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Negligent and intentional fires in Portugal: Spatial distribution characterization

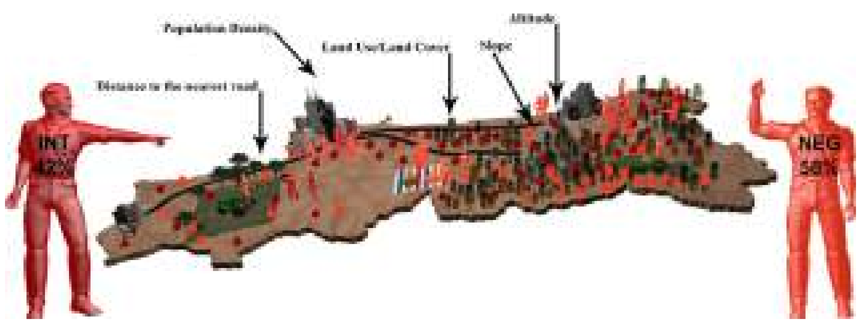
J. Parente [a,*], M.G. Pereira [a], M. Amraoui [a], F. Tedim [b,c]

[a] *Centre for Research and Technology of Agro-Environment and Biological Sciences, CITAB, University of Trás-os-Montes and Alto Douro, Portugal*
[b] *Centre of Studies on Geography and Spatial Planning, CEGOT, Geography Department, Faculty of Arts, University of Porto, Portugal*
[c] *Charles Darwin University, Darwin, Australia*

HIGHLIGHTS

- Average fire size is much higher for intentional than for negligent fires.
- Incidence of negligent and intentional fires has different distribution patterns.
- Higher drivers' influence for intentional fires, burnt area and in the south region
- Human's drivers and altitude are the most important for fire ignitions.
- Negligent (intentional) fires burn more forest and agricultural (human) areas.

GRAPHICAL ABSTRACT



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ABSTRACT

In the European context, Portugal is the country with the highest number of wildfires and the second with more burnt area. The vast majority of these events are of human origin, whether caused by accident, negligence or arson, reason why it is particularly important to know the regime of these wildfires for forest and wildfire management activities. The study focuses on the most recent years of 2001–2014, when wildfire ignition's coordinates are known, and aims to identify and characterize the wildfire incidence spatial patterns of variability as well as their main drivers. After grouping wildfires with human cause into negligent and intentional, we studied their spatial distribution in terms of normalized number of wildfires (NNF) and burnt area (NBA) in the five Nomenclature of Territorial Units for Statistics II regions of mainland Portugal. Results disclose an uneven spatial distribution of the fire incidence, characterized by a south-north gradient, much higher values in *Norte* region and more evident for intentional than for negligent wildfires. Human and biophysical drivers strongly influence NNF and NBA, at regional and national scales. Distribution patterns at regional scale, for negligent and intentional wildfires are quite different from entire mainland and all wildfires. Drivers' influence is higher for intentional than for negligent wildfires, for southern than for northern regions and for NBA than for NNF. The leading drivers of NNF are distance to roads (*d*) population density (*pd*) and altitude (*h*) while of NBA are *h*, *d*, slope and *pd*, and this influence is higher for intentional than for negligent wildfires.

Abbreviations: NF, Number of fires; BA, Burnt area; TNF, Total number of fires; TBA, Total burnt area; CLC, CORINE Land Cover 2006; NUTS, Nomenclature of Territorial Units for Statistics; *AML*, *Área Metropolitana de Lisboa*; *h*, Altitude; DEM, Digital elevation model; *s*, Slope; *pd*, Population density; INE, Portuguese National Statistics Institute; *d*, Distance to the nearest road; PRFD, Portuguese Rural Fire Dataset; ICNF, Portuguese Institute for the Conservation of Nature and Forests; RA, NUTS II region area; RNF, Relative number fires; RBA, Relative burnt area; CA, Class' area of each variable in each NUTS II region; NNF, Normalized number fires; NBA, Normalized burnt area.

* Corresponding author at: Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal.
E-mail addresses: joanaparente@utad.pt (J. Parente), gpereira@utad.pt (M.G. Pereira), malik@utad.pt (M. Amraoui), ftedim@letras.up.pt (F. Tedim).

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1. Introduction

In the last decades, Europe registered a high number of fires (hereafter, NF) and burnt area (hereafter, BA) with different spatial and temporal trends as the result of human-driven fuel transformations and climate change (Fernandes, 2013; Pereira et al., 2013, 2014; San-Miguel-Ayanz et al., 2016; Vilar et al., 2016). The society and the scientific community regard this phenomenon as a natural ecological factor and, at least in some cases, a natural/human disaster (Nunes et al., 2016; Vilar et al., 2016). Despite its smaller land area in comparison with other Mediterranean countries, Portugal is the European country with the highest total NF (hereafter, TNF) and the second largest total BA (hereafter, TBA) (San-Miguel-Ayanz et al., 2016).

The distribution of fire incidence (NF and BA) is one of the characteristics of the fire regime and, in Portugal, presents a high spatial-temporal variability. Weather and climate variability are the main drivers of the temporal distribution. The Mediterranean type of climate of mainland Portugal broadly controls the fire incidence's temporal and spatial variability. This type of climate favours the emergence and growth of vegetation during the wet and humid season as well as water and thermal stress during the dry season, which helps to understand the vast majority of NF and BA occur during the noticeable summer fire season (Amraoui et al., 2015; Pereira et al., 2005; Trigo et al., 2016). The occurrence of extreme weather (e.g., heat waves) and climate variability events (e.g., drought), which also tend to be more frequent and intense during the summer fire season, are main contributors to this sharp seasonal character of the fire incidence in Portugal (Parente et al., 2016; Pereira et al., 2014, 2005; Trigo et al., 2006).

The different subtype of climate in northern and southern Portugal also helps to understand why most of NF and BA is located at north of the Tagus river (Parente et al., 2016; Tonini et al., 2017). However, spatial distribution of fire ignitions and BAs is also highly dependent of other human and biophysical drivers such as demographic, socioeconomic, topographic and land use/land cover factors. In fact, previous studies suggested that a few number of landscape and anthropogenic variables could play an important role on fire risk mapping and the spatial patterns of fire incidence (Botequim et al., 2017; Fernandes et al., 2016; Oliveira et al., 2012; Vasconcelos et al., 2001; Verde and Zêzere, 2010). On this respect, Curt et al. (2016) modelled the spatial patterns of fire regime's features in southern France, using anthropogenic and environmental drivers, and found that socioeconomic factors partially control the fire regime, influencing the timing, spatial distribution and potential size of fires. In Portugal, Catry et al. (2007) studied the distribution of fire ignitions between 2001 and 2005 in relation to topographic and socio-economic variables, and concluded that most of the fire ignitions were intentionally caused and concentrated in the most populated municipalities of the north and centre littoral areas. Nunes et al. (2016) analysed the wildfires' geographical incidence and temporal trends in Portugal at a municipal level, and found that topography, population density, land cover and livestock are significant drivers of both ignition density and BA. Recent studies identified and characterized the role of variables such as altitude, slope and land cover in the fire incidence and to justify the existence, location and size of space-time clusters of fires in Portugal (Parente et al., 2016; Parente and Pereira, 2016; Tonini et al., 2017). Understanding the role of these human and biophysical drivers on the spatial patterns of fire incidence will be of fundamental importance to support forest and fire management as well as the implementation of legislation relating to human activities that may cause fires (Curt et al., 2016; Martínez et al., 2009; Moreira et al., 2010; Nunes et al., 2016).

Irrespective of whether a favourable set of conditions for the occurrence and propagation may be present, a wildfire needs a source of ignition to start, which in turn, is dependent on human activities. In fact, on a global scale, humans cause most of the wildfires, except in the boreal areas of North America and Eurasia, where a significant number of natural wildfires occurs and are responsible for a large part of the TBA (Le Page et al., 2015; Rowe and Scotter, 1973; Stocks et al., 2002; Veraverbeke et al., 2017). In Mediterranean-type ecosystems, wildfires are mostly caused (intentionally or negligently) by human activities which vary spatially and temporally in ways that could affect their size and destructiveness (Curt et al., 2016; Ganteaume et al., 2013; Pereira et al., 2017; Syphard and Keeley, 2015). According to the Portuguese Rural Fire Database (Pereira et al., 2011), currently available for the 1980–2014 period, although the limited confidence in the statistics for the first few years, only 32.8% of the TNF in Portugal have known cause, namely 0.6% caused by lightning, 23.1% by negligence and 76.4% intentionally. Even though most of the fires in Portugal are negligent or intentional, there are still a number of unanswered research questions, namely: The spatial distributions of negligent and intentional wildfires are equal or different? Do negligent and intentional wildfires have the same drivers? Do these factors have the same influence on the two types of wildfire? Are there regional differences in the influence of the drivers on the incidence of negligent and intentional wildfire? Therefore, main objectives of this study, in order to answer the previous questions, are to assess: (i) the spatial distribution of negligent and intentional wildfires; (ii) the influence of human and landscape drivers on the incidence of negligent and intentional wildfires; and, (iii) eventual regional differences in the spatial distribution and role of the drivers. We believe that it is of paramount importance to deepen our knowledge on the regime of negligent and intentional wildfires at regional level since they represent the vast majority of wildfires in the Portugal and are those that cause the greatest impacts and most catastrophic consequences. In addition, negligent wildfires will be those for which campaigns of sensitization and prevention as well as other fire management activities can be more efficient while risk management and monitoring of possible arsonist activities may be more effective.

