Contrasting large fire activity in the French Mediterranean

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Abstract

In the French Mediterranean, large fires have significant socio-economic and environmental impacts. We used a long-term geo-referenced fire time series (1958-2017) to analyse both spatial and temporal distributions of large fires (LF; ≥100 ha). The region was impacted in some locations up to 6 times by recurrent LF and 21% of the total area burned by LF occurred on a surface that previously burned in the past, with potential impact on forest resilience. We found contrasting patterns between the East and the West of the study area, the former experiencing fewer LF but of a larger extent compared to the latter, with an average time of occurrence between LF exceeding 4,000 ha <7 years mostly in the eastern coastal area and >50 years in the West. This longitudinal gradient in LF return level contrasts with what we would expect from mean fire weather conditions strongly decreasing eastwards during the fire season but is consistent with larger fuel cover in the East, highlighting the strong role of fuel continuity in fire spread. Additionally, our analysis confirms the sharp decrease in both LF frequency and burned area in the early 1990s, due to the efficiency of fire suppression and prevention reinforced at that time, thereby weakening the functional climate-fire relationship across the region.

1 Introduction

It is now unanimously agreed that large fires have most significant socio-economic and environmental impacts, threatening or damaging infrastructures, ecosystems, and even costing human life, especially in the expanding wildland-urban interfaces (WUI) (Blanchi et al., 2014; Syphard and Keeley 2015; Radeloff et al., 2018). However, the definitions of what can be considered as a large fire are numerous (Shvidenko and Nilsson, 2000; Stocks et al., 2002; Barbero et al., 2014a, Stavros et al., 2014; Nagy et al., 2018; Tedim et al., 2018), the cutoff being arbitrary or statistically assessed. Usually, large fires represent only a small proportion of the total number of fires but they typically account for the bulk of burned area in many regions throughout the world (Stocks et al., 2002; San Miguel-Ayanz et al., 2013; Stavros et al., 2014, Barbero et al., 2014a, 2014b, Ganteaume and Guerra, 2018) and determine in fact the trend and interannual variability in the total burned area.

Large fires and fire severity have increased over the past several decades across parts of the globe (Pausas and Fernández-Muñoz, 2012; Dennison et al., 2014; Stephens et al., 2014), these changes being attributed to a combination of climate change (Westerling et al., 2006; Bradstock et al., 2009; Flannigan et al., 2009; Barbero et al., 2015; Abatzoglou and Williams, 2016) and past fire suppression (McKenzie et al., 2004; Littell et al., 2009; Miller et al., 2009). However, these upward trends are not universal and some landscapes, mostly in southern Europe, have not experienced such increases in large fires and even showed a decline since the 1990s (San Miguel-Ayanz et al., 2013; Ruffault and Mouillot, 2015; Ganteaume and Guerra, 2018), albeit conflicting signals were found across parts of Portugal and Spain (Turco et al., 2016). This overall fire reduction has been attributed to an increased effort in fire management after the large fires in the 1980s (Turco et al., 2016; Fréjaville and Curt, 2017).

In Mediterranean systems, bottom-up drivers are generally thought to play a strong role in fire activity. Indeed, ignitions are mainly due to human activities (negligence or arson) as seen in California (Syphard and Keeley, 2015; Kolden and Abatzoglou, 2018) or in southeastern France (Ganteaume and Jappiot, 2013) where very few fires are started by lightning strikes (Ganteaume et al., 2013). Likewise, fuel structure and composition control fire spread and, therefore, the location of the largest fires (Duane et al., 2015; Fernandes et al., 2016). The fuel structure is also subject to human activities (Moreira et al., 2011), with agricultural land abandonment or systematic fire suppression leading to the build-up of large amount of fuels (Pausas and Fernández-Muñoz, 2012). Additionally, top-down drivers including fire weather conditions, can help define areas where large fires are most likely to occur (Moritz et al., 2012; Ruffault et al., 2016) but also provide windows of opportunity for fire spread. Large fires in Mediterranean climate ecosystems are often enabled by episodes of severe fire weather of varying duration that can be generated by dry and hot winds as seen in California (Abatzoglou et al., 2013; Kolden and Abatzoglou, 2018) or by cold but dry wind as seen in southeastern France (Ruffault et al., 2016). Collectively, climatic factors alongside ignition sources, fuels, but also suppression forces are thought to influence fire spread. It is noteworthy that changes in fire suppression policy over the last few decades mentioned above have induced sharp decreases in fires, partially modifying the functional relationships linking fire to climate (Fréjaville and Curt, 2017; Syphard et al., 2017), and thus, decreasing fire activity independently of the climate forcing (Hawbaker et al., 2013; Syphard et al., 2007).

