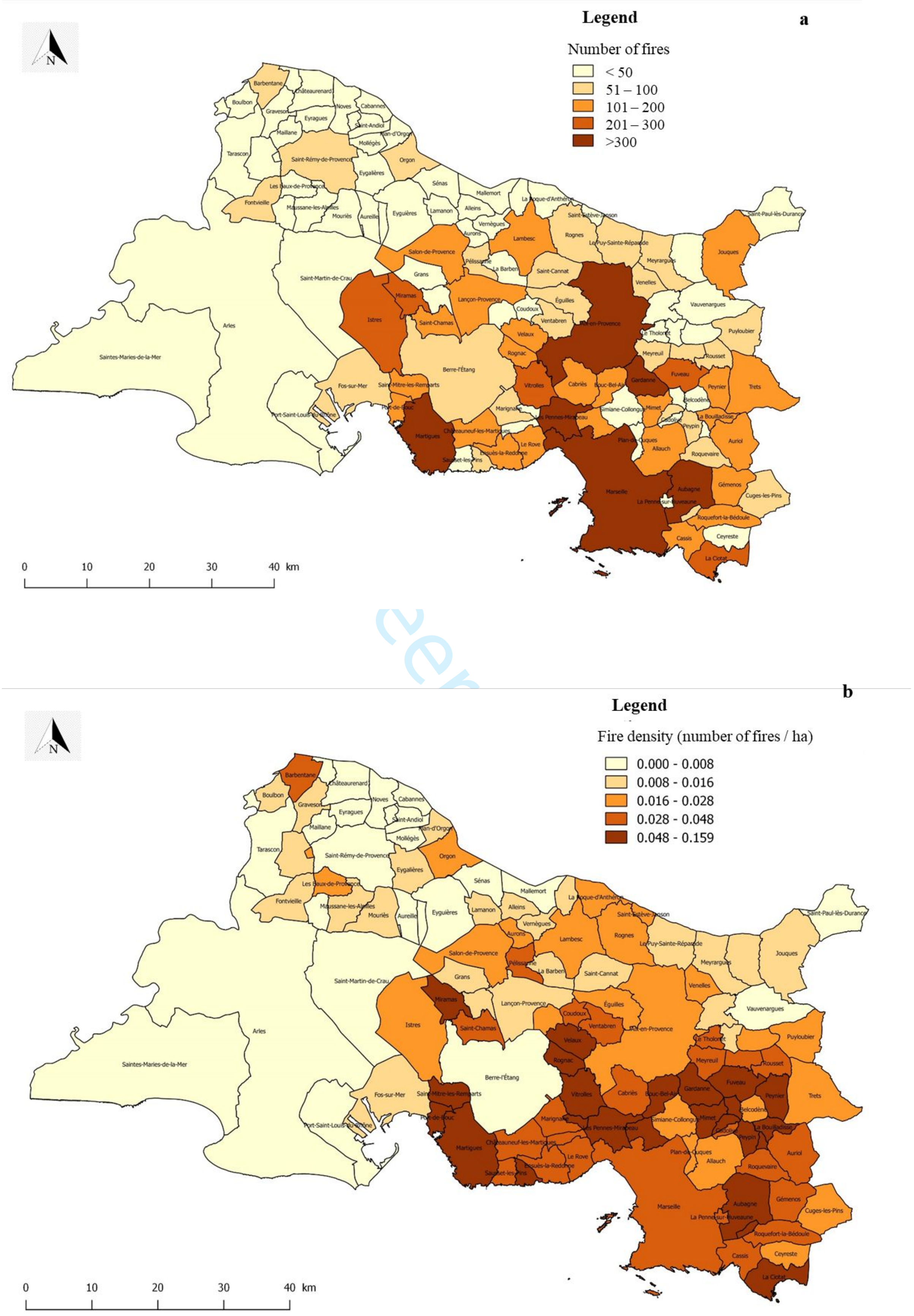

Legend
a
Number of fires
< 50
51 – 100
101 – 200
201 – 300
>300
N
0 10 20 30 40 km
Barbentane
Châteaurenard
Boulbon
Noves
Cabannes
Graveson
Eyragues
Saint-Andiol
Maillane
Plan-d'Orgon
Mollégès
Tarascon
Saint-Rémy-de-Provence
Orgon
Eygalières
Les Baux-de-Provence
Sénas
Mallemort
Fontvieille
Maussane-les-Alpilles
Mouriès
Aureille
Eyguières
Lamanon
Alleins
La Roque-d'Anthéron
Saint-Estève-Janson
Saint-Paul-lès-Durance
Vernègues
Aurons
Lambesc
Rognes
Le Puy-Sainte-Réparade