2. Materials and methods

2.1. Study area

Continental Portugal is geographically located between Spain and the Atlantic Ocean, just at a few hundred kilometres of North Africa with a mainland area of about 90,000 km^2. The altitude is very heterogeneous within the mainland (Fig. 1a), ranging from the sea level in the western and southern coast to about 2 km of the highest point (*Serra da Estrela*) located in the central region (Fig. 1a). Naturally, altitude (value and location) determine the spatial features of slope (Fig. 1b). The Tagus River divide the country into two regions of approximately the same area but with different topography and two sub types of temperate (group C) climate. In accordance with Köppen-Geiger's climate classification (Kottek et al., 2006; Peel et al., 2007; Rubel and Kottek, 2010), the two subtypes of Mediterranean climate in Portugal are: Csb (dry and warm summer) in the north part of the country; and, Csa (dry and hot summer) in the south (Fig. 1c). Consequently, and in accordance with CORINE Land Cover 2006 (hereafter, CLC), these regions present two different predominant vegetation types, namely: Forests (22%) and Scrub and/or herbaceous vegetation associations (30%) in the north region; and, Heterogeneous agricultural areas (27%) and Forests (24%) in the south region.

In 1986, the Portuguese Government adopted the common standard for all member states of the European Commission, designated by the Nomenclature of Territorial Units for Statistics (hereafter, NUTS). The NUTS classification is a single, coherent and hierarchical system for dividing the territory of the European Union for the purpose of collecting, development and standardising a set of common regional statistical rules and procedures (CM, 1986). The NUTS regions were created by the Eurostat group in 1970, and consists of 3 levels of territorial units aggregation whose specific settings in each Member State depends on

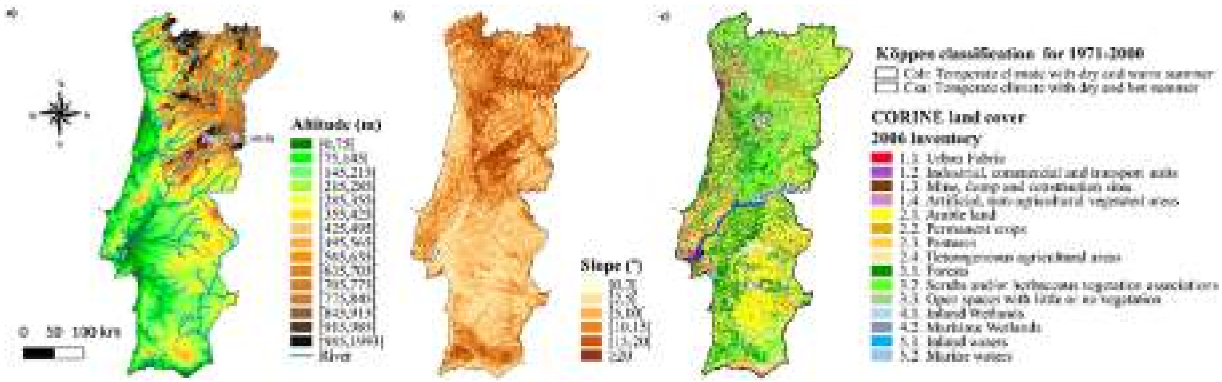

Fig. 1. Mainland Portugal (a) altitude according to the digital elevation model with 25 m resolution provided by Goncalves and Morgado (2008) and including rivers (APA, 2017) and the location of *Serra da Estrela*; (b) spatial distribution of slope; (c) Köppen-Geiger's climate classification (Peel et al., 2007) and CORINE Land Cover 2006 (Caetano et al., 2009) with the location of Tagus River.

national characteristics and regional development policies (Eurostat, 2017; Santos, 2014). In this study, the NUTS level II was adopted which divides Continental Portugal in 5 basic regions (Fig. 2a), namely, *Norte* and *Centro*, in northern Portugal; *Alentejo* and *Algarve* in southern Portugal; and, *Área Metropolitana de Lisboa* (hereafter, *AML*) the smallest but highly urbanized western central region. Statistics of human and biophysical variables presented in the following subsections were computed for the regions mentioned above.

We select the NUTS II regions as the spatial basis of analysis for the following reasons. These regions are: (i) defined according to population, administrative and geographical criteria (EPC, 2003); (ii) extensively used by national governments, Eurostat and other European Union's bodies for statistical purposes and policy matters (EPC, 2003); namely, (iii) as instruments for European Union's Structural Fund delivery mechanisms (EPC, 2003). The selection of NUTS II instead of NUTS III or LAU's (Local administrative units) with much smaller size, increase the spatial resolution of the outcomes, results from the compromise between the number of small regions included in the analysis and the large amount of the obtained results.

2.2. Human and biophysical drivers

Human and biophysical drivers used and tested in this study are the ones suggested by recent studies performed for Portugal, namely: altitude, slope, population density, distance to roads and land use/land cover (Catry et al., 2010; Fernandes et al., 2016; Parente and Pereira, 2016; Vasconcelos et al., 2001; Verde and Zêzere, 2010). The following subsections are devoted to provide a brief description of the cartography and the pre-processing steps performed to obtain the maps of these explanatory variables using QGIS 2.8.1 desktop (Team, 2014).

2.2.1. Altitude

Altitude (hereafter, *h*) map was produced using the most recent high resolution (25 m) digital elevation model (hereafter, DEM) available for Portugal (Goncalves and Morgado, 2008). The northeast of Portugal comprises the regions with highest altitude, especially in the eastern parts of *Centro* and *Norte* while the lowest elevations are located in the southern part of the country (Fig. 1a). The DEM resolution determines the spatial grid size of the slope and distance to road geodatabases.

2.2.2. Slope

To derive the spatial pattern of slope (hereafter, *s*) the authors used the DEM previously mentioned and terrain analysis tool available in QGIS 2.8.1 for raster layers. The *s* classes adopted in Fig. 1b were recently used in Parente and Pereira (2016) and Verde and Zêzere (2010). The *s* map shows a very heterogeneous spatial pattern from north to south but with the classes of highest values located in the inland areas of central and north region.

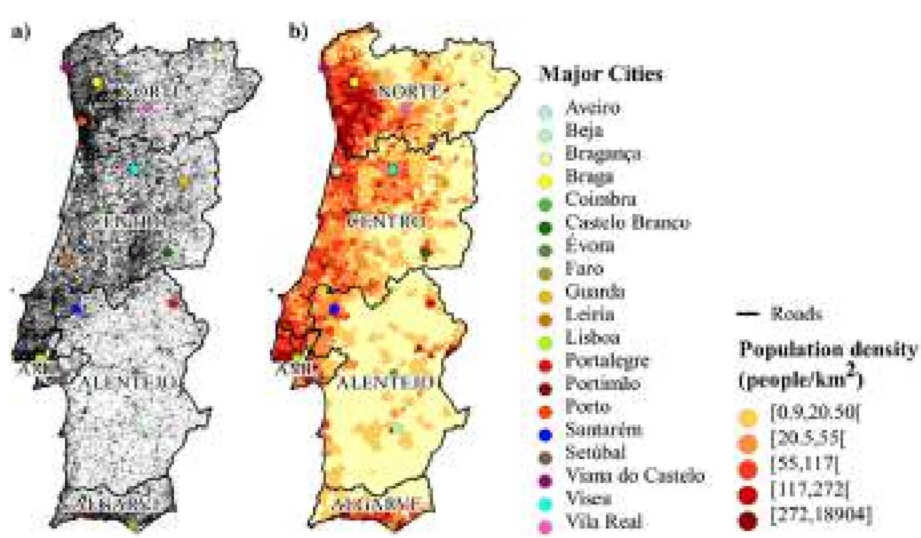

Fig. 2. Mainland Portugal (a) road map (Haklay and Weber, 2008); and, (b) parish population density in 2011 provided by INE (2012). Major cities and NUTS II regions of Portugal are also shown.

2.2.3. Population density

The population density (hereafter, *pd*) map was obtained from the Portuguese National Statistics Institute (INE) and respects the most recent available database produced from the 2011 Census (INE, 2012), which includes the number of people in each parish. This information was updated by assigning the number of people to the last official parish map (DGT, 2016) and computing *pd* (number of people per km^2) for each of the 2882 current parishes in the country mainland. The distribution of population presents the highest densities in the north western and southern coastal areas as well as around major cities and in the lower *h* and *s* regions of all the 5 NUTS II regions (Fig. 2b).

2.2.4. Distance to the nearest road

The Portuguese road map was obtained from the OpenStreetMap project database (Haklay and Weber, 2008), since it contains updated information for all types of roads (main, secondary and tertiary). As expected, high density of roads is located around main cities and areas of higher *pd* (Fig. 2a). The distance to the nearest road (hereafter, *d*) map was obtained using the *Near tool* from the *Proximity* toolset in ArcGIS ™ environment, that simply find the distance from an input feature to another feature class.

2.2.5. Land use/land cover

Land cover types from CLC (Fig. 1c) cartography has a minimum 25 ha map unit and includes built up areas, agricultural and semi natural areas, wetlands and water bodies (Caetano et al., 2009; EEA, 2017). A more detailed information and characteristics about CORINE Land Cover map may be found in Parente and Pereira (2016) and Pereira et al. (2014).

2.3. Fire dataset

The fire data used in this study is the Portuguese Rural Fire Dataset (PRFD) provided by the Portuguese Institute for the Conservation of Nature and Forests (hereafter, ICNF). For the 1980–2014 period, the dataset comprises a total of 680,000 fire events and TBA of 3.8 $\times 10^6$ ha. PRFD comprises precise spatial and temporal information about the fire events (e.g., BA, ignition fire location, ignition and extinction date and time) as well a comprehensive set of additional information including fire type and cause (Parente and Pereira, 2016; Pereira et al., 2011).