We focused here on the French Mediterranean, the most fire-prone region of France, where the largest fire on record reached 11,580 ha despite a highly fragmented landscape. This is also a highly populated area characterized by an extensive WUI and high network density which are highly impacted by fire ignitions especially in the western part (Ganteaume and Long-Fournel 2015) with the potential for several consecutive reburns. The region includes plant communities well adapted to Mediterranean climate conditions that confer on this area a high fire risk but an increase in fire recurrence and a shortening of the period between fires were shown to impact vegetation structure, especially with the decrease in mature tree cover (Ganteaume et al. 2009), including the loss of resilience of *Pinus halepensis* stands (Eugenio et al. 2006). It is thus of interest to quantify reburns across the region given their detrimental impacts on ecosystems.

Additionally, little attention has been devoted to understanding the spatial distribution of large fires along a longitudinal transect. From a bottom-up perspective, fire prone areas along the Mediterranean coast have been extensively built up in the western part of the region, thereby reducing the availability of fuel while increasing the probability of human-started fires (Ganteaume et al., 2013). From a top-down perspective, climatological annual precipitation is increasing eastwards, gradually lowering the weather-induced fire danger. How these two factors, namely fuel continuity and fire weather, modulate the occurrence of large fires is still unclear.

Previous works in the French Mediterranean were based on gridded fire data commencing from the mid-1970s (e.g., Ruffault et al., 2016; Fréjaville and Curt, 2017; Ganteaume and Guerra, 2018; Lahaye et al., 2018). Here, we used for the first time longer time-series of georeferenced fires extending back to 1958 and sought to examine both spatial and temporal distributions of large fires (>100 ha) across the French Mediterranean. More specifically, this paper has a three-fold objective. First, we sought to identify the locations associated with large fire recurrence and quantify the spatial extent of the region with reburns. Second, we sought to establish the mean fire extent and the fire return level along a longitudinal transect spanning the French Mediterranean and identify the possible role of climate conditions and fuel continuity in shaping this longitudinal gradient. This exploratory analysis may provide some insights on a fire aspect that was overlooked in previous studies. Finally, building on previous research, we sought to re-estimate trends in large fires across the region taking advantage of a fire record spanning almost six decades.

2 Material and Methods

2.1 Study Area

The study area (total surface area of 11 157 km^2) is one of the most fire-prone region of SE France in terms of fire frequency (i.e. number of fires) and burned area (Ganteaume and Jappiot, 2013; Ganteaume and Guerra, 2018). The western part is characterized by an extensive WUI where the ignitions are the most frequent (47% of the total ignitions occurred in the WUI) (Ganteaume and Long-Fournel, 2015). Most large fires occur in summer but their cause is often unknown and when it is known, these large fires are mainly due to arson (Ganteaume and Guerra, 2018).

The two parts of the study area (Fig. 1), located on a West-East gradient of the Mediterranean, share most climate characteristics albeit the amount of annual precipitation increases eastwards (Ruffault et al., 2017). These areas also differ in the structure of landscapes; forested massifs are larger in the eastern zone while the proportion of WUI and the urbanization are higher in the western area (respectively, 15% vs 7%, Ganteaume unpublished data, and 394 vs 174 inhabitants km^{-2}, https://www.geoportail.gouv.fr), as well as in the main flammable fuel types, due to the nature of the bedrock (acidic soils being mainly located in the East as opposed to limestone-derived soils in the West). All these differences are hypothesized to affect fire spread and ultimately, the distribution of large fires.

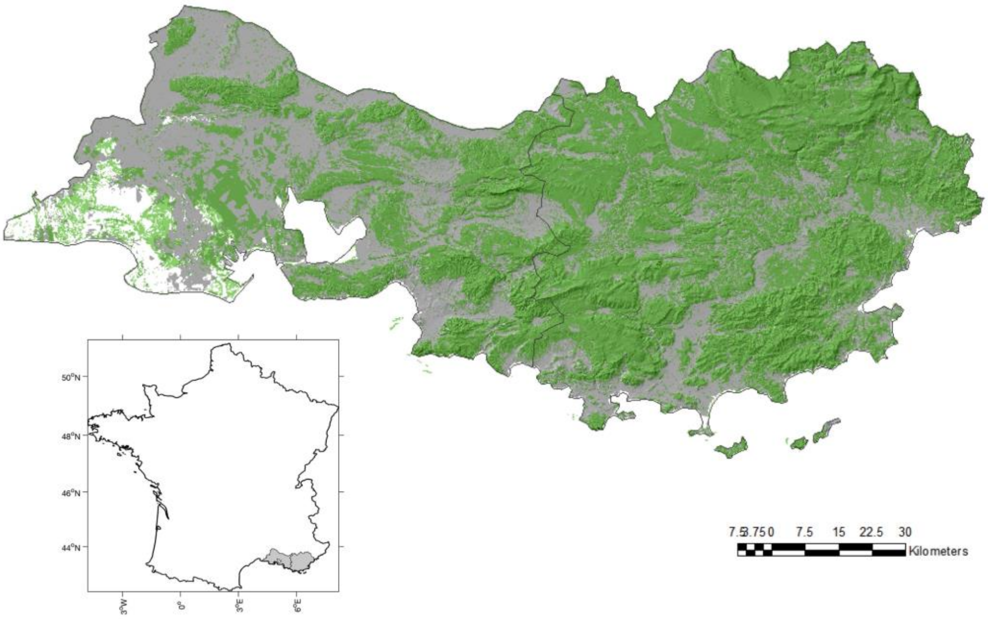

Figure 1: Map of the study area. Forested systems in green were extracted from the “BD Forêt 2014” of the National Geograhic Institute (https://www.geoportail.gouv.fr).

