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The largest forest fires in Portugal: the constraints of burned area size on the comprehension of fire severity

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Abstract

Portugal is a European country with highest forest fires density and burned area. Since beginning of official forest fires database in 1980, an increase in number of fires and burned area as well as appearance of large and catastrophic fires have characterized fire activity in Portugal. In 1980s, the largest fires were just a little bit over 10,000 ha. However, in the beginning of 21st century several fires occurred with a burned area over 20,000 ha. Some of these events can be classified as mega-fires due to their ecological and socioeconomic severity. The present study aimed to discuss the characterization of large forest fires trend, in order to understand if the largest fires that occurred in Portugal were exceptional events or evidences of a new trend, and the constraints of fire size to characterize fire effects because, usually, it is assumed that larger the fire higher the damages. Using Portuguese forest fire database and satellite imagery, the present study showed that the largest fires could be seen at the same time as exceptional events and as evidence of a new fire regime. It highlighted the importance of size and patterns of unburned patches within fire perimeter as well as heterogeneity of fire ecological severity, usually not included in fire regime description, which are critical to fire management and research. The findings of this research can be used in forest risk reduction and suppression planning.

Key words

Forest fire, Fire severity, Large fire, Portugal , Risk management

Introduction

Forest fire incidence is high in Portugal, having the highest density of ignitions and burned area in Europe. The number of occurrences lay between 38% (in 2000, 2003 and 2008) to 51% (in 2010) of the total number of fires in Southern European countries (Anonymous, 2013). The European Forest Fire Information System shows that concerning the annual burned area there was a higher variability although Portugal represented more than 50% of the burned area in South Europe in 2003 (57%), 2005 (57%) and 2010 (51%). This pattern has remained unchanged in recent years.

Since beginning of the official forest fires database in 1980, an increase in the number of fires and burned area as well as the appearance of very large and catastrophic fires have characterized fire activity in Portugal. In 1980, the largest fire was just a little bit over 10,000 ha. However, in the beginning of 21st century several fires occurred with a burned area over 20,000 ha. Although fires bigger than 10,000 ha represent a few number of occurrences (0.002% between 1980 and 2012) and are only responsible for 5.4% of the burned area, they are an important challenge, mainly, when they affect wildland urban interface and destroy or put at risk high number of people and structures. Some of these large events which happened in Portugal reached high intensity and severity and can even be called mega-fires (Tedim *et al.*, 2013).

Designation of "large fire" has been used with different meanings. The first one is related with the extension of burned area (Table 1) as an ex-post fire characteristic. Most definitions focus on a quantitative absolute threshold. In Portugal, the official

Table 1 : The meaning of large forest fire as a function of the absolute size of burned area

Authors	Threshold (ha)
Dickson *et al*. (2006)	≥ 20
Preisler *et al*. (2004)	>40.5
Costa *et al*. (2011); San-Miguel and Camia (2009)	>50
Moreno *et al*. (2011)	>100
Ganteaume and Jappiot (2013)	≥100
Alvarado *et al*. (1998); Preisler*et al*. (2011); Shvidenko and Nilsson (2000); Stocks *et al*. (2003)	≥ 200
Westerling *et al*. (2006)	>400
Butry*et al*. (2008)	>405
Bovio and Camia (1997); San-Miguel *et al*. (2013); Romero and Senra (2006)	> 500
Dimitrakopoulos *et al*. (2011); Viegas (1998); Moreno *et al*. (1998)	>1,000
Barros *et al*. (2012)	≥1,000
Odion *et al*. (2004)	>1,500
Knapp (1998)	>2,008
Moritz (1997)	>4,000
Keane *et al*. (2008); Binggeli (2008)	>10,000
Mensing *et al*. (1999)	>20,000
Olsen and Shindler (2010)	> 40,000

definition of large fire is a fire with at least 100 ha of burned area. However, in international literature different values have been considered. Reviewing the related literature the absolute threshold considered by different authors ranges from ≥ 20 ha (Dickson *et al.,* 2006) to ≥40,000 ha (Olsen and Shindler, 2010).

Some authors have classified fire as large, using a relative approach. Thus, Lutz *et al.* (2011) considered large fires as "those above a specified size threshold variable in function of specifics of the ecosystem". On the other hand, Romero and Senra (2006) considered a forest fire as a large fire when the burned area is higher than the average fire size in the region. Considering the great arbitrary in definition of a large fire Gill and Allan (2008) proposed that the boundary for "large" could be "the area of fire greater than or less than that at which half the total area is burnt".

Another approach for the definition of large fires focuses on the characteristics of fire behaviour. McRae and Sharples (2011) classified the fire that moved onto a small number of adjacent landform elements as large, giving a diversity of fire behaviour. Very large fires are burning on numerous landforms; Plume-driven fires – or extreme fires - are largely landform independent as they are coupled fire-atmosphere events. Moreover, Costa *et al*. (2011) considered that large fire behaviour (related with intensity, spread rate and flame length) overcomes the capacity of suppression activities for a reasonably sustained period.