The ICNF developed an official codification and definition of cause categories with a hierarchical structure of three levels. The first level identifies the six major categories of causes, namely: 1) use of fire; 2) accidental; 3) structural; 4) incendiarism; 5) natural and 6) unidentified. The second level discriminates the causes of the previous one, identifying them in groups and discriminating specific activities. Finally, the third level divides activities into subgroups and discriminates specific behaviours and attitudes leading to 70 different fire causes. We focus the study in the wildfires with human cause, namely negligent and intentional defined as follows: negligent wildfires have fire cause 1 (use of fire) or 2 (accidental) while intentional wildfires have fire cause 3 (structural) or 4 (incendiarism). The original ICNF ground fire dataset and, consequently the PRFD, also include a small number (3.3% of TNF) of rekindled fires concentrated between 1994 and 2000 (2.6%) and 2012–2014 (0.7%). These fire records were excluded from this study since the original cause is unknown.

Between 1980 and 1988, the firefighters determined fire causes empirically but, after this period, the wildfire cause of large wildfires (typically with BA > 100 ha) began to be deeply investigated by the Forest Guard (Pereira et al., 2011). Nevertheless, between 1980 and 2005, most (92.5%) of wildfires still have unidentified cause, as a result of the lack of investigation performed by the Forest Guard and unavailability of useful information (Pereira et al., 2011). Until 2006, intentional and negligent wildfire causes were identified in all years and present approximately similar inter-annual variability but the NF with known cause increase after this year (Pereira et al., 2011) reached about 50% of the annual total NF in the last three years. To increase the representativeness of the findings, the study relied only on confirmed human caused wildfires in the most recent 14-years period (2001–2014) which corresponds to the period when spatial coordinates of wildfire ignition locations are also available. We expect higher dataset quality in recent years due to improved detection, registration and information control procedures (Pereira et al., 2011). In addition, despite of the high spatial-temporal variability of fire in Portugal, we believe that results obtained for the 2001–2014 sub-period should be representative for the entire (1980–2014) available period because fires with indeterminate cause should present similar distribution, in terms of fire cause type, as the fires with confirmed cause. Nevertheless, this subset comprises a significant total number (50495) of negligent (29177) and intentional (21318) wildfires with BA ≥0.01 ha (for homogeneity reasons) which accounts for a TBA of almost 870,000 ha.

2.4. Methodology

The methodological procedure includes the update of the fire database by adding the NUTS II region where the ignition occurs to each record, the production of maps of all variables, and the intersection with the fire dataset in order to compute the fire incidence statistical descriptors. The statistical analysis relied on NF and BA for the entire country, for each region and every variable class. Statistics were also computed for each NUTS II region to detect potential regional differences.

Both NF and BA are extensive quantities so their value depends on the extent of the system under study (Tolman, 1917). The correct comparison between values of these quantities requires their conversion to intensive, which is achieved by dividing them by a measure of the system size. In this study, the area of the region and/or class was the adopted normalizing measure. Consequently, NF and BA were divided by the area of each NUTS II region (hereafter, RA), given rise to the NF and BA density, respectively (Fig. 3). Therefore, to properly assess the relative importance of results obtained for each variable in different classes and regions as well as fire types, relative fire incidence statistics (RNF = NF/TNF and RBA = BA/TBA) were normalized, dividing their values by classes' areas (hereafter, CA), giving rise to NNF = RNF/CA and NBA = RBA/CA (Figs. 4, 5, 6, 7 and 8).

In order to simplify the comparison of results obtained for each variable between regions and classes, the normalized statistics are presented (in percentage), relative to their sum value for each region (e.g., $\mathrm{NNF}(\%) = \frac{\mathrm{NNF}}{\sum_{\mathrm{region}} \mathrm{NNF}}$). Then, the differences between the normalized statistics of fire incidence (in percentage) computed for intentional and negligent wildfires ($\Delta NNF = NNF_{Int} - NNF_{Neg}$ and $\Delta NBA = NBA_{Int} - NBA_{Neg}$), were used to assess and compare eventual changes in the results obtained for the two categories of wildfires.

Results are presented in maps created with QGIS 2.8.1, which display the conditional spatial distribution of fire incidence, i.e., will take into account each human/biophysical variable, and put in evidence eventual differences between NUTS II regions. For comparison purposes and a better understanding of the results, we adopted five equal size (i.e., equal NF) classes for all variables based on the quantiles of human and biophysical variables, except for land cover/land use where the CLC classes were used. This aimed defining a sufficiently large number of classes to assess variables' signature on fire incidence but also ensuring that each class has a similar and significant NF records, i.e. to assure results' statistical significance. However, the adoption of five equal NF classes does not imply a uniform distribution of NBA. Instead, a different distribution means that the corresponding variable have a clear signature in BA spatial pattern.

Although it is not one of the objectives of the study, it is important to know the relative importance of the drivers. A variable will not be a driver if the distribution pattern of fire incidence's measures, in terms

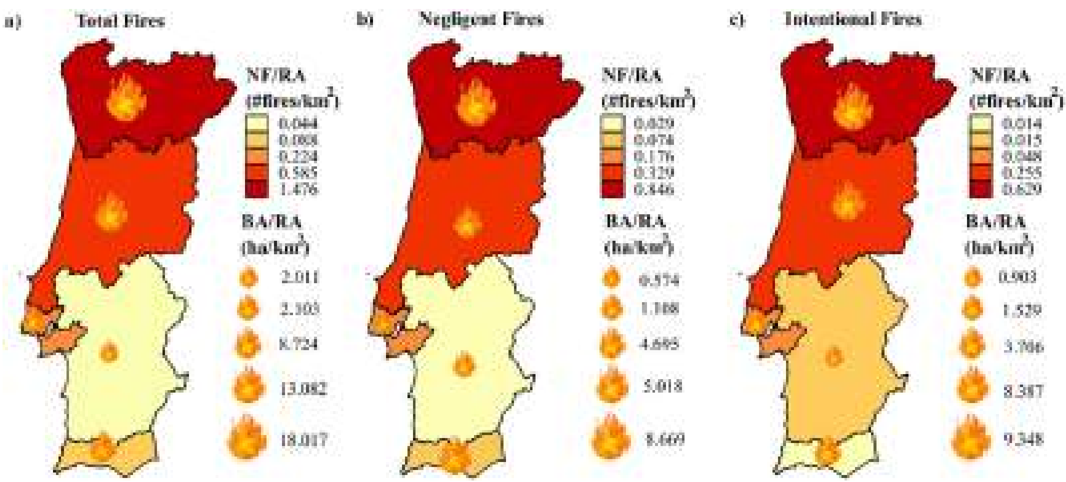

Fig. 3. Density of number of fires (NF/RA) and burnt area (BA/RA) taking into account the NUTS II region area (RA) of Continental Portugal (Fig. 2), for (a) the 2001–2014 period and for (b) negligent and (c) intentional wildfires. Size of the flames is proportional to the BA density.

of that variable, is uniform. Alternatively, the importance of a driver will be as important as greater heterogeneity causes in the distribution pattern. Thus, dispersion statistics, such as the standard deviation, computed for each region and the whole country can be a measure of the relative importance of each driver.

Finally, drivers' influence may depend on fire size and statistics computed for large NUTS II regions may not be able to detect local effects, such as uneven distribution or over densities of wildfires. In this sense, we map wildfires for different BA quintile ranges, by plotting each event as a small coloured circle with the same colour palette used to represent variables' classes as well as all wildfire events concurrently, as circles with area proportional to their BA. The huge number of concurrent events may mask the relationship between wildfire events and the drivers. Nevertheless, these maps allow to assess the potential dependence of the drivers' influence on the wildfires' size and to detect local effects and regional asymmetries in the distributions within NUTS II regions. To simplify and limit the number of figures in the manuscript, these maps were transferred to Supplementary material (Figs. S2 to S6).

3. Results

3.1. Regional fire incidence density statistics

For all wildfires (negligent + intentional), RNF and RBA is much higher (95% and 87%, respectively) in the northern half of the country, especially in *Norte* region. This is particularly interesting because of *Norte*'s smaller area in comparison with *Centro* and *Alentejo* but is a consequence of 62% of TNF and 44% of TBA occurred in this NUTS II region. Results obtained when NUTS II region's area are take into account allow to properly assess regional differences (Fig. 3a). NNF present a similar pattern to RNF, with 85% of total NNF and 71% of total NBA in the North (*Norte* and *Centro*). However, NBA is also non-despicable in *Algarve*, where reaches 20% of total NBA.

Negligent (Fig. 3b) and intentional (Fig. 3c) NNF and NBA general pattern is quite similar to, respectively, the spatial distribution of NNF and NBA for all wildfires. For NNF, this pattern presents a pronounced South-North gradient, from *Algarve* to *Norte* for intentional wildfires and from *Alentejo* to *Norte* for negligent wildfires. However, some differences in normalized statistics for negligent and intentional wildfires are worth noting. Intentional TNF is lower (−27%) than negligent TNF but the difference in NNF is much more significant in the South (−50% *Alentejo* and −80% in the *Algarve*) than in the north (−22% in *Centro* and −26% in *Norte*). However, intentional TBA is larger (+29%) than negligent TBA, especially in the north (79% in *Centro* and 8% in *Norte*), but lower in the South. In *AML*, these differences are even more expressive. Difference between TNF for intentional and negligent is −73%, while for TBA is 166%. Otherwise, the average size of intentional wildfires is much larger than of negligent wildfires in all regions (10× in *AML*, 4× in *Algarve*, 2.5× in *Centro*, and 1.5× in *Alentejo* and *Norte*). In short, there are far fewer intentional than negligent wildfires, but intentional BA is proportionally much larger than the negligent one. The following sub sections present the spatial distribution of the fire incidence in terms of the human and biophysical drivers.