2.2 Fire Data

Large fires in the French Mediterranean have already been studied in previous works using shorter time series based on the gridded regional fire database Prométhée that recorded fires since 1973 (Fréjaville and Curt, 2015; Ruffault and Mouillot, 2017; Ruffault et al., 2018). However, this gridded data provides neither the fire perimeter needed to assess reburns nor the temporal length needed to assess return periods in large fires. Here, we used the georeferenced fire perimeter database compiled by the Office National des Forêts (ONF) and Directions Départementales des Territoires et de la Mer (DDTM Bouches du Rhône and Var) available from 1961 to 2017 in the western part and from 1958 to 2016 in the eastern part of the study area. Fire perimeters were derived from aerial photography and remote sensing (the latter since 2016) and confirmed by ground truth targeting mostly fires larger than 10 ha in the earliest period. Approximate perimeters of older fire events (i.e., before 1990) have been corrected using aerial photos and Landsat satellite images when available (i.e. a more accurate delineation of fire perimeters adjustment were performed) (Faivre, 2011).

We focused on large fires ≥ 100 ha (hereafter LF), representing only 28% of the total number of fires ≥1 ha (N=1277) but accounting for 94% of the total burned area. This detection threshold is within the range of thresholds used in previous works in the French Mediterranean ranging from 30 ha (Ruffault and Mouillot, 2017) to 250 ha (Ruffault et al., 2017).

2.3 Climate and Land Cover Data

We computed the daily Fire Weather Index (FWI) from the Canadian Forest Fire Weather Index system using daily surface meteorological variables at a 8-km spatial resolution from the quality-controlled SAFRAN dataset providing maximum temperature, minimum relative humidity, precipitation and wind speed over France from 1959-2017 (Vidal et al., 2009, 2010, 2012). The FWI computation usually requires noon observations. However, given that SAFRAN is a daily meteorological database, we calculated FWI using maximum temperature and minimum relative humidity as surrogates of noon observations following prior analyses (e.g., Jolly et al. 2015; Abatzoglou et al., 2018). Although the FWI was empirically calibrated for estimating whether atmospheric conditions and fuel moisture content are prone to wildfire development in Canada (VanWagner, 1987), the FWI has already proven useful to track large fire in Mediterranean regions (Dimitrakopoulos et al., 2011) including the French Mediterranean (Barbero et al., 2019). Grid cells of the FWI lying within the study area were first averaged across the June-September season and then averaged across all latitudes spanning the region of interest to form a longitudinal cross-section of mean summer FWI conditions.

We extracted fuel cover data from the “BD Forêt 2014” of the National Geographic Institute (https://www.geoportail.gouv.fr) and regridded the data onto 8-km spatial grid. The percentage of land area covered by forest types was computed across all latitudes spanning the region of interest to form a longitudinal cross-section as described above.

2.4 Spatial Analyses

Based on a sequence of 58 layers of annual large fire scars covering the 1958–2017 period, the following fire attributes were extracted: (i) fire frequency or the number of fires that occurred on a same location over the period studied and (ii) time since the last fire.

2.5 Temporal Analyses

Monotonic trends in LF frequency and in burned area due to LF were assessed using the non-parametric Mann-Kendall test (Kendall, 1975) and a change point detection test (Standard Normal Homogeneity Test (SNHT); Alexandersson and Moberg, 1997) was used to identify potential abrupt changes in the time series.

We estimated annual maximum burned area (AMBA) return levels in the eastern and western part of the study area using the so-called block (here 1-year) maxima approach. We extracted the AMBA in both areas and selected the type of distribution that best fitted both series using the Akaike Information Criteria (AIC). In both areas, the gamma distribution was found to best describe the AMBA series. Using this distribution, the inverse cumulative distribution was calculated allowing the determination of the theoretical quantiles from which we derived the return levels (AMBA) associated to different return periods ranging from 5 to 100 years. Asymmetric confidence intervals were calculated using a resampling approach. This approach consists in creating new sub-samples from the original sample (75% of the original sample are extracted at random) using a bootstrapping process with replacement and then estimating a return level for each of the resampled data (N=1000). The resulting empirical distribution can then be used to derive the 95% confidence intervals from the resulting collection of estimates.

3 Results

3.1 Spatial distribution of large fires and reburned areas

In total, 353 LF were recorded in the region between 1958 and 2017 (194 in the western part and 159 in the eastern part) with, however, a higher burned area in the East nearly doubling the area burned in the West (respectively, 199,404 and 112,043 ha representing 3379.7 and 2000.8 ha burned per year; Tab. 1). LF were responsible for most of the total burned area in the East (97%) as well as in the West (87%), which supports the relevance of the fire-size threshold selected (100 ha).