The other classification approach is related with the characteristics of suppression operations and their complexity, *i.e.,* initial attack fires, extended attack fires, large fires and mega-fires (Bartlett *et al.,* 2007; Williams, 2010). This forest fire continuum runs from very small, short duration and non-complex to extraordinary large, long duration and very complex events (Bartlett *et al.,* 2007). In this approach large fires require greater suppression resources, more sophisticated management organization and higher levels of support and leadership. Under extreme fire weather conditions (e.g. droughts, heat waves, strong and variable winds) and substantial accumulation of fuels large wildfires may develop into a mega-fire. Mega-fires exceed all efforts at direct control even in the best prepared regions of the world (Stephens and Ruth, 2005; Bartlett *et al.,* 2007; Ozturk *et al.,* 2010; Williams, 2010).

Considering the characteristics of fire activity in Portugal and the focus of this research in forest fire risk reduction, definition of a large fire based on the size of burned area in absolute terms is the most adequate, although it is recognized that the other classifications are very useful to address large fire problems in different contexts. The present study aims to discuss: the characterization of large fire trend since 1980, in order to understand if the largest fires that occurred in Portugal are exceptional events or evidences of a new trend; and the constraints of fire size to characterize fire effects usually, it is assumed that larger the fire is greater the damages caused.

Materials and Methods

Study area : The paper presents a general overview on large fire (≥ 100 ha) occurrence in Portugal, located in Southern Europe. Although most of the large fires occurred in north and central Portugal, the largest and more disastrous fire events were recorded in the Algarve Region (Southern Portugal) and in the inner central region of the country (Tedim *et al*., 2013). In the Algarve Region, the largest events (≥10,000) appeared in 2003, but new occurrences of same size occurred in 2004 and 2012. These largest fires represented just 0.1% of the occurrences between 2000 and 2012, although they account for 62% of the burned area.

From the Algarve Region, two case-studies were selected in order to analyse the constraints of fire size as a proxy measure of fire severity (Fig.1). The first case-study, called Monchique-Silves, resulted from the combination of three individual and consecutive events, which were responsible for burning 56,331 ha and producing severe damages. The first one, affected the municipalities of Monchique, Portimão, Aljezur and Lagos, between 7th and 17th of August 2003, and burned roughly 22,968 ha. On 12th of same month, a new occurrence started in Silves municipality, burning an area of 11,098 ha and also affecting a part of Monchique's municipality. A month later a new outbreak took place again in Monchique municipality which affected the neighbourhood municipalities of Silves, Odemira and Aljezur. Lasting for nine days and burning around 22,265 ha, this last event also threatened nearby urban settlements and damaged wildland urban interface and created a spatial link between the two previous events.

The second case-study, called Tavira, resulted from a single occurrence, burning 23,301 ha, affecting both Tavira and São Brás de Alportel municipalities, between 18th and 22nd of July 2012. These four occurrences were within the largest ones registered in the Algarve Region as well as in the entire country. Although, it would have been interesting to include in this research the large fire that occurred in 2004 in the Algarve region, it was not possible as high quality satellite imagery was unavailable for this year.

Forest fire database : The research was carried out using official Portuguese database on forest fires, managed by the Institute of Nature Conservation and Forests (ICNF) which has two components: the statistical component, with information since 1980,organized by fire event (available at http://www.icnf.pt/portal/florestas/dfci/inc/estatisticas); the cartographic component, available since 1990, includes the cartographic annual data of the fire perimeters, in shapefile format. A fire perimeter mapped in this database represents a burned area which can result from a single or multiple events occurring in the same year. The absence of correspondence between the two components of the database restricts the possibilities of analysis.

From the statistical component of data base were selected the fires with at least 100 ha that occurred from 1980 to 2012. The obtained dataset, organized in three fire size classes (100-999 ha; 1,000-9,999 ha; ≥ 10,000 ha), was analysed using different statistic methods. Firstly, it was used a descriptive analysis. Secondly, to identify any increase trend in the number of large fires in Portugal, the statistical meaningful trend analysis, a method proposed by Bryhn and Dimberg (2011) was performed. Considering the low number of fires larger than 10,000 ha this analysis along with the application of non- parametric methods were performed only for two fire size classes (≥ 100 ha and ≥ 1,000 ha). Values of $R^2 \geq 0.65$ and $p \leq 0.05$ were considered as statistically significant. Finally, non-parametric methods were used as follows. The data set was divided in three periods (1980-1989; 1990-1999; and 2000-2012) and analysed using Kruskal-Wallis test separately for the two above mentioned fire size classes. The two hypotheses identified were: H_0- The occurrence of fires of each fire size classes in the three periods are similar; H_1- There is at least a period that presents differences from the others. The Mann-Whitney test was also applied for the two fire size classes comparing the three periods two by two. The asymptotic significance (2-tailed) *p*-value considered for both tests was 0.05.