3.2. Population density

The NNF present a clear general increasing trend with *pd*, not only at national level (from 5% to 35%) (Fig. 4a) but also in all regions (Fig. 4b) This trend is less pronounced in *Alentejo* (4% to 20%), *Norte* (6% to 25%) and *Algarve* (6% to 30%) but more marked in *Centro* (9% to 43%) and *AML* (8% to 54%). The NBA for entire Portugal has a unimodal distribution with maximum at the medium *pd* class (Fig. 4e). The distribution pattern of NBA for *Norte* is identical but for all other regions is characterized by higher NBA values in extreme *pd* classes (Fig. 4f). However, as will be clear later, both the distribution patterns at national and regional scales are the consequence of a clearly different regional distribution of NBA according to *pd* for intentional and negligent wildfires.

The distribution patterns of normalized NNF statistics for intentional wildfires at country and regional scales are, in general, similar to those obtained for the whole country but also present some differences important to point out. ΔNNF tend to be positive in classes of medium to high *pd* (and negative in other classes), which means that intentional (negligent) wildfires are relatively more frequent than negligent (intentional) wildfires in those classes, not only at country but also at regional level (Fig. 4c and d). The only exception is *AML* where intentional wildfires are more likely to start in the lower *pd* class and less frequent in the higher *pd* class. This general pattern of ΔNNF is also observed for ΔNBA but with much more impressive figures, including in the classes of highest *pd*, namely in *AML* (+26%) and *Centro* (+19%). This means that the BA by intentional wildfires (Fig. 4h) initiated in higher *pd* areas tends to be larger than the NBA caused by negligent wildfires (Fig. 4g), and that this relative difference can be of about +10% in classes for the whole country, and in the *Norte*, +20% in the *Centro*, *AML* and *Alentejo*, and +80% in the *Algarve*.

In addition to this general pattern, there are still some distinctive features in regional NBA distributions, namely the concentration in only a few but also different classes of *pd* depending on the types of wildfire considered. In fact, most of the NBA in *Algarve* is concentrated

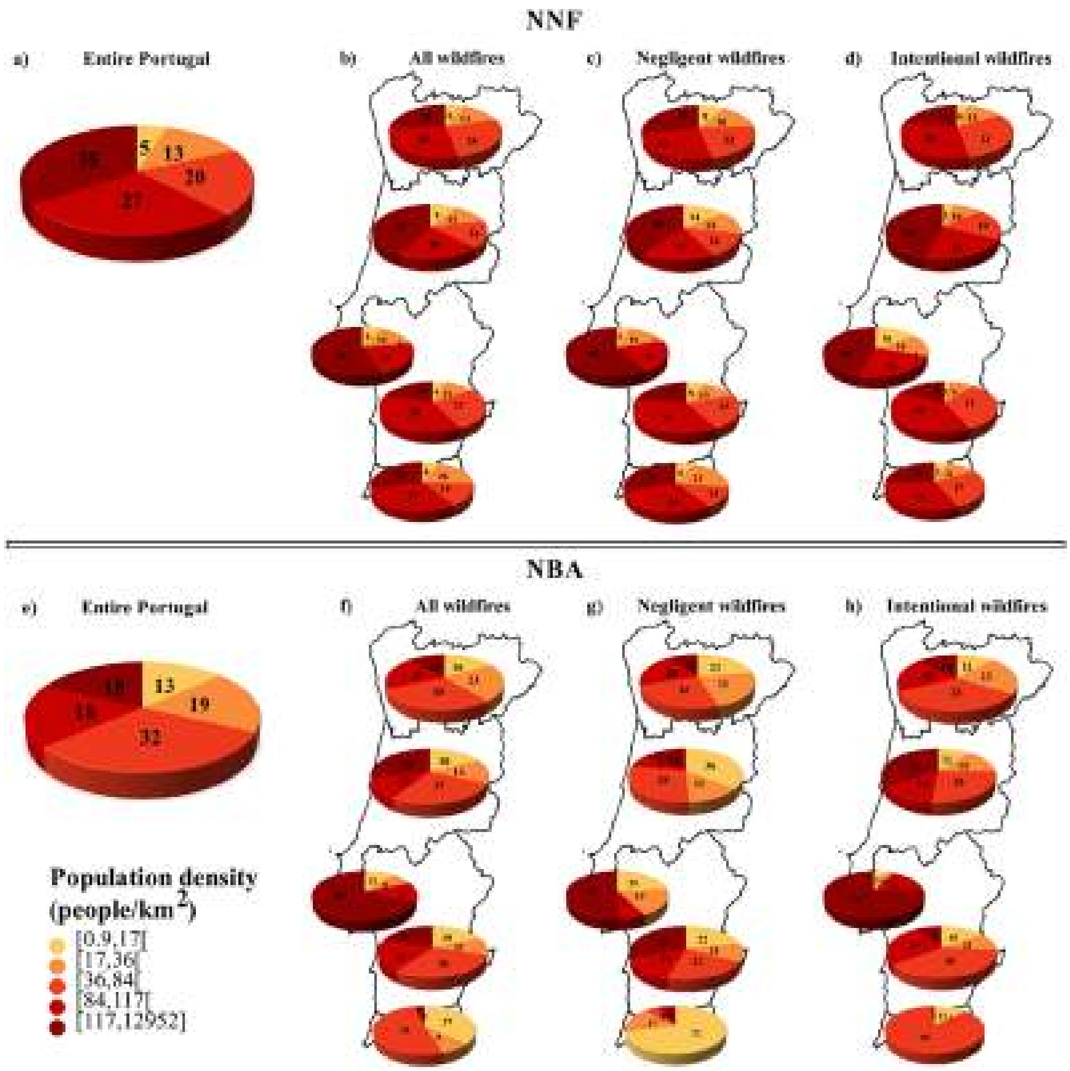

Fig. 4. Distribution of normalized number of wildfires, NNF (top panels), and burnt area, NBA (bottom panels), for all wildfires and entire Portugal (a and e) as well as in each of the Portuguese NUTS II regions for all (b and f), negligent (c and g) and intentional (d and h) wildfires in terms of population density classes. Values expressed as percentage of the sum of the measures' values for all classes.

in the lower *pd* class for negligent wildfires but in the class of medium *pd* for intentional wildfires. Higher NBA in *Alentejo*, may be found in classes 1, 3 and 5 for negligent but is also concentrated in the class of medium *pd* for intentional wildfires. In *AML*, most (51%) of the NBA is concentrated in the highest *pd* class and the two classes of lowest *pd* contain 43% for negligent wildfires but most of the NBA is concentrated (76%) in the class of highest *pd* for intentional wildfires. In *Centro*, highest NBA displaced from the classes of lowest to the highest *pd* when considering negligent and intentional wildfires, respectively. These different regional patterns for negligent and intentional wildfires per se clearly explain the distribution patterns obtained for all wildfires.

3.3. Distance to the nearest road

The distribution pattern of NNF in terms of *d* for all wildfires and entire Portugal clearly present a strongly decreasing trend (43% to 5%) which is also characterized by a significant concentration of NNF in the class of lowest *d* ($d < 22$ m) (Fig. 5a). This pattern is equally evident for all regions as well as for negligent and intentional wildfires at country scale while the concentration in the shorter *d* class is even higher (NNF $\approx$ 50%) in the southern NUTS II regions (Fig. 5b). Values of ΔNNF are particularly small (<10%) and do not present a clear pattern with *d*.

At national scale and for all wildfires, NBA clearly decrease with *d* (Fig. 5e). This decline is also observed and even intensified from *Norte* to *Alentejo* associated to a concentration of NBA in the lower class of *d* (Fig. 5f). On the other hand, in *Algarve*, NBA present two peaks in two specific classes, namely $22 \leq d < 49$ m and $d \geq 168$ m. This distinctive distribution pattern in *Algarve* is the result of NBA being concentrated, separately, in exactly those two classes (72% of total NBA in the 2nd class of lower *d*) for intentional and (also 72% of total NBA but in the class of greatest *d*) negligent wildfires, respectively (Fig. 5g and h). For the other regions, ΔNBA is positive for the first class and negative for the others, which means that intentional wildfires tend to start more frequently at shorter *d* while negligent wildfires are more common at longer *d*. In fact, at national scale, NBA decrease much more gently with *d* for negligent than for intentional wildfires.

3.4. Altitude

The NNF for all wildfires in Continental Portugal increase in the first four classes of (lower) *h* (Fig. 6a). However, this pattern is only observed at regional level, in *Centro*, since NNF significantly decrease with *h* in