Regarding the LF age distribution (Fig. 2), the most frequent LF belonged to the 31-40 year-class resulting in the most LF-prone decade. In the East, recent LF were mainly located on the coast while the age distribution was more homogeneous in the western part. Notice that most LF growths were in the main wind direction blowing from Northwest. A total surface area of 312,447 ha was burned during the period studied of which 21% occurred on a surface that already burned in the past (Fig. 3), due to multiple overlaps in burned areas by recurrent fires (i.e. LF occurrence on the same surface). LF reburns occurred up to 6 times in the East but represented only a small part of the recurrence (0.3%; Tab. 2). One to two reburns were the most frequent patterns in the western part of the study area (39.4 and 39.9% of the recurrence, respectively; Tab. 2) while in the East, most reburns occurred only once (46.3%). The surface impacted by only one LF represented 74.5% and 71.2% of the total area burned by LF in the West and the East, respectively (Tab. 2).

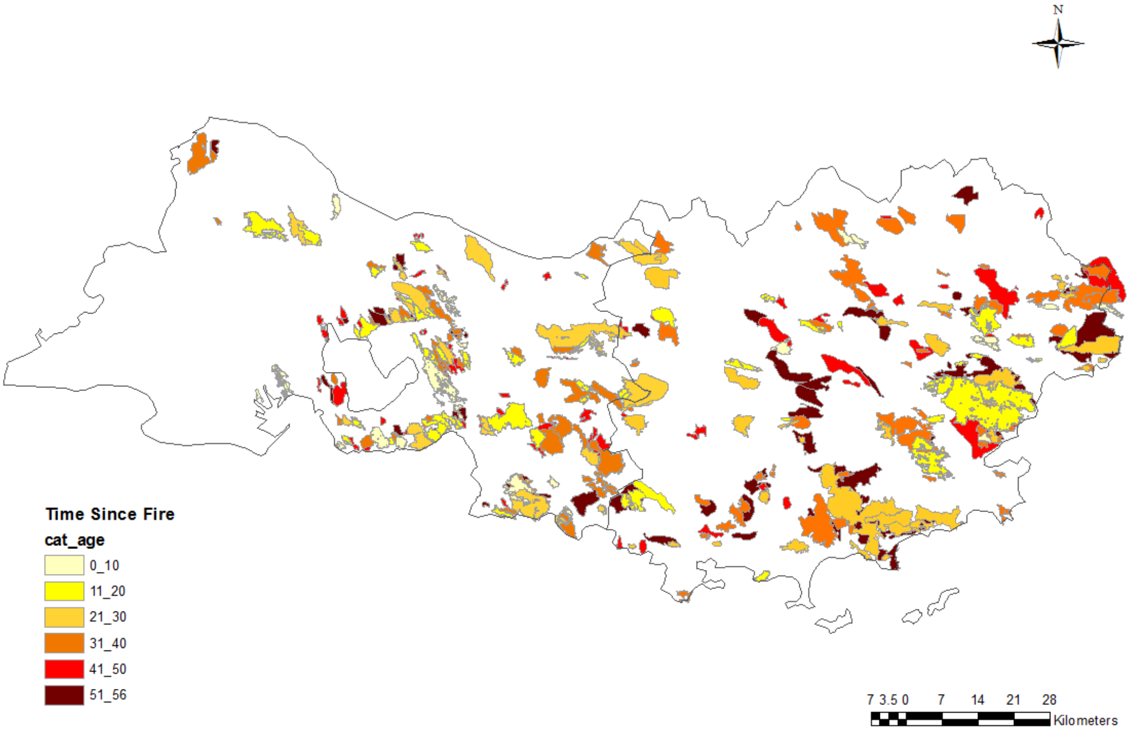

Figure 2: Time since the last LF (cat_age in years).