Meyrargues
Jouques
Salon-de-Provence
Pélissanne
La Barben
Saint-Cannat
Venelles
Saint-Martin-de-Crau
Grans
Miramas
Lançon-Provence
Éguilles
Vauvenargues
Istres
Saint-Chamas
Coudoux
Ventabren
Aix-en-Provence
Le Tholonet
Puyloubier
Arles
Velaux
Rognac
Meyreuil
Rousset
Saintes-Maries-de-la-Mer
Berre-l'Étang
Fos-sur-Mer
Saint-Mitre-les-Remparts
Vitrolles
Cabriès
Bouc-Bel-Air
Gardanne
Fuveau
Peynier
Trets
Port-de-Bouc
Marignane
Simiane-Collongue
Mimet
Belcodène
Port-Saint-Louis-du-Rhône
Les Pennes-Mirabeau
Cadolive
La Bouilladisse
Martigues
Châteauneuf-les-Martigues
Peypin
Le Rove
Plan-de-Cuques
Allauch
Auriol
Roquevaire
Gignac-la-Nerthe
Ensuès-la-Redonne
Sausset-les-Pins
Gémenos
Marseille
Aubagne
Cuges-les-Pins
La Penne-sur-Huveaune
Roquefort-la-Bédoule
Cassis
Ceyreste
La Ciotat
Legend
b
Fire density (number of fires / ha)
0.000 - 0.008
0.008 - 0.016
0.016 - 0.028
0.028 - 0.048
0.048 - 0.159
N
0 10 20 30 40 km

Fig. 2

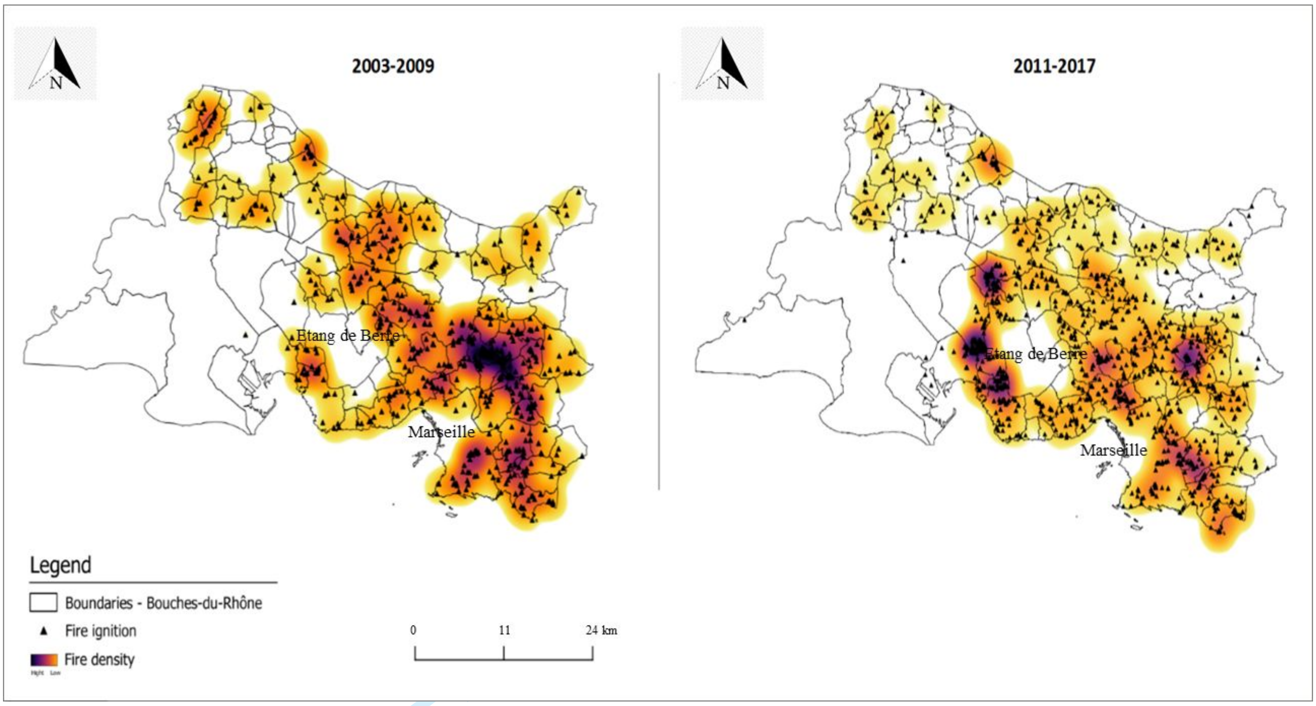
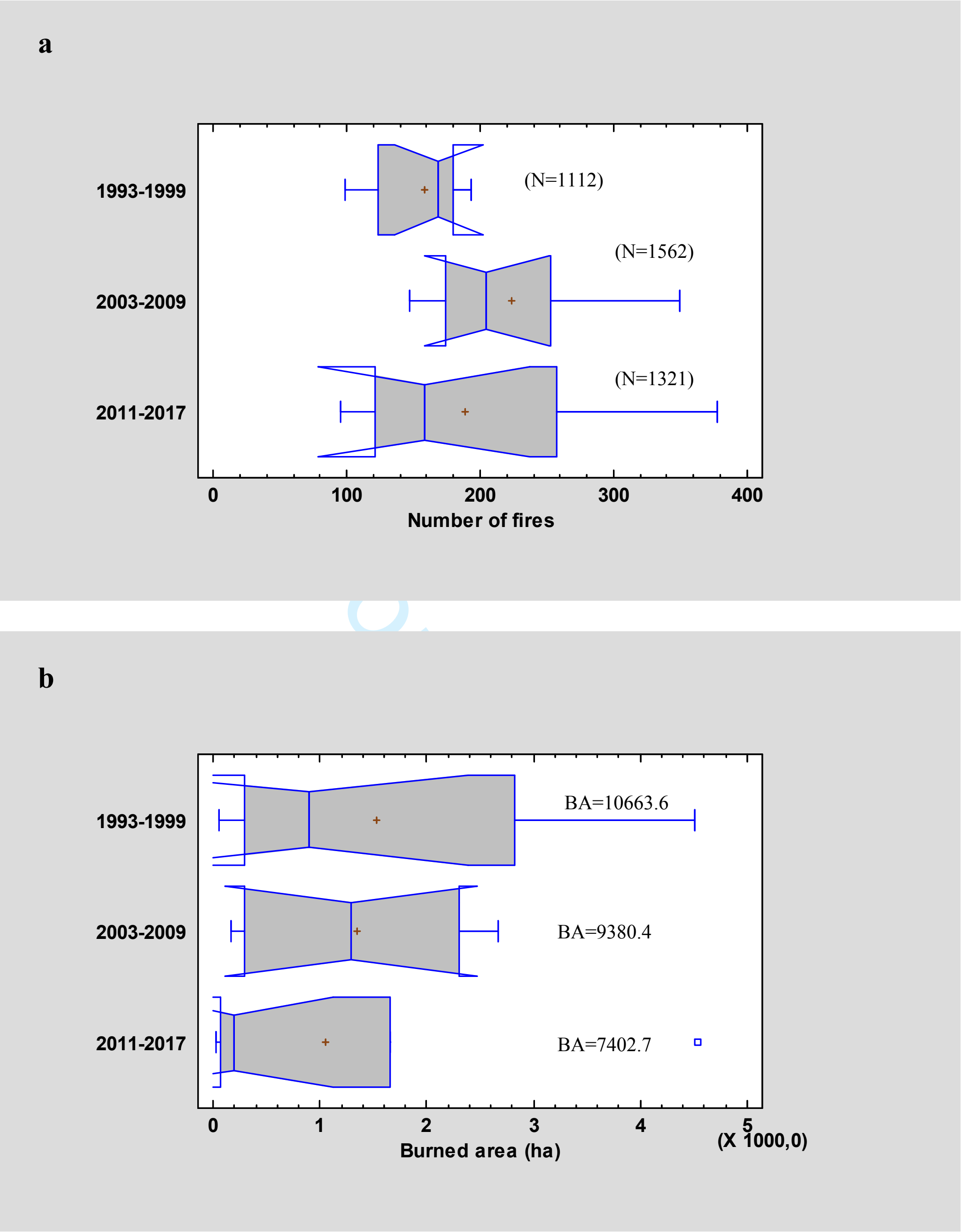