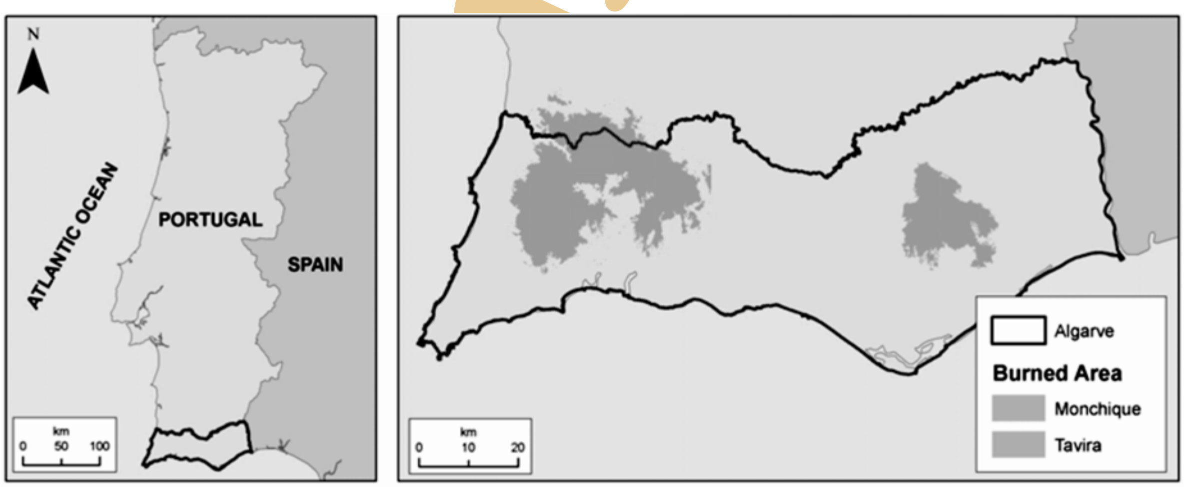

Fig. 1 : Location of the case-studies: Monchique-Silves is located in the western part of the Algave region and Tavira in the eastern part

The maps of fire perimeter available on the forest fire database were the starting point for the analysis of the constraints of fire size as a proxy measure of fire severity. However, for the evaluation of the burning mosaic within the fire perimeter the use of satellite imagery was fundamental.

Satellite imagery processing: For Monchique-Silves and Tavira case-studies Landsat 5 TM (4th July 2003, 24th October 2003 and 26th July 2011) and Landsat 7 ETM+ (21st August 2012, 6th September 2012, and 21st October 2012) were used. The images were selected according to the two major criteria: (i) reduction of the seasonal phenological differences of vegetation as well as shadowing effects through the selection of close acquisition dates; (ii) no clouds present over the study area, opting for a 0% cloud cover when possible. The images were converted to Top of the Athmosphere (TOA) reflectances and topographically corrected using a pixel based Minnaert method (Lu *et al.*, 2008).

Gaps in the Tavira imagery resulting from Landsat 7 SLC (Scan Line Corrector) degradation were corrected using a multi-temporal approach. Two additional post fire images were used: 6th of September and the 21st of October. The iteratively re-weighted MAD (multivariate alteration detection) transformation method (Canty and Nielsen, 2008) was applied in the radiometric normalization of the additional imagery using the 21st of August as a reference. Considering seasonal changes in illumination and vegetation responses the images were stacked according to their chronological order. An average correlation of R^2=0.99 and R^2=0.96 was achieved for September and October, respectively. The September image filled 93% of the gaps. The image from October was used to fill the remaining gaps.

In order to compensate for reflectance changes over time and space, MADroutine was applied in both test cases. The post-fire images were normalized using the pre-fire images as reference data achieving average correlations of R^2=0.99 and R^2=0.97 for Monchique-Silves and Tavira, respectively.

Burned area mapping: Remote sensing is used in many countries to map fire perimeter. In Portugal, the fire perimeters mapping is usually performed by field teams with the support of Global Positioning System (GPS) technologies. Despite its potential for the identification and distinction of burned areas and its role in the validation and calibration of remote sensing products it also presents large limitations. In burned areas of large extent and complex perimeters, like the ones selected for this study, the difficulties in the access make it hard to distinguish between burned and unburned areas as well as the drawing of existing unburned patches. Taking into consideration the complexity and size of the study area an interactive mapping methodology was applied. Focusing on a change detection analysis between pre and post-fire conditions; traditional methods of analysis like the difference Normalized Difference Vegetation Index (NDVI) and the difference Normalized Burnt Ratio (dNBR) are powerful and efficient methods for burned area mapping and fire severity estimation. However, as stated by Escuin *et al.* (2008), land cover as well as vegetation phenological characteristics of the observed landscape impose themselves as important conditioning factors limiting the potential for precise burned area delimitation. According to Escuin *et al.* (2008) post-fire indices do not provide good results when forced to discriminate between burned and water covered surfaces as well as surfaces marked by the presence of bare soil and rocks. Considering the identified limitations of both indices additional spectral information was introduced in order to exclude potential miss–classifications. In both Monchique-Silves and Tavira, NDVI ((B3 - B4) / (B3 + B4)) was used as support information to exclude non-vegetated and water covered areas. In both study areas, a NDVI threshold of 0.2 was applied over the pre-fire imagery. dNBR, estimated as difference between pre and post-fire NBR