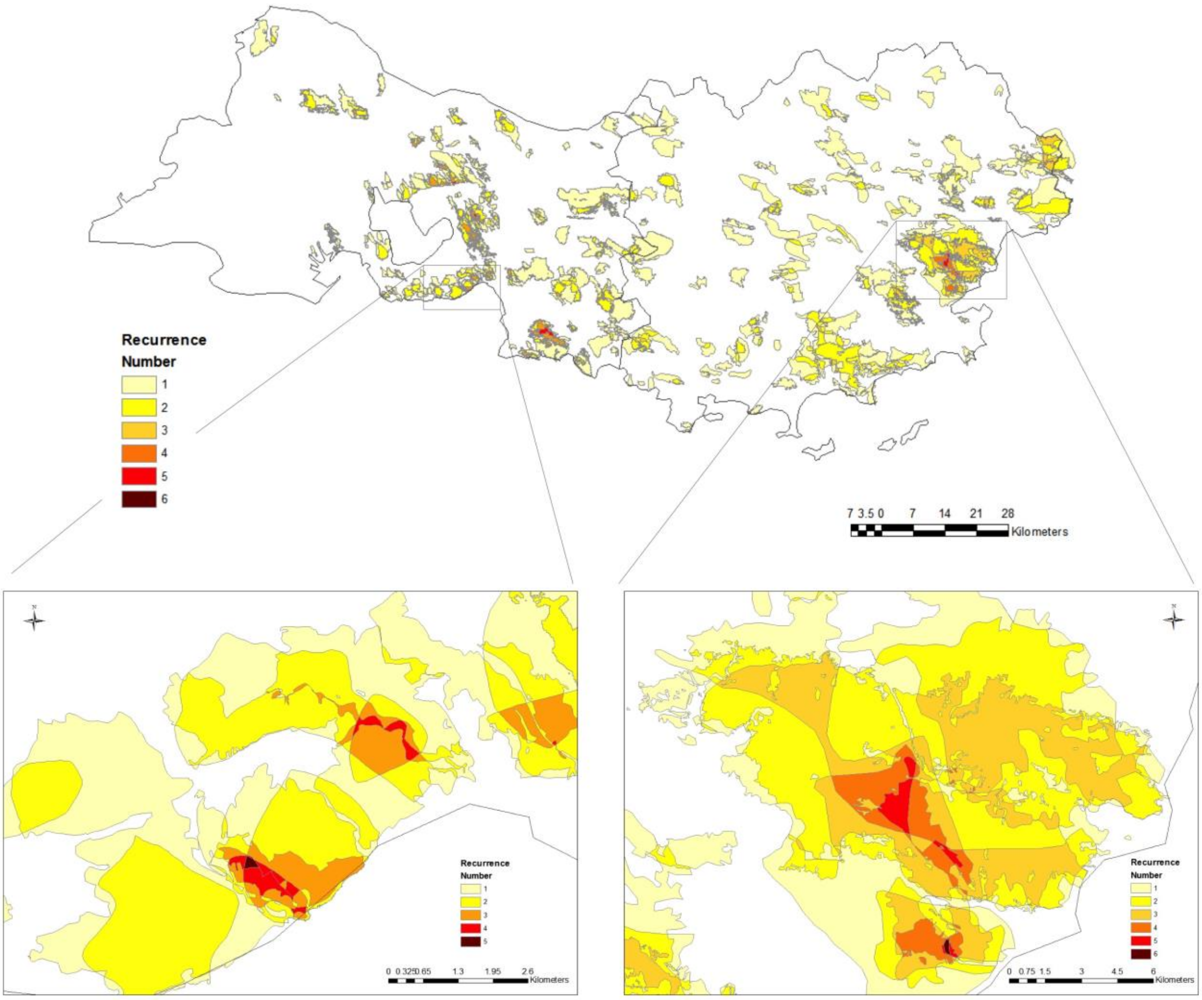

Figure 3: Fire recurrence on the 1961-2017 and 1958-2016 period in the western and eastern part, respectively.

3.2 Longitudinal contrast in large fire extent

The mean LF extent varied along a longitudinal gradient, increasing from the West to the East (Fig. 4 top). This signal contrasts with the mean summer FWI gradient decreasing towards the East but is consistent with the sharp increase in biomass towards the East (Fig. 4 bottom). This suggests that LF spread is not limited by climate conditions across the region but strongly fuel-limited in the West, due to landscape fragmentation and the high proportion of WUI. Indeed, the landscape has undergone substantial transformation with time in the western part contributing to reduce fuel cover and thereby mean LF extent. This highlights the role of fuel continuity on fire spread as shown in previous research (Hargrove et al., 2000; Finney et al., 2007) and the need to include fuel cover in future projections of fire activity based on fire weather indices only.

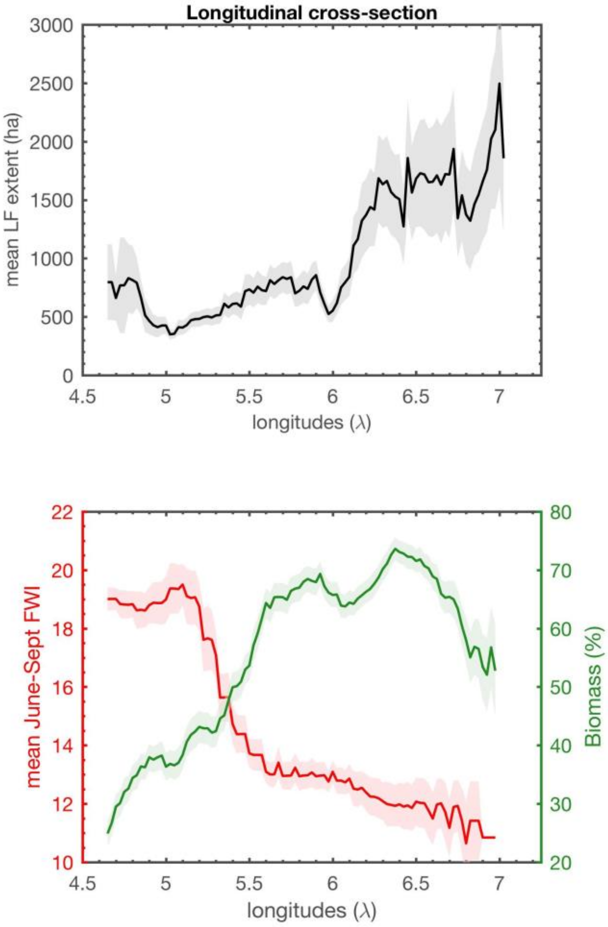

Figure 4: Top) Longitudinal cross-section of mean LF extent computed over 30-km sliding windows. The 95% confidence intervals were estimated using a bootstrapping approach. Bottom) Same as top panel but for mean June-September FWI (in red) and the percent of biomass (in green).