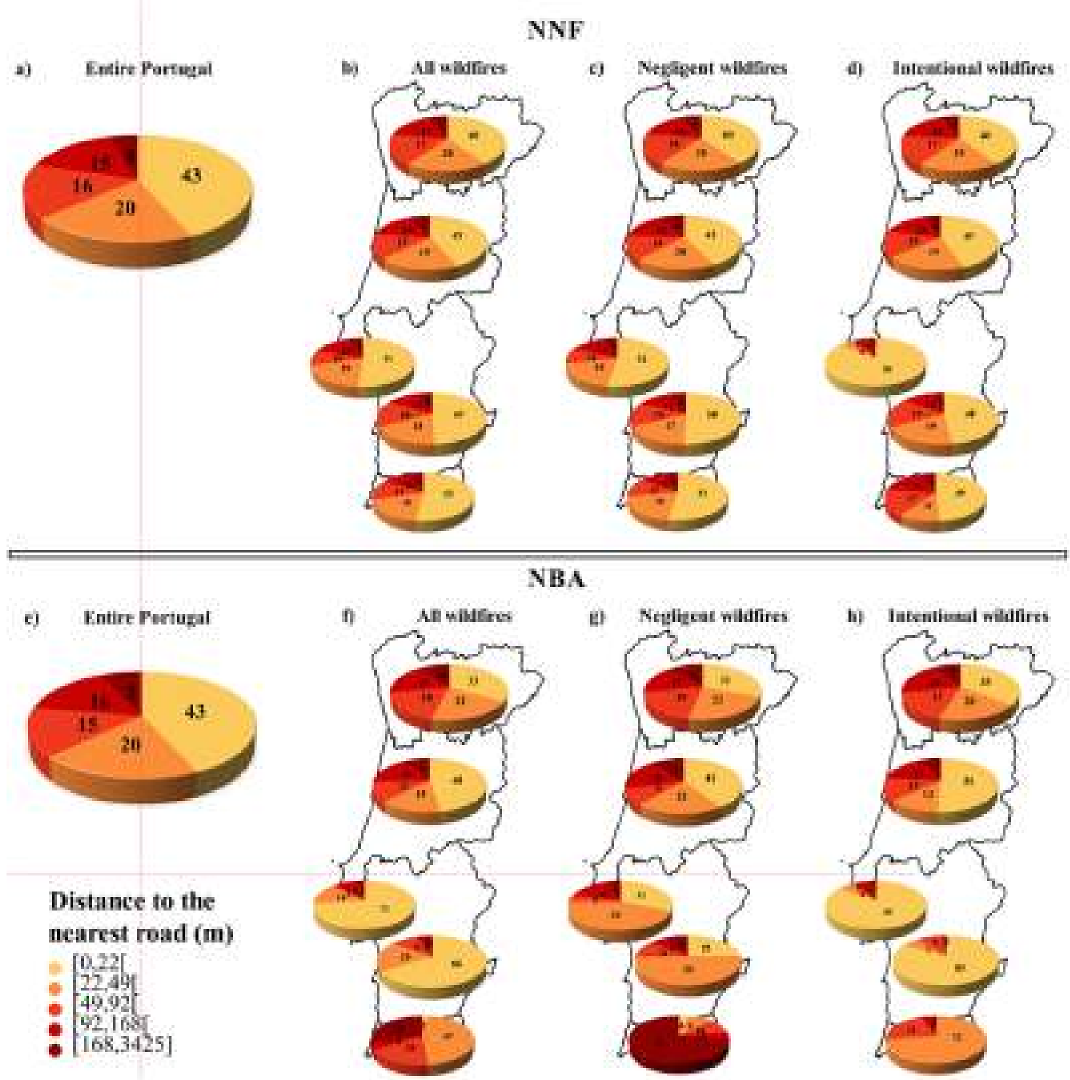

Fig. 5. Distribution of normalized number of wildfires, NNF (top panels), and burnt area, NBA (bottom panels), for all wildfires and entire Portugal (a and e) as well as in each of the Portuguese NUTS II regions for all (b and f), negligent (c and g) and intentional (d and h) wildfires in terms of distance to the nearest road classes. Values expressed as percentage of the sum of the measures' values for all classes.

Norte and present isolate peaks in specific *h* classes in other regions (Fig. 6b). For example, a higher fraction of NNF is concentrated (87%) in the first two classes in *AML* and (48%) in just one class in *Algarve*. Distribution patterns of NNF for negligent wildfires are very similar to ones obtained for all wildfires but some differences are worth noting for intentional wildfires, especially in *Algarve*, *Alentejo* and *Centro* (Fig. 6c and d). In these regions, lower *h* classes contain a much higher fraction of total NNF. In addition, values of ΔNNF reveal that intentional wildfires tend to initiate more frequent in lowlands and less frequent in the highlands than negligent ones.

At national scale, the NBA by all wildfires presents an even more evident increasing trend with *h* (Fig. 6e). Nonetheless, this distribution pattern is not observed at regional level (Fig. 6f). Actually, a slightly increasing trend is only noticed in *Norte* and, to some extent, in *Centro* while, in southern regions, NBA is high concentrated in one (or two) classes of *h*. For example, NBA is 81% in class 2 (143 m ≤ *h* < 308 m) in *AML*, 77% in class 4 (482 m ≤ *h* < 672 m) in *Alentejo* and 65% in class 3 (308 m ≤ *h* < 482 m) in *Algarve*. In general, NBA's distribution for negligent wildfires follows the same distribution patterns of NBA for all fires with a higher concentration in the classes of maximum *h* and a significant increasing trend in *Centro* (Fig. 6g). On the contrary, NBA for intentional wildfires tends to be higher at lower *h*, which is confirmed by the negative values of ΔNBA in first classes (Fig. 6h).

3.5. Slope

For all wildfires and at national scale, NNF increase in the first four classes (from 10% to 26%) and slightly decrease in the class of highest *s* (Fig. 7a and b). *Alentejo* is the only region with similar distribution pattern while in *Algarve* NNF evidently decrease with *s*. For all other regions, NNF present a unimodal distribution, symmetrical in *Norte* and *AML*, left skewed in *Cento* and right skewed in *Alentejo*. Values of ΔNNF reveal a higher propensity of negligent wildfires to start at lower *s* and a higher frequency of intentional wildfires initiating at higher *s* (Fig. 7c and d). In general, the distributions' patterns of NBA at national scale and regional scale are relatively similar in northern regions (Fig. 7e and f). In southern regions, NBA is highly concentrated in the highest *s* class in *Alentejo* (54%), and in the second lowest *s* class in *AML* (50%) and *Algarve* (63%). Differences between NBA patterns for negligent and intentional wildfires are almost despicable at national scale as well as in *Centro* and *Norte* (Fig. 7g and h). In fact, higher NBA caused by intentional wildfires tend to occur in lower to medium *s*

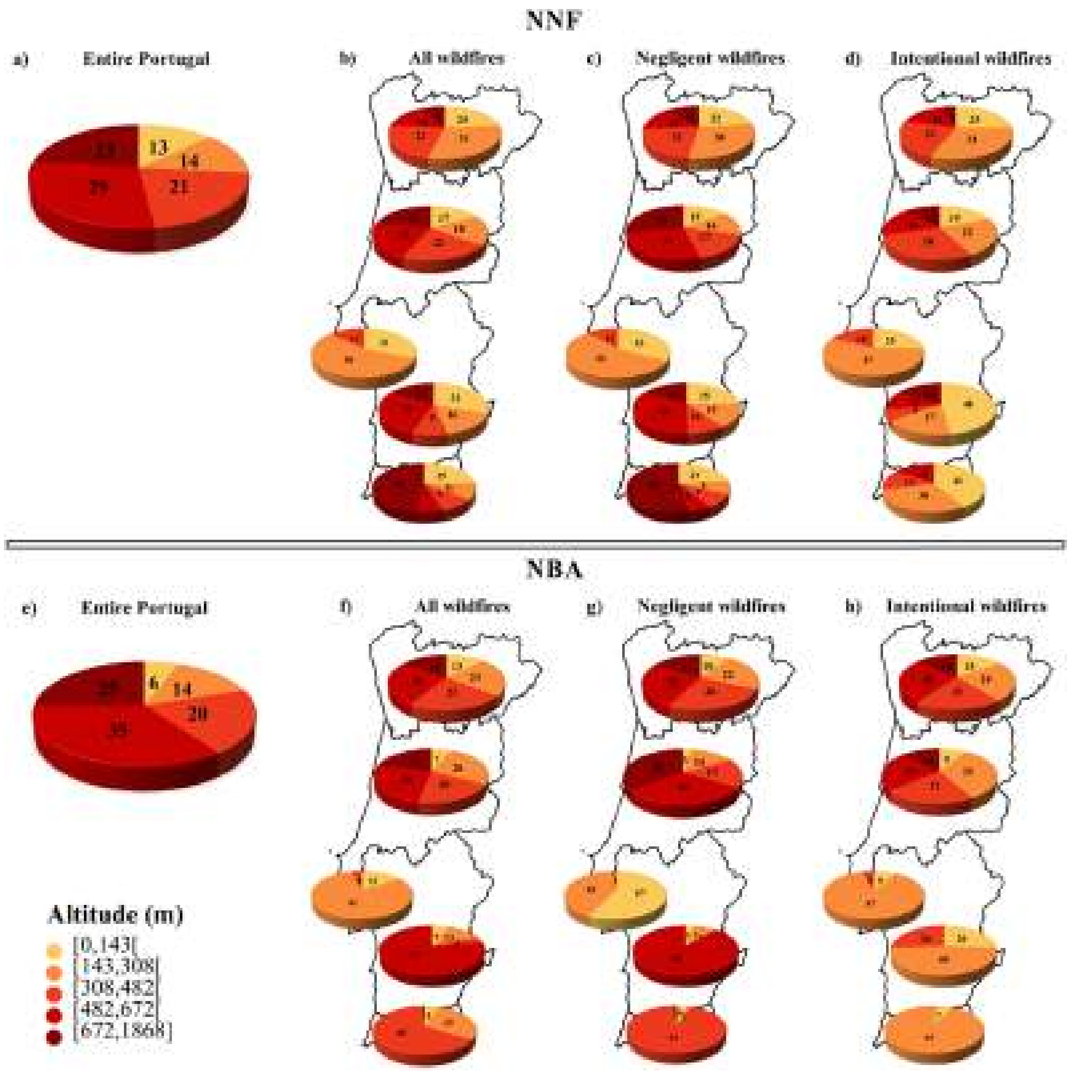

Fig. 6. Distribution of normalized number of wildfires, NNF (top panels), and burnt area, NBA (bottom panels), for all wildfires and entire Portugal (a and e) as well as in each of the Portuguese NUTS II regions for all (b and f), negligent (c and g) and intentional (d and h) wildfires in terms of altitude classes. Values expressed as percentage of the sum of the measures' values for all classes.