2003-2009
2011-2017
N
N
Etang de Berre
Marseille
Etang de Berre
Marseille
Legend
Boundaries - Bouches-du-Rhône
Fire ignition
Fire density
0
11
24 km

Fig. 3


a
1993-1999
2003-2009
2011-2017
(N=1112)
(N=1562)
(N=1321)
0
100
200
300
400
Number of fires
b
1993-1999
2003-2009
2011-2017
BA=10663.6
BA=9380.4
BA=7402.7
0
1
2
3
4
5
(X 1000,0)
Burned area (ha)

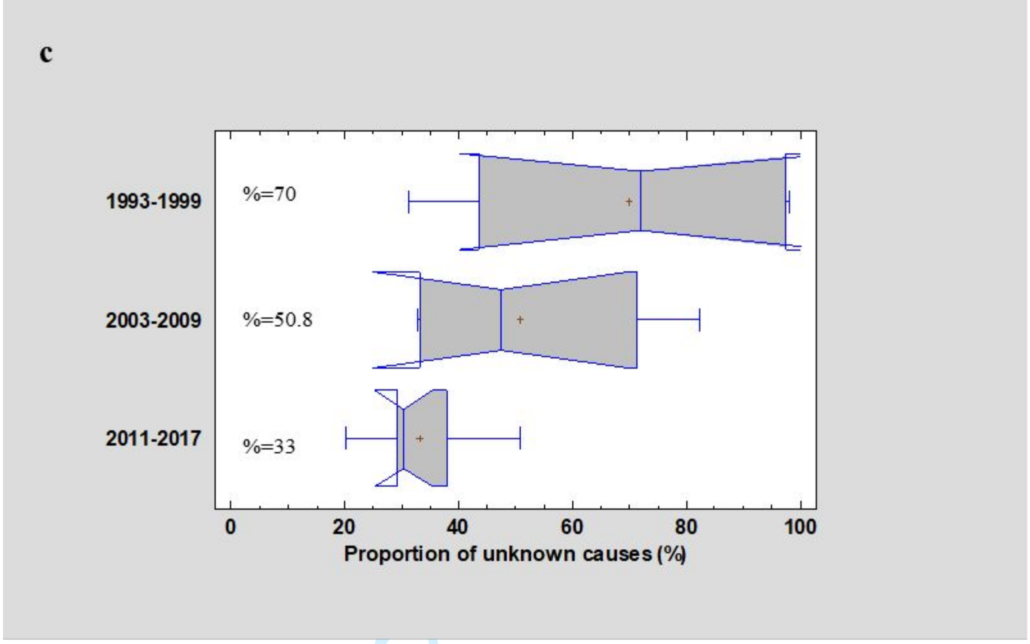

c
1993-1999
%=70
2003-2009
%=50.8
2011-2017
%=33
0
20
40
60
80
100
Proportion of unknown causes (%)

Fig. 4

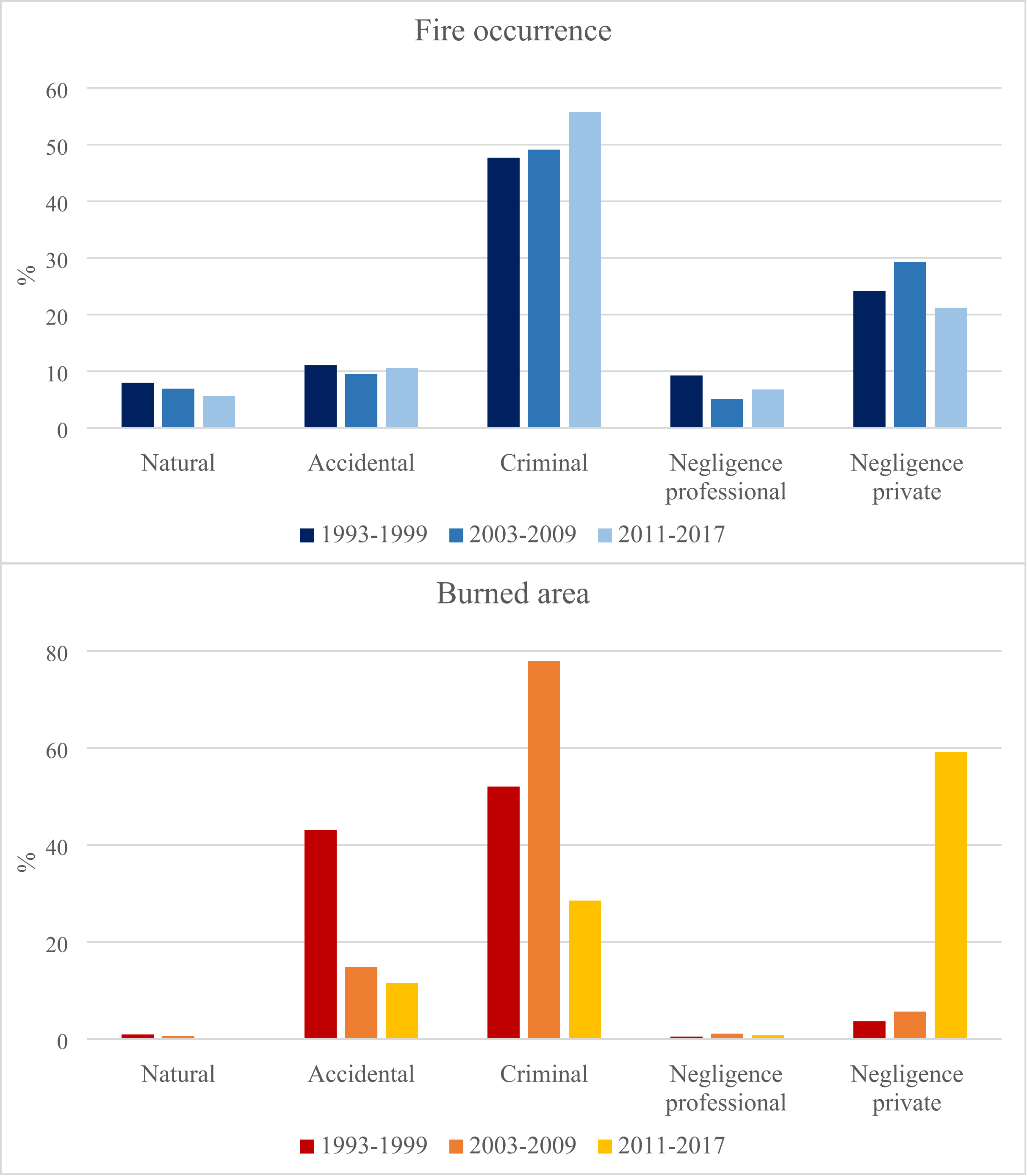
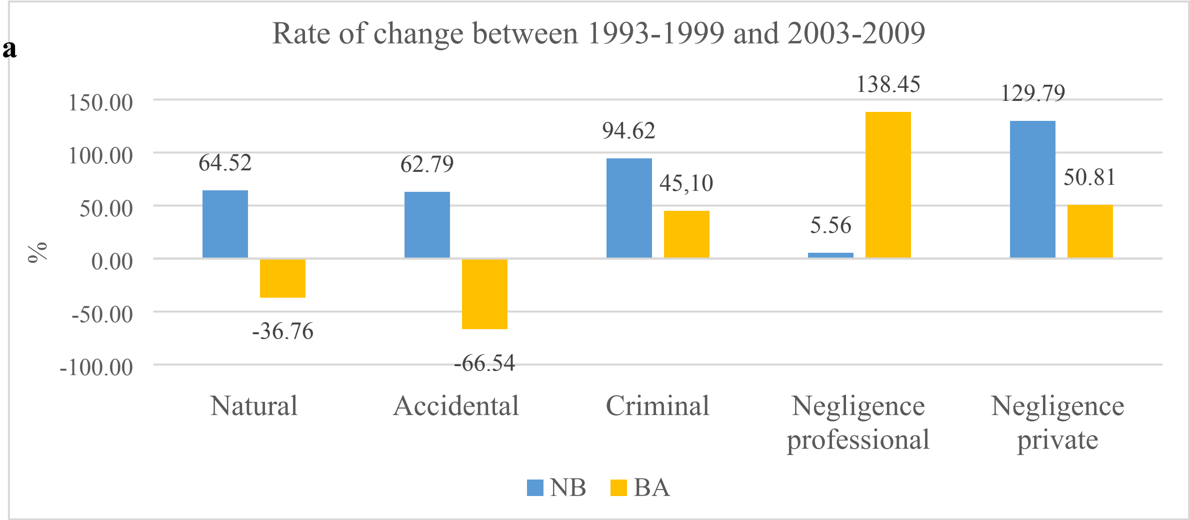