3.3 Long-term trends in large fires

A significant decline in annual LF frequency alongside area burned by LF was found across the region according to a Man-Kendall test (Fig. 5). This overall decline is consistent with a significant change point in both LF metrics in 1991 as shown in previous findings (Fox et al., 2015; Ruffault and Mouillot, 2015). This signal was especially evident in the eastern part (Fig. 5c) while neither a change point nor a significant trend ($p>0.05$) were detected in the western part for both LF metrics (Fig. 5b). We then examined how interannual correlations between mean June-September FWI and LF activity have changed over time across both regions (Fig. 5d). Higher correlations prevailed in the western part throughout the period but the relationships strongly weakened with time in both regions in agreement with previous findings (Ruffault and Mouillot, 2015), passing below significance levels across recent years.

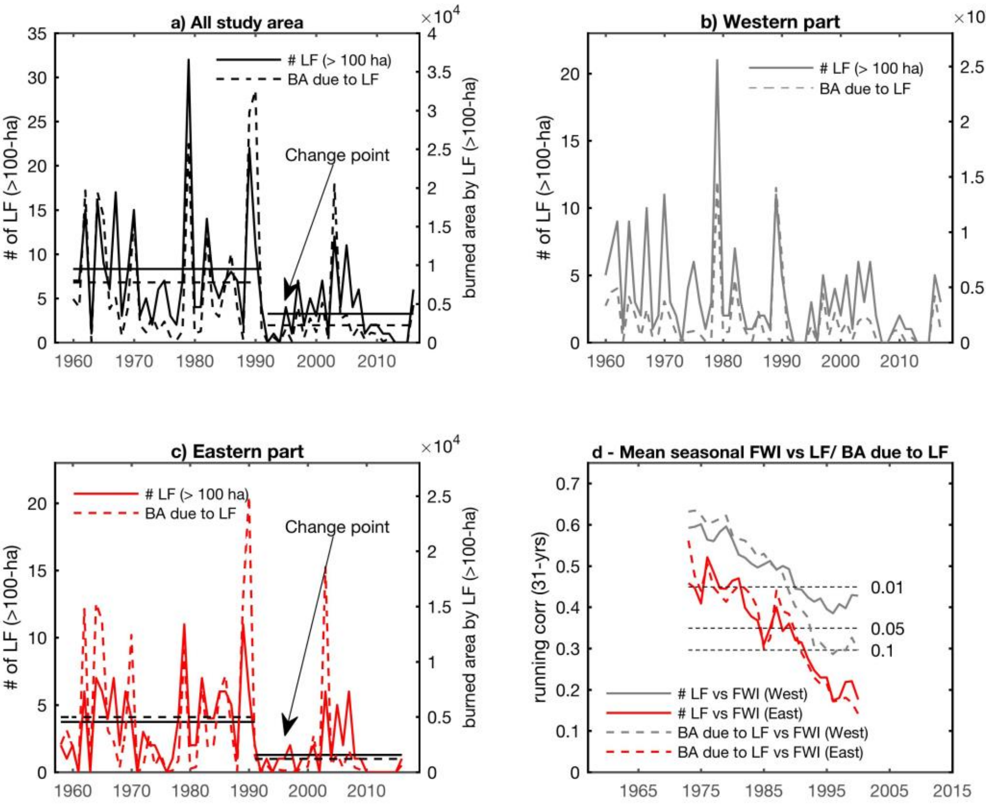

Figure 5: a) Annual number of LF (in black) and area burned by LF (in red) across the region. Significant change points at the 5% confidence level according to a Standard Normal Homogeneity Test (SNHT) in both metrics are indicated. Horizontal solid lines indicate the overall mean observed before and after the change point. b) Same as a) but for the western part. c) Same as a) but for the eastern part. d) Sliding correlations on 31-year windows between mean June-September FWI and annual LF frequency (solid lines) and annual burned area due to LF (dashed lines) in the western

(gray) in eastern part (red). The horizontal dashed lines indicate different significance levels of the Pearson correlations. Correlations are indicated for the middle of the sliding windows.

Figure 6 shows the AMBA in each part of the study area (panel a) as well as the Gamma distribution models that were found as the best fit to the data (panels c,d). Estimates of AMBA return intervals show that a LF >4000 ha occurs on average every 7 years in the eastern part and every 55 years in the western part (Figure 6b), supporting results of Figure 4 indicating an overall increase in LF extent eastwards.