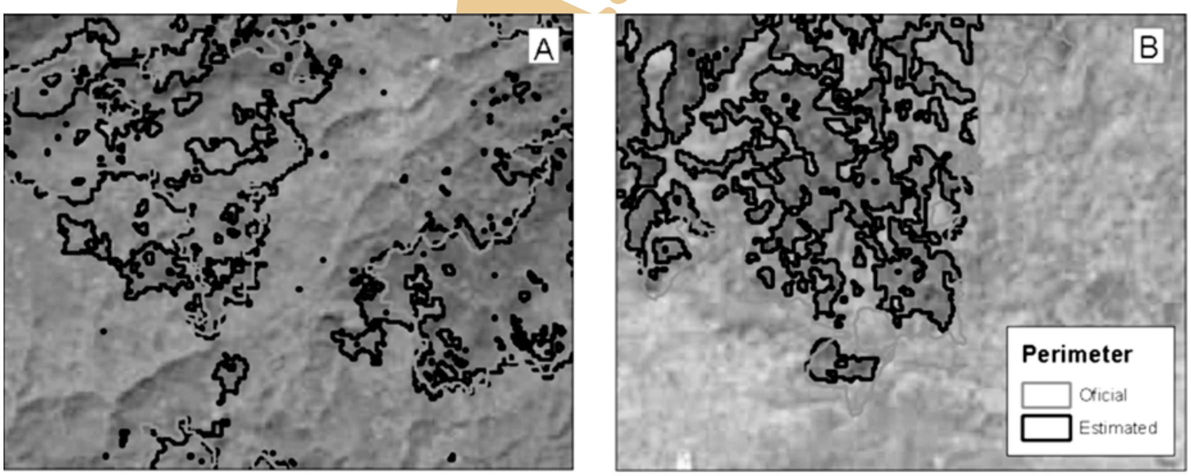

Fig. 2 : Comparison of theofficial and estimated fire perimeters: examples from Monchique-Silves (A) and Tavira (B)

((B4 - B7) / (B4 + B7)), was used to distinguish between burned and unburned areas. Official land cover information provided by the ICNF was used to mask agriculture land uses.

For validation purposes, both delineated burned areas were compared with official cartography in order to assess the presence of potential over estimation of their geographical boundaries. Considering the fire perimeter, an increase of 8 and 10% was revealed while a decrease of 17 and 20% in the burned area was found for Monchique-Silves and Tavira, respectively. Analysing the acquired results, it should be reminded that for both test cases, delimitation of official burned area and perimeters was done using mainly GPS mapping methodologies. As shown Fig. 2, under these circumstances, the coverage of the affected area as well as a clear distinction between burned and unburned areas largely depend on the mobility constraints imposed by the terrain. As a result, reduction of burned area as well as an increasing complexity (and length) of the perimeter were obtained. The estimated burned areas were then used as a basis for further analysis.

Results and Discussion

Since 1980 the number of large fires (≥100 ha) increased in 103% (Table 2). In 1980-89,the annual average number of large fires was 116. In the following decade, there was an increase and from 2000 to 2012 the same average reached 180 events. Despite these evidences, it was not possible to find a statistically meaningful trend for large fire increase (R^2=0.0474 and p=0.2315). The results of the Kruskal-Wallis and Mann-Whitney tests did not reject H_0 (Table 3). So there was no significant difference between the three periods. However, if p-value <0.1 was considered, a difference between first (1980-89) and third time periods (2000-12) was found.

The fire size class of ≥1,000 ha presented similar results. Although there was an increase in the number of fires (180%) even more significant than in the case of fires ≥100 ha, findings for the possibility of an increasing trend analysis (R^2=0.0424 and p=0.2583) and hypothesis tested (see table 3) did not show significant difference between three time periods.

Concerning the largest fires (≥10,000 ha) in 1980s, only one fire of this size was recorded in the forest fire database, while after 2002 twelve events of this size were registered.

At the same time, the size of the largest fires has been increasing. As mentioned, earlier in 1980s the largest fires were just a little bit over 10,000 ha. However, in 2003 this threshold exceeded and fires larger than 20,000 ha appeared (Fig.3). During this year, nine fires ≥10,000 ha were recorded, and most of them (89%) occurred during a short period time (July 30th and August 20th). This was the worst fire season ever recorded mainly due to extreme meteorological conditions associated with heat wave (Trigo *et al.,* 2006).Three forest fires of ≥10,000 ha were again recorded in 2004 (with approximately 14,500 ha), 2005 (about 11,700 ha) and 2012 (more than 20,000 ha) with less extreme meteorological conditions. For instance, in 2012, the total number of fires registered was 12% inferior to the average of fire events recorded in the previous years despite of severe drought observed during winter and spring of 2012. However, 2012 fire remained the largest fire event ever recorded in the statistical Portuguese forest fire database.