(+64% for $6° \leq s < 9°$) in *Algarve*, *Alentejo* and *AML*, while high NBA caused by negligent wildfires are particularly significant for lower s in *AML* (+30% for $s < 4°$) and *Algarve* (+61% for $4° \leq s < 6°$) and for the highest s in *Alentejo*.

3.6. Land use/land cover

For all wildfires in entire Portugal, most of NNF (Fig. 8a) and NBA (Fig. 8e) is concentrated in Agricultural areas (47% and 55%) and Artificial surfaces (36% and 27%) while only a small fraction of these statistics respect to wildfires started in Forests (13% and 18%). CLC classes with higher NNF are Urban fabric (24%), Pastures (24%) and Heterogeneous agricultural areas (12%). These CLC also present higher NBA but with different fractions (18%, 30% and 12% respectively). The north part of country (*Centro* and *Norte*) also present this general tendency for NNF (Fig. 8b). However, in the southernmost regions there is slightly higher concentration of NNF in Urban fabric (37% in *Algarve* and 59% in *Alentejo*), Open spaces with little or no vegetation and Scrub and/or herbaceous vegetation associations (10% and 7%, both in *AML*). However, national and regional distribution patterns of NBA are characterized by high concentration in specific CLC classes (Fig. 8e and f). This concentration is higher in southern than in northern parts of the country. Urban fabric is the only CLC class with high NBA in all regions, ranging between 12% in *Norte* to 55% in *Alentejo*. The CLC class with higher NBA in each region are: Pastures (43%) and Heterogeneous agricultural areas (12%) in *Norte*; Urban fabric (21%), Heterogeneous agricultural areas (19%) and Industrial, commercial and transport units (15%) in *Centro*; Urban fabric (34%) and Industrial, commercial and transport units (31%) in *AML*; Urban fabric (55%) and Permanent crops (25%) in *Alentejo*; and, Heterogeneous agricultural areas (53%), Urban fabric (23%) and Scrub and/or herbaceous vegetation associations (21%) in *Algarve*.

Distribution patterns of NNF (Fig. 8c and d) and NBA (Fig. 8g and h) for intentional and negligent wildfires are quite different from the ones obtained for all wildfires, especially for some regions and CLC classes. There is a relatively high number of non-despicable values of ΔNNF but, in general, there no clear trend in ΔNNF within each of the CLC level 1 classes. Results obtained for NNF reveal that the CLC classes where intentional wildfires are more likely to start, comprises: Artificial, non-agricultural vegetated areas (6%) in *Norte*, Urban fabric (6%) in *Centro*, Scrub and/or herbaceous vegetation associations (10%) and Heterogeneous agricultural areas (8%) in *AML*, Urban fabric in *Alentejo* (19%) and *Algarve* (12%). On the other hand, wildfires are more frequently initiated by negligence in Urban fabric (8%) in *Norte*, Pastures

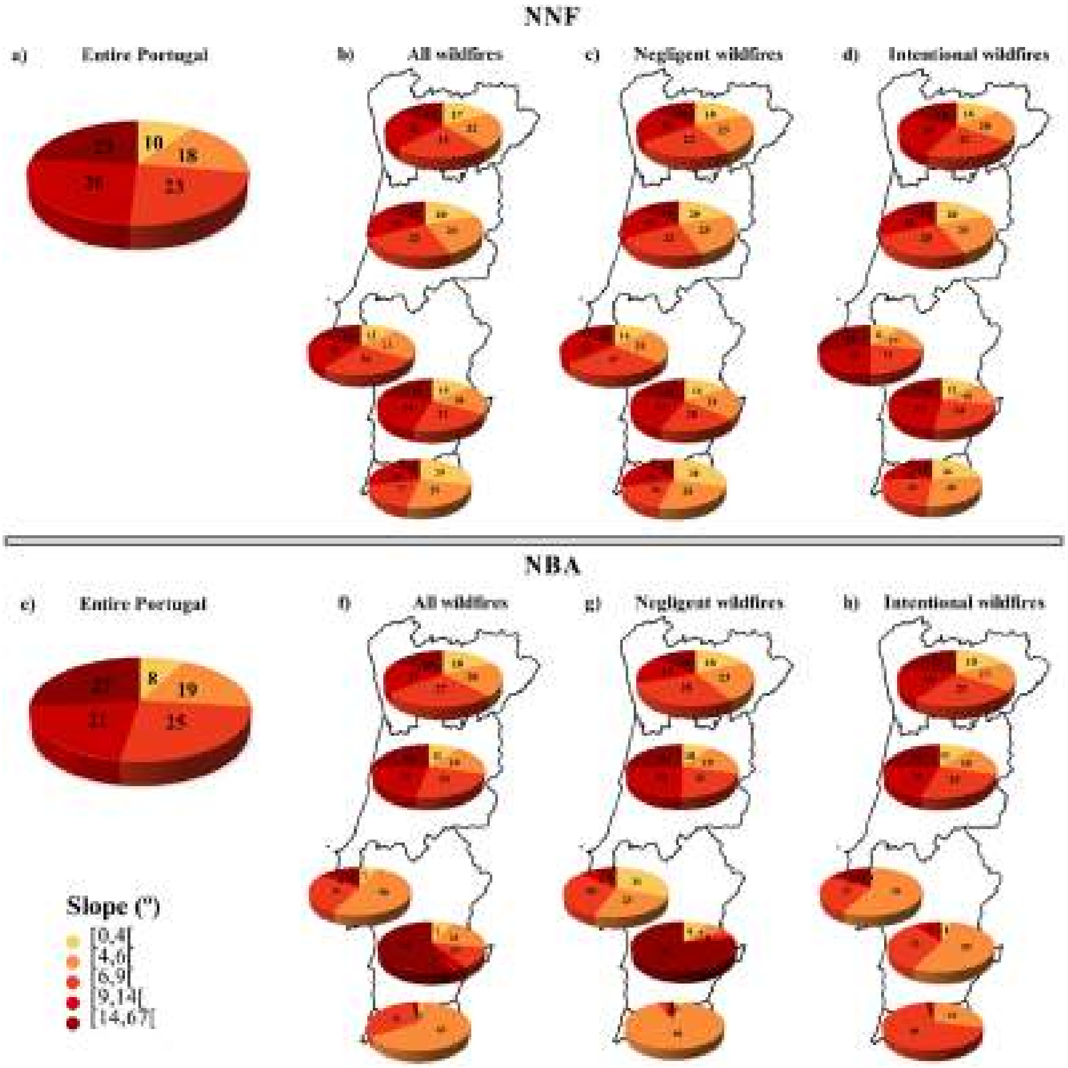

Fig. 7. Distribution of normalized number of wildfires, NNF (top panels), and burnt area, NBA (bottom panels), for all wildfires and entire Portugal (a and e) as well as in each of the Portuguese NUTS II regions for all (b and f), negligent (c and g) and intentional (d and h) wildfires in terms of slope classes. Values expressed as percentage of the sum of the measures' values for all classes.

(10%) in *Centro*, Open spaces with little or no vegetation (11%) and Mine, dump and construction sites (10%) in *AML*, Industrial, commercial and transport units (17%) in *Algarve*.

On the other hand, only a few number of CLC classes concentrate the non-despicable and, consequently, significant values of ΔNBA. Obtained results reveal that the intentional wildfires which caused relatively more NBA started in Industrial, commercial and transport units (22%) in *Centro*, Urban fabric (66%) and Heterogeneous agricultural areas (14%) in *AML*, Permanent crops (34%) in *Alentejo* and Scrub and/or herbaceous vegetation associations (63%) in *Algarve*. Highest NBA associated to negligent wildfires were obtained for *AML* (48% in Industrial, commercial and transport units and 14% in Mine, dump and construction sites), *Alentejo* (16% in Forests) and in *Algarve* (31% in Urban fabric and 29% in Heterogeneous agricultural areas).

3.7. Wildfire events' spatial distribution

The spatial distribution of wildfires according to their BA discloses a perceptible shift of their location from west to east as BA increases. When tested variables are also considered, results obtained for increasing BA, can be summarized as follows. There are much more small wildfires in regions of high *pd* and high predominance of largest wildfires (BA ≥ 3 ha) in regions of low *pd* (Fig. S2). It is also observed a tendency for larger wildfires to occur preferentially further from the roads (Fig. S3), at higher *h* (Fig. S4) and *s* (Fig. S5). Results also suggest that more BA means less fires in Urban Fabric, Arable land and Permanent crops as well as in Heterogeneous agricultural areas (Fig. S6).

3.8. Drivers' importance assessment

The standard deviation of NNF and NBA in terms of each variable, for each NUTS II region and for entire mainland allow us to assess the importance of the tested variables. In general, results reveal that drivers' influence is higher: (i) for southern than for northern regions; (ii) for intentional than for negligent wildfires; (iii) at regional than national scale; and, (iv) for NBA than for NNF. It should be noted that this last result is true for: all variables and wildfires types in *Algarve*; for all variables and wildfires types in *AML* except for negligent wildfires, *pd* and *d*; and in all variables except *pd* in *Alentejo* and *Centro*. *Norte* is the only region where CLC is the only driver with higher influence on NBA than in NNF. Most important drivers of NNF at national scale seems to be *d* and *pd* while at regional scale *h* also play also an important role. The most influential drivers of NBA at regional scale are *h*, *d*, *s* and *pd* while the influence at national scale of all drivers reduced to about half.