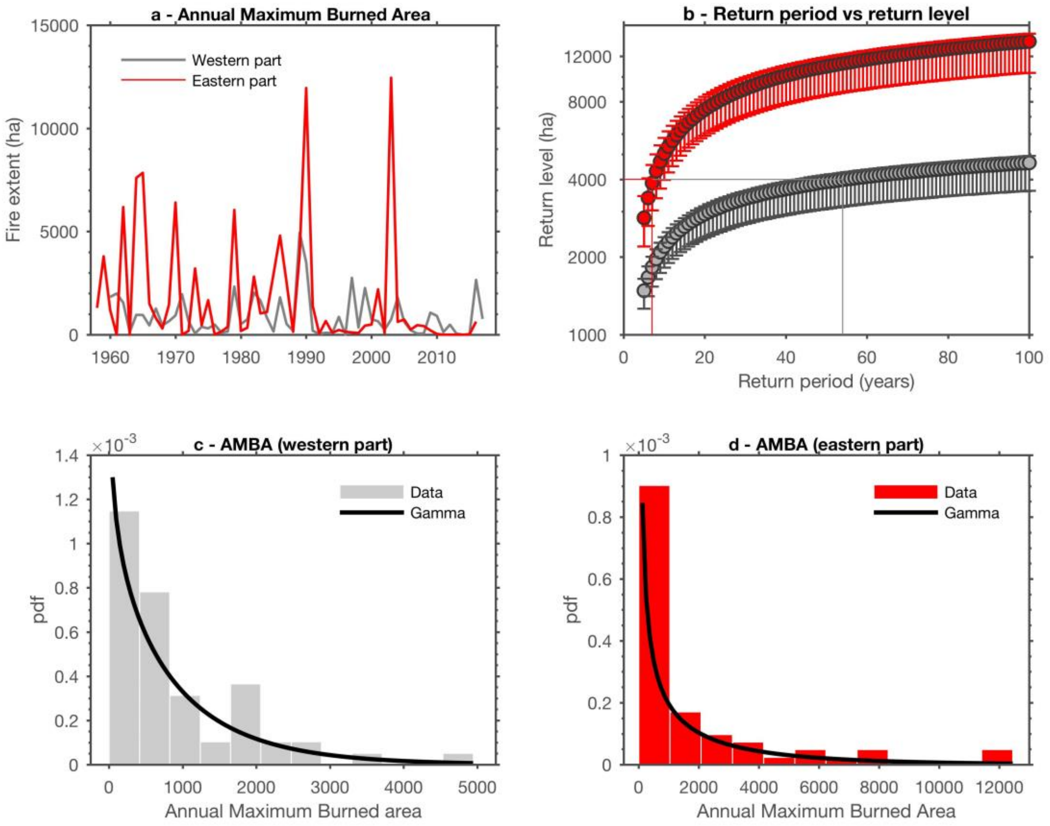

Figure 6: a) Time series of the annual maximum burned area (AMBA) in the western part (in gray) and in the eastern part (in red). b) Return levels in AMBA in the western part (in gray) and in the eastern part (in red) for different return periods ranging from 5 to 100 years. The 95% confidence intervals were estimated using a bootstrapping approach. c) Distribution of AMBA in the western part (bars) with the gamma distribution (black line) that was found to best describe the data. d) Same as c but for the eastern part.

4 Discussion

Improving our understanding of large fire activity is of upmost importance to fire prevention and management to mitigate their impacts. Here, we presented a comprehensive analysis of spatial and temporal patterns of LF in the French Mediterranean. To our knowledge, the fire database compiled and analysed in this framework provides for the first time a detailed description of LF recorded on geo-referenced long time series.

4.1 Spatial distribution of large fires and reburned areas

In total, 21% of the burned area occurred on a surface that already burned in the past due to multiple overlaps in burned areas by recurrent fires (up to 6 times in the East). These areas of higher recurrence could induce a loss of resilience of the forest types such as *Pinus halepensis* stands with an increase in the number of fires and/or a decrease in the time-since-fire (Eugenio et al., 2006). Results showed that there was a strong spatial variation of LF according to the time-since-fire, with clusters of recent LF along the coast (where the recurrence was the highest) and more ancient LF in the central and northern part of the eastern area where the tourist pressure is lower. In contrast, LF were homogeneously distributed in the West, regardless of their age and most reburns corresponded to WUI areas.

We found that the return level was higher in the eastern part of the study area although LF were more frequent in the West. These contrasted regional return levels may provide critical and useful information for risk assessment and local decision-making. Indeed, LF >4000 ha may occur within seven years in the East against 55 years in the West. In other words, LF are less probable in the east where fire ignitions are more limited but when an ignition does occur, the fire is likely to spread over larger areas. This longitudinal gradient is likely due to the variation in landscape fragmentation. Indeed, the western area presents a mosaic of wildlands interspersed with agricultural areas and WUI, LF being thereby concentrated in natural spaces less extended than in the eastern part where large forested massifs mostly located on the coast allowed fire spread. By contrast, LF were more frequent in the West where population density, the proportion of WUI, and infrastructures (railroads and roads) are the highest, as shown in previous works (Keane et al., 2008; La Puma, 2012; Alexandre et al., 2016; Nagy et al., 2018). Fox et al. (2015) showed that, in an area located East of our study area, neither WUI characteristics (despite the 60% increase between 1964 and 2009 in this area) nor fire weather were major drivers of fire frequency and burned area, the climate control becoming less important as the fire regime shifted to more frequent human-started fires (Zumbrunnen et al., 2009).