Fire occurrence
%
60
50
40
30
20
10
0
Natural
Accidental
Criminal
Negligence professional
Negligence private
1993-1999
2003-2009
2011-2017
Burned area
%
80
60
40
20
0
Natural
Accidental
Criminal
Negligence professional
Negligence private
1993-1999
2003-2009
2011-2017

Fig. 5

a


Rate of change between 1993-1999 and 2003-2009
150.00
100.00
50.00
0.00
-50.00
-100.00
%
64.52
-36.76
62.79
-66.54
94.62
45,10
5.56
138.45
129.79
50.81
Natural
Accidental
Criminal
Negligence professional
Negligence private
NB
BA

b

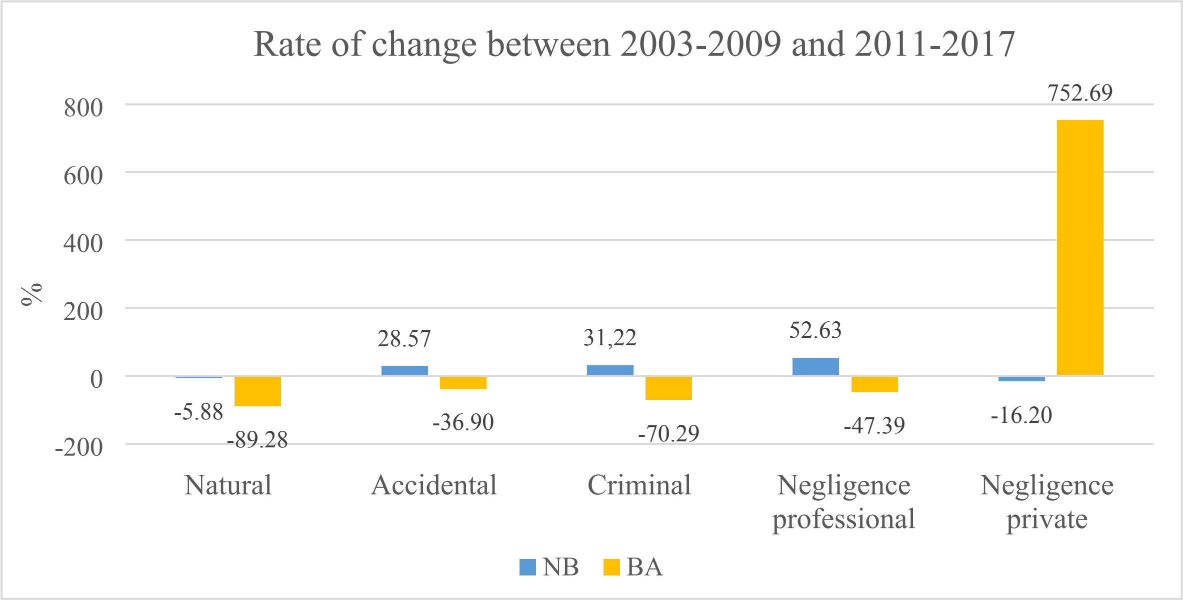

Rate of change between 2003-2009 and 2011-2017
800
600
400
200
0
-200
%
-5.88
-89.28
28.57
-36.90
31,22
-70.29
52.63
-47.39
-16.20
752.69
Natural
Accidental
Criminal
Negligence professional
Negligence private
NB
BA

Fig. 6

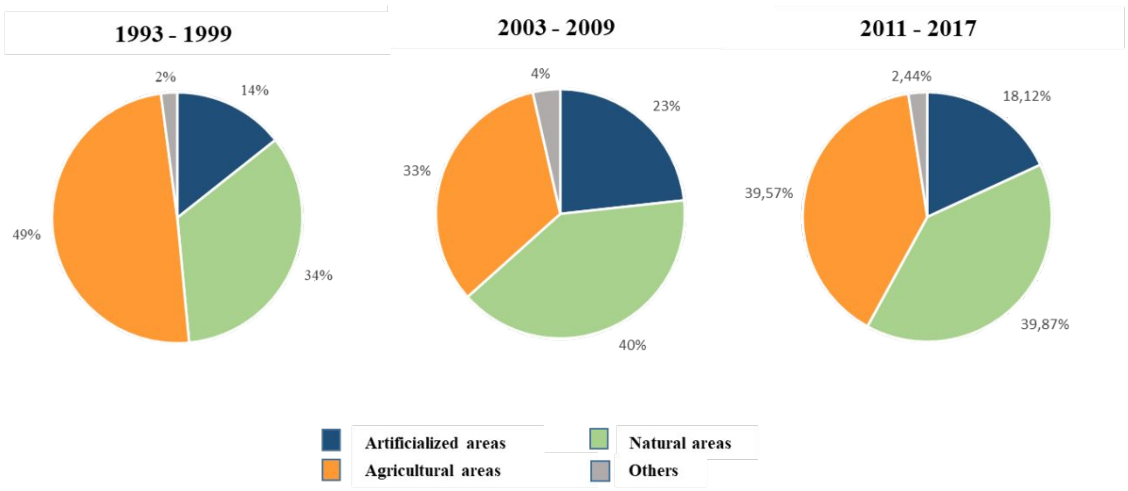

1993 - 1999
2%
14%
49%
34%
2003 - 2009
4%
23%
33%
40%
2011 - 2017
2,44%
18,12%
39,57%
39,87%
Artificialized areas
Natural areas
Agricultural areas
Others