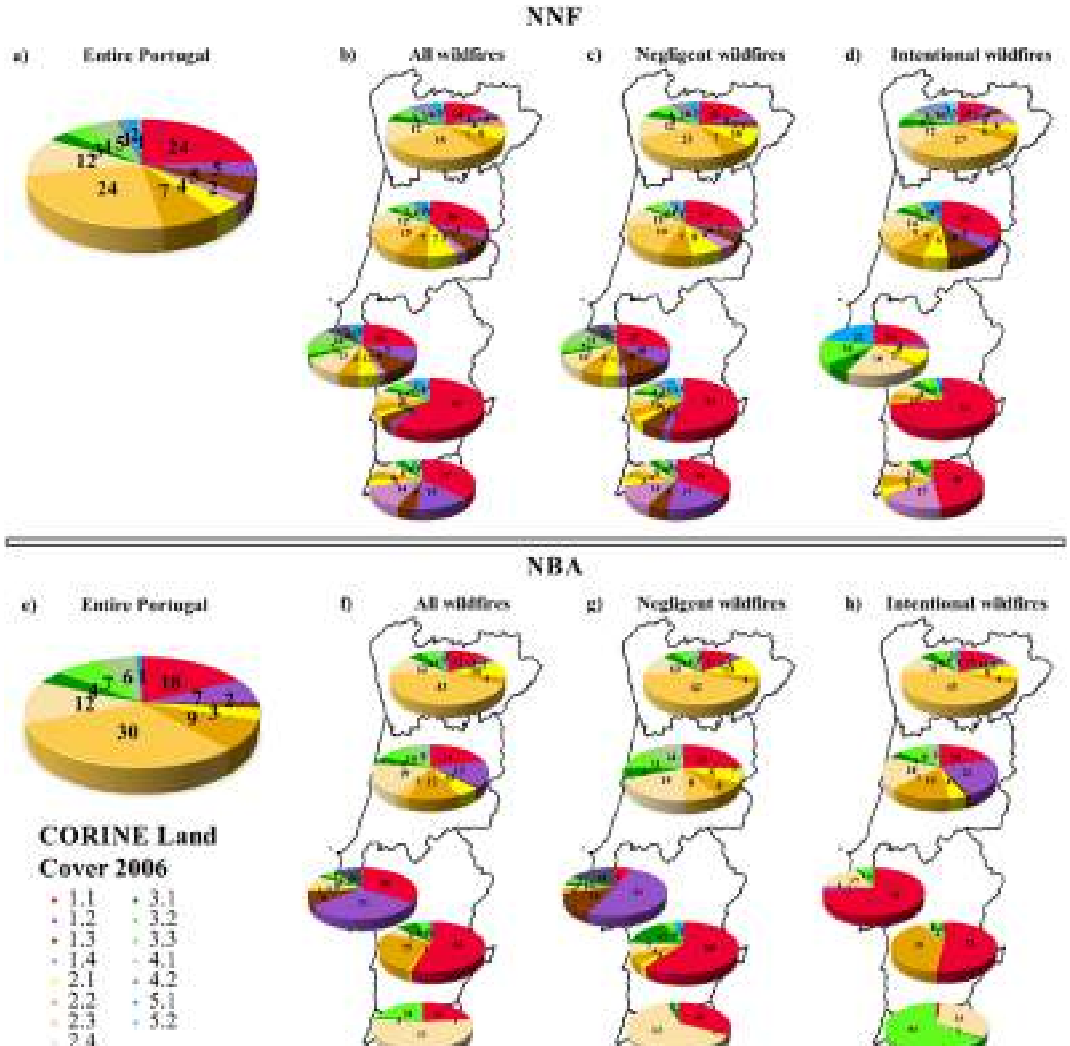

Fig. 8. Distribution of normalized number of wildfires, NNF (top panels), and burnt area, NBA (bottom panels), for all wildfires and entire Portugal (a and e) as well as in each of the Portuguese NUTS II regions for all (b and f), negligent (c and g) and intentional (d and h) wildfires in terms of CORINE Land Cover 2006 classes. Values expressed as percentage of the sum of the measures' values for all classes.

4. Discussion

NUTS II provides a division of the country into 5 regions, each one specific characteristics in terms of landscape, population and fire incidence distribution (Figs. 1, 2 and 3). Spatial patterns of burnt area and number of fires density on the basis of NUTS II regions for all fires (Fig. 3a) are in very good agreement with results obtained in previous studies, even with those using different fire datasets and study periods (Parente et al., 2016; Pereira et al., 2015, 2011). This suggest that the study period may be sufficiently long to capture main characteristics of the fire incidence's spatial distribution and, therefore, be representative of the fire regime. In the previously mentioned studies, this pattern was associated with the different characteristics of northern and southern parts of Continental Portugal (Figs. 1 and 2) respecting to the type of climate, topography, river network/water availability and, consequently, vegetation cover and land use (Parente et al., 2016; Pereira et al., 2011, 2015). However, spatial patterns for negligent and intentional wildfires are slightly different (Fig. S1). Intentional wildfire density is higher in *Alentejo* than in *Algarve* while BA density for negligent wildfires is the lowest in *AML* and the second highest is not in *Centro* but in *Algarve* (Fig. 3b and c). These results may be associated to the combined effect of very different *pd*, land use/land cover and main socioeconomic activities in these regions. In fact, the fraction of region area devoted to Artificial surfaces, Agriculture, Forest and semi natural areas is: 4%, 40% and 53% in *Algarve*; 1%, 61% and 36% in *Alentejo*; and, 22%, 43% and 27% in *AML*. It is also worth noting *Algarve*'s economy is strongly based on tourism where temporary population increases considerably during the summer vacation period enormously (Petrov et al., 2009).

The separation of the wildfire events by the quantiles of the variables aimed to assess driver's influence by the adequate comparison of fire incidence statistics at national and regional scales. In addition, as explained in Section 2.4, normalized statistics (divided by the area of the region and variable class) are the adequate basis to compare the differences between regions and variables' classes (Pereira et al., 2011). Despite informative, relative statistics were not shown and, therefore, will not be discussed. It should also be underlined that ignition points identify the wildfires, concentrate the BA and the values of the variables attributed to the wildfires are those verified at that point, so the calculated fire incidence statistics refer to fire ignitions and area burnt by fires started in that point.

All human and biophysical variables present a very heterogeneous spatial distribution within Continental Portugal (Figs. 1 and 2) and play a different role on the spatial patterns of fire incidence. At global scale, all variables tested in this study influence BA but previous studies suggested that this relationship should be non-linear (Oliveira et al., 2012; Vilar et al., 2010), which is precisely the observed pattern in fire incidence densities (Fig. 3a). Wildfires are more frequent in highly populated and in central/coastal areas (Fig. S2) which is in agreement with the fact that the wildfires in Portugal have predominantly human origin (please see Section 2). Apparently, this is not reflected by relative statistics (not shown) but is evident in normalized statistics (Fig. 4a–d). On the contrary, the likelihood of having larger NBA is greater in areas of low *pd* (Fig. 4e–h) and in inner country (Fig. S2) which is in good agreement with previous studies which found that the probability of having high burnt area is inversely related to *pd* (Catry et al., 2007; Moreira et al., 2010).

Spatial patterns of NNF (Fig. 4c and d) and NBA (Fig. 4g and h) for intentional and negligent wildfires in terms of *pd* are also in line with previous studies on fire incidence performed for Portugal (Catry et al., 2010; Pereira et al., 2011). In fact, there is a notorious increasing trend in negligent NNF with *pd*, while negligent NBA tends to occur in periurban lower *pd* classes. This decreasing trend in NBA is more evident for intentional than for negligent wildfires which is in accordance with the existence of higher vegetation cover in lower *pd* areas and arsonists' intentions (Ganteaume and Jappiot, 2013).

All wildfires occur in a short distance (4 km) from roads. In fact, 95% of total NNF occur in $d < 168$ m and the remaining 5% are only responsible for 7% of total NBA. *AML* is where most of the wildfires (80%) occurs at shorter distance to roads ($d < 92$ m), eventually because road network's density is too high in this region. These results are in accordance with the findings of previous studies performed for Portugal (Catry et al., 2010) and Spain (Vilar et al., 2010). For example, Vasconcelos et al. (2001) conclude that, for central Portugal, fire ignition is more likely to occur close to man-made features, such as distance to roads, that can act as ignition sources. These findings confirms the role of the relatively dense road network (Fig. 2a) which, in one way, provides easy access to vegetated areas of both tourists and pyromaniacs but also fire suppression resources to fire locations (Catry et al., 2010; Oliveira et al., 2012; Yang et al., 2015). Obtained results also points to higher intentional than negligent NBA near to roads (Fig. 5g and h), which could be related to the need of the arsonist to runway from the crime scene and of the forest users and workers to move farther away from the roads to depart from urban areas and to take advantage of the forest services.

The relationship between fire incidence and altitude was studied in other European countries but is very dependent on the study area, specifically on altitude range (Pavlek et al., 2017). For example, in northern Sweden and NE Spain, the probability of a fire to affect a forest stand is higher at lower altitudes due to the influence of high latitude and mountain ranges, vegetation and snow cover (Engelmark, 1987; Gonzalez et al., 2006). The decrease of the fire incidence in the highest altitude class in Portugal can be associated to the influence of altitude on combustion characteristics. On this respect, Li et al. (2009) showed that the burning rate, radiation heat flux and flame temperature at high altitude is lower than at low altitude for equal BA and, conversely, radiation heat flux at high altitude is lower than at low altitude for the same burning rate, though higher average flame temperature. In fact, high-altitude environment is characterized by low atmospheric pressure and temperature, low air and oxygen density, which significantly affects fire behaviour (Yan et al., 2017). In addition, cloud cover and precipitation tend to increase with altitude due to topographic effect (Gonzalez et al., 2006). However, it is important to take into account that most of the fire activity in Portugal occur during summer when some of these factors lose some relevancy (Telesca and Pereira, 2010). Nevertheless, it should be noted that more than half of wildfires started in locations above 482 m of altitude.