Some recent studies across Euro-Mediterranean countries emphasized that large fire preferentially occurred under specific synoptic patterns associated with high temperature (Pereira et al., 2005; Trigo et al., 2013; Hernandez et al., 2015). In southern France, large fires were also facilitated by wind events blowing from Northwest (Ruffault and Mouillot, 2015, 2017). The shapes of

LF which were more elongated in the wind direction in the western part support the results of Ruffault et al. (2018) pinpointing that the main wind-driven large fires that had occurred in 2016 were located in the western part while the main heat-driven large fires that occurred in 2003 were located in the East of the area. Taking into account other metrics describing the LF patch complexity (e.g. azimuthal angle or shape index) as in Laurent et al. (2018) could allow deriving additional information on the role of wind on their geometry or on the fraction of LF driven by wind.

4.2 Long-term trends in large fires

The overall reduction in both LF frequency and burned area observed over the last 6 decades is in agreement with previous works that highlighted a decrease in fire activity across parts of southern Europe in response to an increased effort in fire suppression (Turco et al., 2016), taking place in early 1990s in the French Mediterranean (Ruffault and Mouillot, 2015, Fox et al., 2015; Curt and Fréjaville, 2017). Indeed, the region was highly impacted by fires during the 1970-1990 period and developed a thorough fire suppression and prevention system in the beginning of the 1990s, allocating more means for fire management that allowed faster reactivity in case of fire start (the strategy became extinguishing the fires at their initial stage by massive attack to prevent their spread). The decrease in both LF frequency and burned area since 1991, especially evident in the eastern part of the region, is likely due to this change in firefighting policy and fire prevention regulations (fire suppression could be more intense in the East as fires were historically larger in that region).

Climate projections suggest that atmospheric conditions conducive to large fire will increase in the future. Indeed, the warming and drying trends projected in southern Europe are expected to facilitate fire spread (Turco et al., 2018), at least where fuel and ignitions are not limiting. This trend towards more extreme fire weather conditions is likely to overcome prevention efforts in the French Mediterranean (Lahaye et al., 2018), a region where expanding forests (Abadie et al. 2017) are increasing fuel loading and may offer opportunities for future fire spread.

5 Conclusions

This work, based on long-term geo-referenced fire time series (1958-2017) analysed both spatial and temporal variations of LF throughout one of the most impacted areas of the French Mediterranean. On the whole, 21% of the total area burned by LF occurred on a surface that already burned in the past, the region being impacted in some locations up to 6 times by recurrent LF (coastal areas of the eastern part of the study area). LF were less frequent in the eastern part but larger than LF occurring in the West mostly in WUI. This longitudinal gradient in LF extent, featuring a shorter time of occurrence between LF in the East with respect to the West, contrasts with what we would expect from mean fire weather conditions strongly decreasing eastwards but is consistent with larger fuel cover in the East. Indeed, fuel continuity in the East allows fire to grow large and to reach on average 4,000 ha every 7 years, a spatial extent in burned area observed only every 50 years in the West.

An abrupt decline in LF was evident across the eastern part in the early 1990s, mostly due to a change in fire management policy thereby contributing to the weakening of the climate-fire relationship. However, despites large means allocated to fire suppression, large fire outbreak is still possible in the French Mediterranean (such as in 2003 or 2016), as specific weather conditions can overwhelm fire suppression efforts (Fernandes et al., 2016; Lahaye et al., 2018). A better knowledge of LF drivers is necessary to strengthen fire prevention by providing valuable information on priority areas where LF are more likely to occur.

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TABLES

Table 1: Statistics on fires (≥ 1 ha) and LF (≥ 100 ha)

Study area	Total number of fires	Total burned area (ha)	Number of LF:	%	Area burned by LF (ha)	%	Record length (years)
West	975	128 196	194	20	112 043	87	56
East	302	204 535	159	52	199 404	97	58
Total	1277	332 731	353	28	312 447	94	

Table 2: Percentages of burned area (relative to the total burned area) affected by recurrent LF and percentages of recurrence relative to the LF frequency (when number=1, LF is considered as non-recurrent).

	Western part		Eastern part	
Number of LF on same location	Area burned by recurrent LF	Frequency	Area burned by recurrent LF	Frequency
1	74.5%	39.4%	71.2%	46.3%
2	20.3%	39.9%	22.3%	34.7%
3	4.5%	16.6%	5.5%	13.1%
4	0.7%	3.9%	0.8%	4.1%
5	0.005%	0.2%	0.2%	1.5%
6	-	-	0.008%	0.3%