Fig. 7

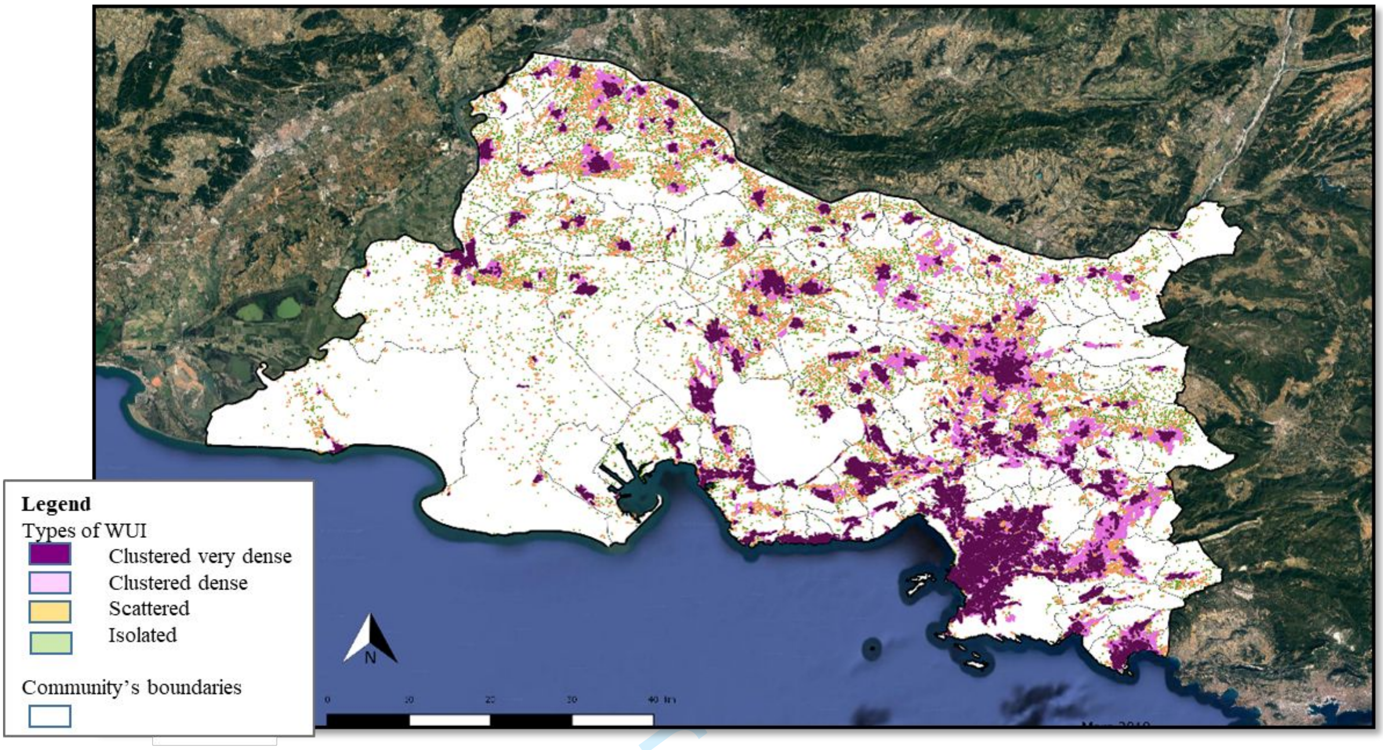

Legend
Types of WUI
Clustered very dense
Clustered dense
Scattered
Isolated
Community's boundaries
N
0
10
20
30
40 km