Fire size is usually one of the metrics used to characterize fire activity. However, burned area is also one of the most inconsistently recorded metric of forest fire activity. Furthermore, within fire perimeter there were unburned areas and

Table 2 : Number of fires (No.) and burned area by size (ha) between 1980 and 2012 in Portugal

Years	<100 ha		100-999 ha		1,000-9,999 ha		≥10,000 ha	
	No.	Burned area (ha)	No.	Burned area (ha)	No.	Burned area (ha)	No.	Burned area (ha)
1980-89	71,918	235,745.00	1052	279,656.90	107	209,409.20	1	10,032.00
1990-99	206,978	320,462.13	1392	394,086.26	147	303,812.62	0	0.00
2000-12	309,083	428,651.55	2047	599,944.78	290	707,632.46	12	189,517.72

Source: Data from ICNF, 2012

Table 3 : Results of Kruskal-Wallis and Mann-Whitney tests

	≥100 ha		≥1,000 ha	
Kruskal-Wallis	Chi-square	Asymptotic significance	Chi-square	Asymptotic significance
	3.303	0.192	0.079	0.961
Mann-Whitney	Mann-Whitney U	Asymptotic significance	Mann-Whitney U	Asymptotic significance
1st/2nd period	34.000	0.247	47.500	0.850
1st/3nd period	33.500	0.080	56.000	0.792
2nd/3rd period	51.000	0.553	57.500	0.869

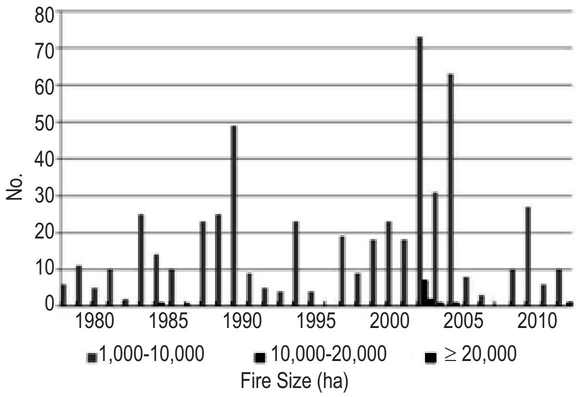

Fig. 3 : Evolution of the occurrence of fires larger than 1,000 ha between 1980 and 2012

heterogeneous burn patterns (Kolden *et al.,* 2012). Inside the Monchique-Silves and Tavira case-studies, about 7,191 ha and 3,188 ha of unburned area were found which represented, 13% and 14% of each fire perimeter. These unburned areas within the fire perimeter were distributed among 1,171 and 435 patches, respectively, for Monchique-Silves and Tavira events (Table 4). Although the former presented almost the triple of unburned patches than the latter, density of unburned patches per 100 ha (calculated as the division of the number of unburned patches by the burned area) was very similar (2.1 for Monchique-Silves and 1.9 for Tavira).

The frequency analysis of patches size did not show relevant difference between the two case-study since most of them (at least 80%) had less than 5 ha. In both cases the minimum size was 0.81 ha. However, existence of unburned areas larger than 5 ha was relevant in both cases. The unburned patches with more than 100 ha explained 28% and 37% of the total unburned area within fire perimeters of Monchique-Silves and Tavira, respectively. In Monchique-Silves the largest unburned island had 390.2 ha and in Tavira the largest one reached 1166.9 ha. The patch size average was 6.1 ha in Monchique-Silves and 7.3 ha in Tavira. Standard deviation regarding patch size was higher in case of Tavira (56.29) than in Monchique-Silves (21.14). The main difference regarding patch size in two case-studies was that in Tavira only one patch larger than 100 ha was found and in Monchique-Silves eleven were identified.

Variety and large dimension of unburned islands are very important for the comprehension of fire behaviour and impacts of vegetation recovery. The formation of unburned islands can be ascribed to landscape condition (e.g. heterogeneity of fuel type), fire behaviour, weather-related circumstances or chance (Gill *et al.,* 2003). The suppression activities focus in protecting settlements can also explain some of the unburned patches.

The burned area of Monchique-Silves was mostly forest (55%) and the type of vegetation affected was, mainly, eucalyptus (*Eucalyptus*), arbutus (*Arbutus unedo*) and cork oak (*Quercus suber*) (Table 5). In contrast, in Tavira most of burned area was composed of shrubs (63%). The most affected forest species were cork oak (*Quercus suber*), arbutus (*Arbutus unedo*), and stone pine (*Pinus pinea*). The burned area with eucalyptus (*Eucalyptus*) was insignificant. Characterization of unburned patches and burned area were similar in both cases. The main difference was high percentage of agricultural land (about 20%) in the unburned patches. Overall the landscape metrics showed that the unburned patches in Monchique-Silves were more irregular and complex than the ones of Tavira (Table 6).

Globally, the Monchique-Silves event presented higher fire severity than the Tavira event (Fig. 4) because most of the burned area (63%) were classified into two categories with highest severity (medium high severity category, dNBR=0.44 - 0.65; high severity category, dNBR=≥ 0.66) and the maximum values of dNBR was higher. Conversely, in Tavira just 34% of the pixels fitted in the same categories whereas most of the burned area (54%) was classified as medium low severity (dNBR=.0.27 - 0.43).