Fig. 8

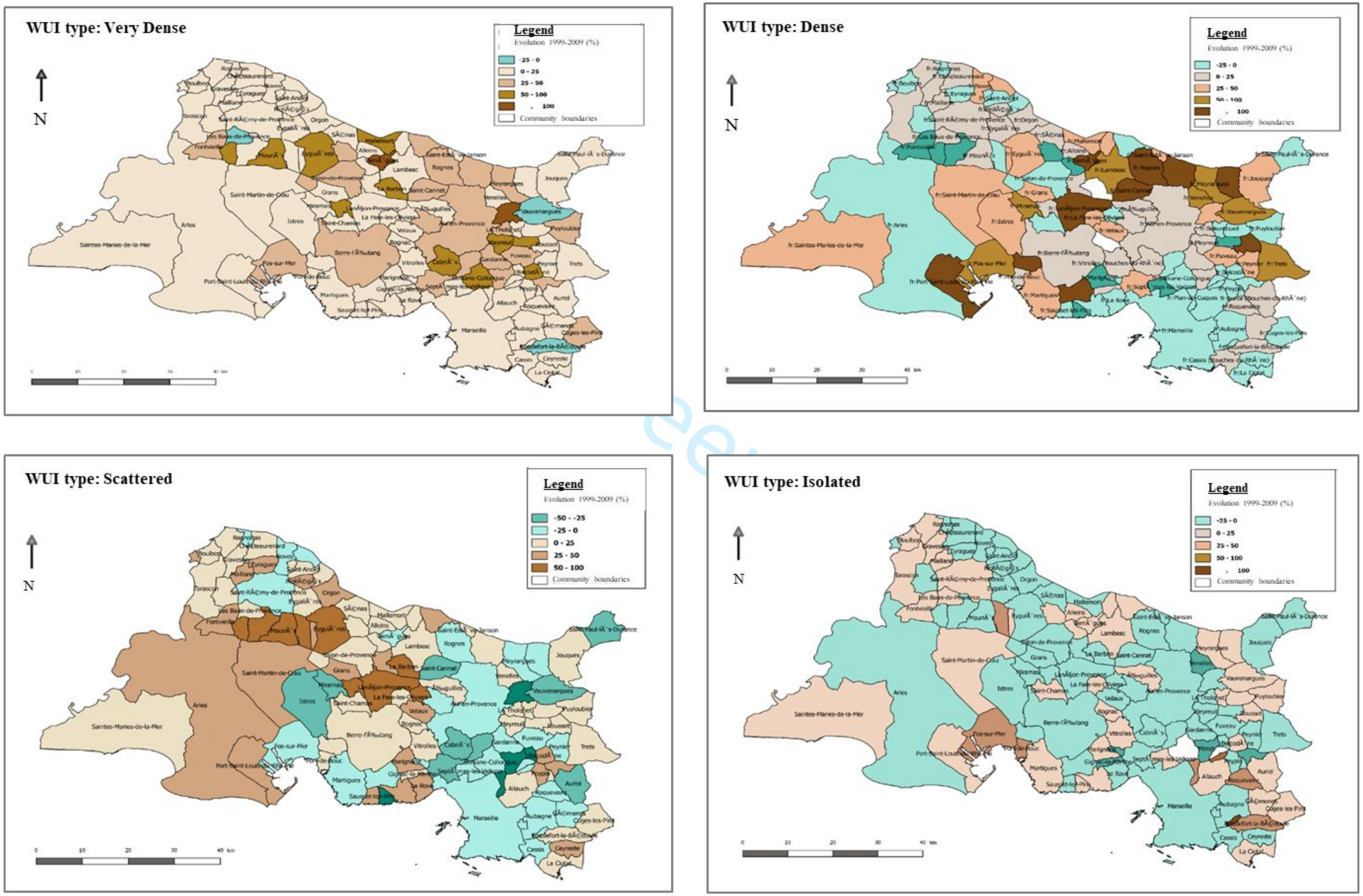

WUI type: Very Dense
WUI type: Dense
WUI type: Scattered
WUI type: Isolated
Legend
Evolution 1999-2009 (%)
-50 - -25
-25 - 0
0 - 25
25 - 50
50 - 100
> 100
Community boundaries
N
0 10 20 30 40 km

Fig. 9

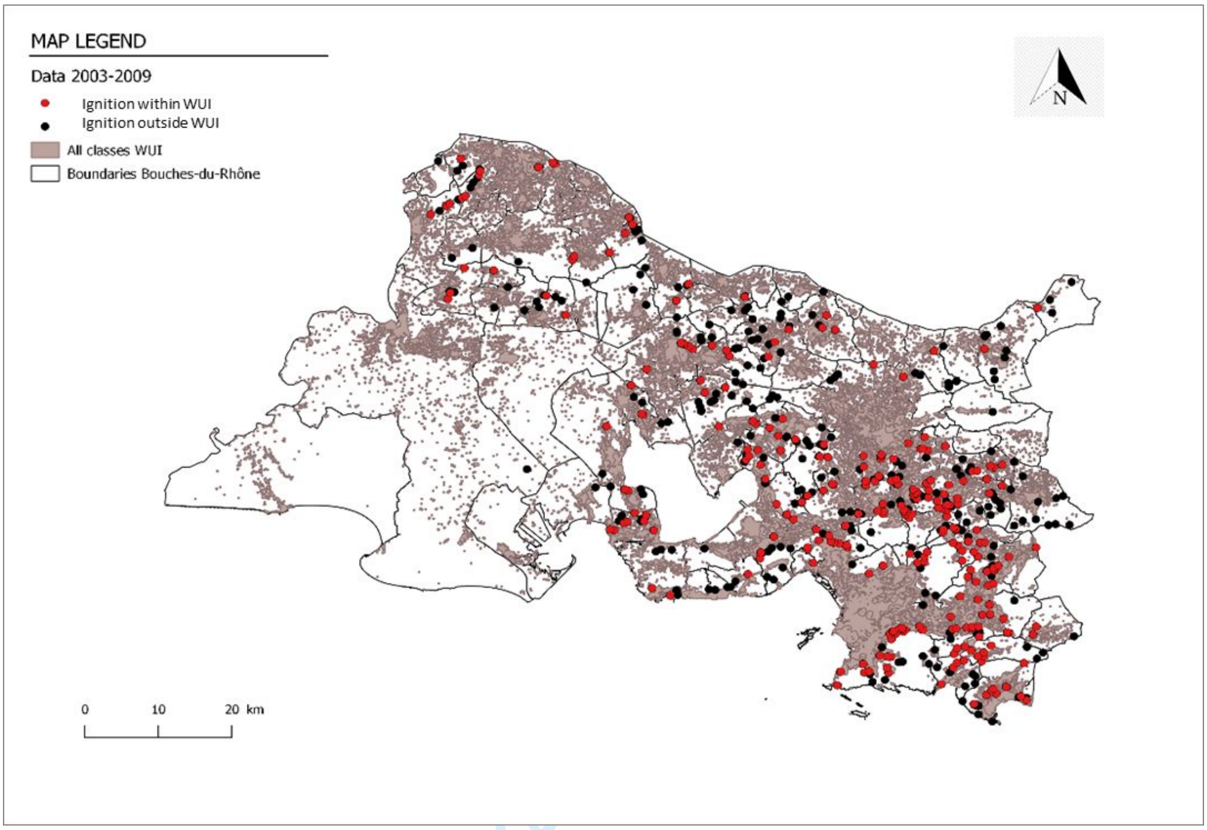

MAP LEGEND
Data 2003-2009
● Ignition within WUI
● Ignition outside WUI
▨ All classes WUI
☐ Boundaries Bouches-du-Rhône
N
0
10
20 km

Fig. 10