Table 4 : Number and dimension (ha) of unburned patches

Patches dimension (ha)	Number of patches				Patches size (ha)				Average size (ha)	
	Monchique-Silves		Tavira		Monchique-Silves		Tavira		Monchique-Silves	Tavira
	No.	%	No.	%	Area	%	Area	%		
<1	238	20.3	71	16.3	211	2.9	64	2.0	0.9	0.9
1 – 4.9	718	61.3	279	64.1	1,505	20.9	637	20.0	2.1	2.3
5 – 9.9	100	8.5	40	9.2	713	9.9	262	8.2	7.1	6.5
10 – 19.9	53	4.5	23	5.3	739	10.3	312	9.8	13.9	13.6
20 – 49.9	39	3.3	17	3.9	1,165	16.2	492	15.4	29.9	29.0
50 – 99.0	12	1.0	4	0.9	818	11.4	253	7.9	68.2	63.3
≥ 100	11	0.9	1	0.2	2,041	28.4	1,167	36.6	185.5	1,166.9
TOTAL	1,171	100	435	100	7,191	100	3,188	100	6.1	7.3

Concerning fire severity by land use, the average as well as the maximum values of dNBR for each of the different land use categories were always higher in Monchique-Silves than in Tavira (Table 7). There was no significant difference in fire severity for forest areas since the average dNBR for the two case studies was similar (0,464 for Tavira and 0,495 for Monchique-Silves) although, the maximum values were pointed out for higher severity in Monchique-Silves. For all the forest species, maximum values of dNBR were higher in Monchique-Silves than in Tavira fire. In agricultural areas, Monchique-Silves also presented higher severity than Tavira although in both cases the dNBR average values obtained could be considered of medium low severity. The largest difference (29%) between Monchique-Silves and Tavira fire severity were found in the areas of shrubs. The dNBR of the former was in medium high severity category while the latter presented medium low severity values.

The great variability on the concept of large fires, related to their absolute size (from 20 ha to 40,000 ha) is not a limitation for its study not even for international comparative research. Considering different landscape characteristics and different dimensions of the countries, it is neither possible nor adequate to establish a threshold that would be accepted around the world. However, within a country or a region, for management purposes, it is adequate to establish a boundary to classify fires as large.

Table 5 : Land use in burned and unburned patches

Land use	Monchique-Silves		Tavira	
	Unburned patches	Burned area	Unburned patches	Burned area
Agriculture	19%	6%	21%	11%
Forest	45%	55%	20%	24%
Shrubs	33%	37%	57%	63%
Other uses	3%	2%	2%	2%

Table 6 : Unburned patches landscape metrics

Landscape metrics	Monchique -Silves	Tavira
Area Weighted Mean Shape Index	3.638	2.565
Mean Shape Index	1.988	1.776
Mean Perimeter-Area Ratio	461.7	398.4
Mean Patch Fractal Dimension	1.379	1.355
Area Weighted Mean Patch Fractal Dimension	1.392	1.37
Total Edge	$2x10^6$	$6x10^5$
Edge Density	266.4	286.6
Mean Patch Edge	1637	1335
Median Patch Size	1.711	2.071
Patch Size Coefficient of Variance	344.3	180.3
Patch Size Standard Deviation (PSSD)	21.16	8.397
Landscape Area	7197	2022
Class Area	7197	2022

Changes in forest fire regime justified changes over time in this boundary. In 1970s, a fire with 10 ha of burned area was already a large fire in Portugal (Ferreira-Leite *et al.,* 2012). Nowadays, threshold is 100 ha. Considering the increase in fire size, a higher limit could be suggested to define a large fire. However, a threshold of 100 ha is considered adequate to Portuguese context, as it represents fires which are difficult to be suppressed and a reality that should be avoided. Nevertheless, between 100 ha and the largest fire recorded in the country, there was not only a big difference in the size of burned area but also differences in terms of fire behaviour and complexity of suppression. Large fires are not "simply small fires, only bigger, but something fundamentally different" (Butry *et al.,* 2008), being so dynamic processes present in fires of 100 ha and 20,000 ha are also different. This statement leads us to propose changes in the classification of large fires. So, it is suggested that events between 100 ha and 1,000 ha be considered as large fires; events between 1,000 and 10,000 ha be considered as very large fires; and events with at least 10,000 ha be considered as extreme fires (meaning fires with very low frequency but a burned area size that surpasses most of forest fires ever recorded).This classification is based on burned area not considering either fire behaviour or severity for the definition of these thresholds. We valued only the frequency of fire size in the country and the lessons learned from past events. So, even if there is an increase in the size of fires belonging to last category mentioned above, in future, the proposed classification still remains valid.

At European scale, the use of a common threshold for comparative analysis could be useful. Which threshold? In European context different thresholds has been proposed even lower than 100 ha (see Table 1). The proposals were as follows: 100 ha (Ganteaume and Jappiot, 2013), 500 ha (San-Miguel *et al,* 2013; Romero and Senra, 2006) or even 1,000 ha (Barros *et al.,* 2012; Dimitrakopoulos *et al.,* 2011; Viegas, 1998; Moreno *et al.,* 1998). Considering several criteria (i.e., the fire size frequency distribution in European countries; inexistence of an official definition of large fire occurred in Greece; 500 ha adopted in Italy by the Corpo Forestale dello Stato; and Spain by the official statistics)100 ha is proposed as the minimum value to consider a large fire at the European level. Consideration of two other classes of very large and extreme fire could better accommodate fire size reality across the Europe.

The frequency analysis showed that large fires (≥100 ha) occurred more frequently in Portugal. Adding to this, there was an evidence of an increase in the fire size. In 1980s, the average size of large fires was 430 ha. In the following decade this value raised to 454 ha, while in the beginning of 21^{st} century this average reached about 635 ha. This increase was observed despite improvement of suppression activities and enhancement of a "muscled" initial attack, showing the importance of paying closer attention to fire prevention, namely, through landscape planning and fuel management, in order to decrease the likelihood of a fire

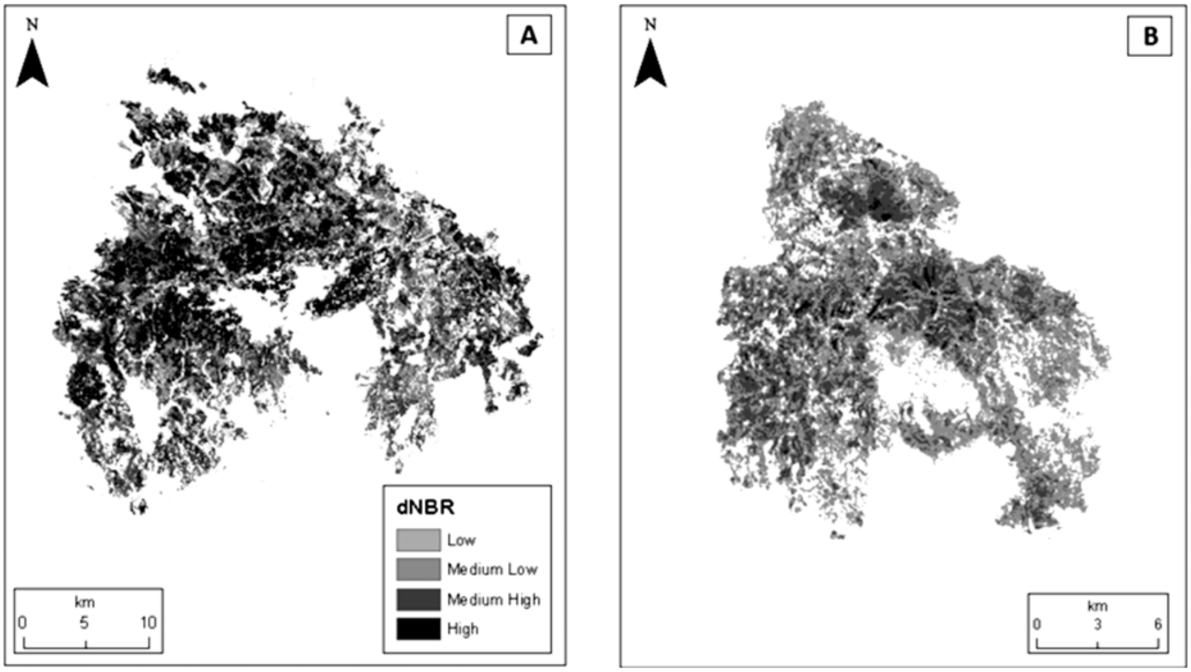

Fig. 4 : Fire severity in Monchique-Silves (A) and Tavira (B) using dNBR

to become large. In spite of these evidences, no significant trend of increase in large fires was found. Also the non-parametric tests confirmed that there were no significant differences between the three time periods. These results are in agreement with the findings of Bermudez *et al.* (2009) who did not find an increasing trend in large fire occurrence in Portugal, but found a cyclical pattern with a return period of 3-5 years.

The largest fire events ever recorded in Portugal, with a burned area larger than 20,000 ha, appeared in 2003, during a season with very extreme meteorological conditions. However, that threshold exceeded again in less than 10 years (2012) within a fire season where less extreme meteorological conditions were observed.

The largest forest fires in Portugal can be seen as exceptional events because they present low frequency but at the same time there are evidences of a new fire regime which, in turn, demands a better knowledge of fire burning patterns to develop more cost-effective prevention measures as well as to improve fire recovery.

The published fire perimeter maps from Portuguese forest fire database are a useful tool for forest fire risk management, however it is important to recognise their limitations and identify ways to improve them. In fact, the accuracy of fire perimeter delimitation can decrease with the increase of terrain complexity (Kolden and Weisberg, 2007) as demonstrated in this research. Another limitation is related with the assumption that there is homogeneity in fuel burning within the fire perimeter ignoring the existence of a "mosaic of burning patches" (Gill *et al.,* 2003) and the significance of unburned islands (Kolden *et al.,* 2012). Usually, fire recurrence maps are built based on the assumption that all the area within fire perimeter burned homogeneously, making forest fires risk assessment maps not as accurate as desirable. It is important to enhance fire perimeter accuracy and the knowledge of unburned islands not only for management purposes (e.g. enhance forest fire risk assessment) but also for research (e.g., to better understand fire behaviour, the impact of prevention measures).

This study highlighted that unburned islands can represent a significant portion inside fire perimeter. In the Monchique-Silves and Tavira it represented13% (7,191 ha) and 14% (3,188 ha), respectively, of the total fire perimeter. Moreover, the unburned patches were not randomly distributed. These unburned patches are a consequence of fire behaviour conditioned by several factors (topography, weather and climate conditions, fuel load and characteristics, prevention measures, suppression efforts) as well as by the presence of human structures.

Kolden *et al.* (2012) found patterns of decreasing unburned proportion with increasing fire severity in USA. The values of unburned area within fire perimeter obtained for two Portuguese case studies are similar to the ones proposed by Kolden *et al.* (2012) in their research to classify a situation of moderate-to-high severity fire. Following this logic Monchique-

Table 7 : Fire severity (dNBR) by land use

Land use	**Monchique-Silves**			**Tavira**		
	Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Agriculture	0.200	1.077	0.409	0.031	0.760	0.350
Shrubs	0.200	1.086	0.507	0.088	0.822	0.390
Forest most affected species	0.200	1.102	0.495	0.109	0.860	0.464
Holm oak(*Quercus ilex*)	0.201	0.805	0.390	0.184	0.759	0.446
Cork oak (*Quercussuber*)	0.200	1.072	0.565	0.126	0.822	0.456
Arbutus (*Arbutus unedo*)	0.200	1.102	0.608	0.210	0.860	0.546
Eucalyptus(*Eucalyptus*)	0.200	1.092	0.448	0.245	0.640	0.455
Maritime pine (*Pinuspinaster*)	0.200	1.065	0.555	0.138	0.818	0.464
Stone pine (*Pinuspinea*)	0.200	0.961	0.441	0.109	0.759	0.421
Social	0.200	0.824	0.373	0.227	0.510	0.332

Silves and Tavira belonged to the same fire regime category. The difference in unburned patches density were not very significant although the value presented by Monchique-Silves was slightly lower.

A "better knowledge of the factors and interactions that influence islands formation would improve forest management and would offer clues for designation of less fire-prone landscapes" (Román-Cuesta *et al*., 2009). Furthermore, it is believed that this research findings would be of critical importance for forest fire management (e.g. develop more cost-effective prevention measures and support recovery decisions).

Our research show that severity analysis based only on the average of dNBR was clearly insufficient, being recommended that the minimum and the maximum values of dNBR should be considered, as shown by the following examples. The average dNBR for forest in Tavira and Monchique-Silves were very similar (0.464 and 0.495 respectively), considering the minimum and the maximum values of dNBR allowed some important conclusions. In fact, these values reinforced the differences between the two case-studies pointing out that forest burned with higher intensity in Monchique-Silves than Tavira, since in the former the minimum dNBR was 0.200 and in the later only 0.109. The maximum values of 0.860 and 1.102 for Tavira and Monchique-Silves, respectively, reinforcing the previous conclusion. At the forest species level an interesting example is provided by the dNBR of eucalyptus (*Eucalyptus*). In Tavira, where the eucalyptus burned represented a residual area, the average dNBR was higher than in Monchique-Silves (0.455 and 0.448, respectively), where eucalyptus (*Eucalyptus*) was the most affected tree species. However, in Tavira the dNBR interval (0.245 -0.640) was shorter and did not reach the value of 1.092, as happened in Monchique-Silves.

The differences in fire severity can at least be in part explained by land use differences which can affect fire behaviour. The distribution of land used burned in the two case-studies showed that the forest area was mostly affected in Monchique-Silves while in Tavira, much of the burned area was shrubs. In the case of Monchique-Silves, higher extension of forest in extreme meteorological conditions developed crown fires of high intensity, explaining higher extension of forest area burned. Moreover, for all the forest species the maximum dNBR was found in Monchique-Silves.

In a country like Portugal located in a fire prone area and with a high extension of forest lands seems fundamental to prevent the spread of potentially large wild fires not only through fuel management but also through the adaptation of forest management to the fire regimes of each region, in order to reduce the intensity and severity of expected fires (Costa *et al.,* 2011).

In Portugal, it is not common to evaluate fire ecological and social effects whereby it is usually considered that larger the fire higher the damages. However, burned area is neither well correlated with fire ecological severity (Lutz *et al.,* 2011) nor with social impacts (Gill and Moore, 1998). In the present study it was found that 2012's Tavira fire event was the largest single event, although it presented lower ecological severity. This finding would have been reinforced if we had considered separately the two events from the Monchique-Silves case study with similar size. The 2012's Tavira fire event clearly point out that even though this is the event with larger burned area recorded in Portuguese forest fire database, the fire effects were not as severe as the ones occurred in 2003 in similar or even lower fire size events. This finding shows that the fire size is a measure of fire activity with several constraints and consequently should not be used as a proxy of fire severity.

The present study highlights that the largest fires could be seen at the same time as exceptional events and as evidence of a new fire regime. The fire perimeter as a continuous and homogeneous area as it is considered in the development of forest fire risk mapping in Portugal as well as the concept that larger the fire more severe its effects, are far too simplistic approaches.

It is fundamental to assess the importance of size and patterns of unburned patches within fire perimeters as well as heterogeneity of fire severity, usually not included in fire regime description, which are critical to fire management and research. This approach is fundamental to define a new pattern in forest fire occurrence and to support the design of a new generation of forest fire risk management and suppression activities.

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