At regional scale, patterns of normalized fire incidence measures (NNF and NBA) with *h* can be quite diverse in southern and northern regions (Fig. 6) due to the combination of different trends of fire incidence and altitude CA. In fact, some of the highest altitude classes are residual or do not exist in southern regions. The trend of NNF with altitude is negative for intentional wildfires in all regions (Fig. 6d) but positive for negligent wildfires except in *AML* and *Norte* (Fig. 6c). NBA by intentional wildfires is concentrated in lower *h* classes and present an essentially increasing trend (except in *AML*) for negligent wildfires. These patterns of NNF and NBA can be explained, in the latter case, by the use of forest areas for leisure and, in the former, by the usual uphill fire spread which suggest the arsonist to start the fires at lower altitude to raise the probability to set up a large fire (Vasconcelos et al., 2001).

Spatial patterns for *s* at national scale (Fig. 7) reflect the key role of these variables on fire spread (Dupuy, 1995; Viegas, 2004). In fact, an increasing trend is observed not only in NBA but also in NNF, for all wildfires but more significantly for intentional wildfires. At regional scale, the trend can be negative in some regions but, in these cases, the existence of classes with residual or zero CA as well as the decrease of classes' area cannot be disregarded. In fact, *s* proved to be a very useful variable to model ignition due to arson but not due to negligence, which could be associated with the interest of the arsonist to start fires in regions of fast spread conditions (Vasconcelos et al., 2001).

Obtained results reveal that most of 83% of total NNF started in Agricultural areas (47%) and Artificial surfaces (36%) while most (94%) of total NBA occurred on Agricultural areas (57%), Forest and semi natural areas (36%) (Fig. 8). These results are compatible with the fact humans caused almost all fires in Portugal, either by negligence or intentionally. In addition, similar BA statistics have been found by Catry et al. (2007, 2010) for the 2000–2005 period. Most affected CLC classes in terms of NBA were Heterogeneous agricultural areas, Scrubs and Forests. Similar findings were obtained by Pereira et al. (2014) for 2000–2013 period although using a different fire dataset. Patterns of normalized fire incidence statistics put in evidence the role of Artificial surfaces in NNF distribution for both negligent and intentional causes (Fig. 8c and d) as well as disclose the preference of arsonists for Pastures and negligent wildfires for Urban fabric. It should be noted that about 47% of total, intentional and negligent wildfires started in Agricultural areas but correspond to 56% of intentional NBA and 59% of negligent NBA. This may be explained with the use of fire as a management tool in Agricultural areas (Ganteaume and Jappiot, 2013; Moreira et al., 2010). It is also important to take into account the large size of Agricultural and Forest areas in Portugal, which may be the reason why these CLC variables are not all necessarily selected in models of fire occurrence in Mediterranean Europe (Fernandes et al., 2016; Oliveira et al., 2012; Vasconcelos et al., 2001) and the lower fire proneness of agricultural areas in comparison to scrublands and forests (Pereira et al., 2014).

Drivers' influence on the spatial distribution of the wildfire events taking in account their size is in good agreement with previous studies. For example, Pereira et al. (2015) found that, when fire size increase, there is a eastward displacement of the fire events, a decrease of fire and population densities as well as a predominantly rural land use. They found that fire clusters centred in the coastal areas clearly present higher *pd* and higher fraction of TBA in Artificial surfaces land cover types while clusters located in the interior present lower *pd*, higher mean *h*, slightly lower mean *s* and higher fraction of BA in Forest, semi natural and Agricultural areas land cover types.

Finally, aforementioned studies identified the variables tested in this study as the main drivers of fire incidence in Portugal. The importance of the drivers at regional and national scales assessed here are in a very good agreement with previous findings of other researchers. For example, Marques et al. (2011) shown that population density is the most important driver of fire ignitions followed by distance to roads. Moreira et al. (2010) concluded that population density is more important than land cover for large wildfires (BA > 500 ha) and the probability of ignition of large fires is higher in low population density interior areas. Vasconcelos et al. (2001) discovered that most important drivers for intentional fires are *h*, *s*, *d* and distance to urban areas while, for negligent fires are *h*, *d* and distance to urban. Finally, Fernandes et al. (2016)

studied the most influent variables on the occurrence of large fires (100 < BA < 23,219 ha) and found that climate-weather top-down (climate–weather, landform, land use) variables only explain 15% of the fire size distribution while and bottom-up (the state of the fuels and topography) variables describe the remaining 85%.

The potential of other biophysical and human variables such as weather, climate, aspect, unemployment, livestock, etc., were not tested in this study for the following reasons. Weather and climate variables are among the most important driver of the fire incidence in Portugal (Amraoui et al., 2015; Pereira et al., 2005; Sousa et al., 2015; Trigo et al., 2006, 2016). They play a most significant role all stages of fire from occurrence (lighting) through development (wind, air temperature and humidity) and extinction (precipitation). However, the influence of meteorological parameters is much more important in the temporal distribution. Unemployment is associated with economic crisis, human depression and rural abandonment, and was not included in the analysis since previous studies did not find a strong relationship with fire incidence in Portugal (Oliveira et al., 2012). Livestock density was not considered because it has a dual influence. It tend to increase NF through burnings for pasture renewal (Koutsias et al., 2010; Martínez et al., 2009) and to decrease both NF and BA by the reduction of the fine fuel load/accumulation through pasture (Oliveira et al., 2012; Romero-Calcerrada et al., 2008; Sebastián-López et al., 2008).

In any empirical study, obtained results are dependent on the quality of the databases. This study is based on the concepts of intentional and negligent fire, for which it should be underlined the consequence of eventual fire classification errors in the conclusions of this study. In addition, results may be affected by other errors and uncertainties in the fire database, such as those associated with the exact location of ignition points and burnt area. Eventual errors in other databases such as in the road map and classification of land use/land cover types resulting, among other factors, from its minimum spatial resolution.

5. Conclusion

This study aimed to characterize the spatial distribution of negligent and intentional wildfires' incidence in terms of human and landscape drivers at national and regional scale. Previous studies suggested a list of potential drivers, which comprises population density, distance to the nearest road, altitude, slope, and land use/land cover. Wildfires with human causes were grouped into negligent (accidental and use of fire) and intentional (structural or arson) fires and statistics computed for entire mainland and NUTS II regions as well.

The most important general conclusion of this study is that the spatial distribution's patterns of the incidence of intentional and negligent wildfires, at national and regional scales, are generally very different from those obtained for all wildfires and national level, which justifies this study. In general, previous studies analysed simultaneously the entire set of fires along with the values of associated variables, which allowed them only to assess the influence of the drivers in their entire study areas. This type of analysis does not allow detecting and characterizing regional differences and the usage of their findings to specific fire types or regions with different distribution patterns is clearly compromised.

Other specific conclusions can be summarized as follows. Regardless of the statistics used, northern regions of *Norte* and *Centro* tend concentrate most of the fire incidence (95% and 87% of TNF and TBA, respectively). The preponderance of these regions is increased for intentional (97% of TNF and 92% of TBA, respectively) and decreased for negligent wildfires (94% of TNF and 84% of TBA, respectively). Fire incidence per unit area is characterized by a significant South-North gradient clearly defined for NF/RA while, for BA/RA, *Algarve* present expected values (20%) and the dominance of northern regions decrease (85% and 71% of total NF/RA and BA/RA, respectively). Differences between fire densities (NF/RA) for intentional and negligent wildfires are intensified (92% and 74 for intentional wildfires; 81% and 67% for negligent wildfires). Intentional wildfires cause higher burnt area density (BA/RA) than negligent in *Centro* (35% vs 23%) and *AML* (6% vs 3%) but lower in other regions, especially in *Algarve* (16% vs 25%).

Results obtained when considering all the fires in the dataset allow us to conclude that: (i) NNF increase with *pd* in all regions but NBA present a unimodal centred distribution, skewed to the high values of *pd*; (ii) NNF sharply decrease with *d* and NBA show the same pattern except for *Algarve* where present two peaks on specific *d* classes; (iii) wildfires tend to start at lower altitude except in *Algarve*, where highest *h* class present the maximum NNF while NBA clearly increase with altitude except in the highest *h* class; (iv) slope is the driver with the lowest influence on NNF but lead to increase of NBA with a secondary maximum in medium slope class; and, (v) wildfires tend to start mainly in the Artificial surfaces (specifically in the Urban fabric), Pastures and Heterogeneous agricultural areas while NBA is higher in Agricultural areas, Forests and semi natural areas.

In general, NNF regional and national patterns for all wildfires are only similar for human drivers (*pd* and *d*). Regional patterns for biophysical variables are very different form national ones, except for *h* in *Centro*, *s* in *Alentejo* and, to some extent, CLC in *Norte*. NBA regional patterns are much more diverse and this diversity is particularly evident in the southern and *Centro* regions. Difference between distributions of NNF and NBA allowed us to conclude about the different drivers' influence on the two types of wildfires not only at national but also at regional scale. Intentional wildfires tend to start more frequently in classes of medium to higher *pd* and *d*, lower *h*, medium to higher *s* in the south and medium to high *s* in the north as well as in Agricultural areas, Forests and semi natural areas. On the other hand, negligent wildfires tend to be more frequent in classes of lowest and highest *pd*, lowest *d* in the south and highest *d* in *Centro* and *Norte*, higher *h*, low *s* (especially in the south) as well as in Artificial surfaces (except in *Centro*).

Results also suggest that the intentional wildfires that cause the greatest NBA are those that begin at medium to high *pd*, lower *d*, lower to medium *h* and *s* as well as in Artificial surfaces. On the other hand, negligent wildfires causing higher NBA are those starting in Urban fabric (+31%) and Heterogeneous agricultural areas (+29%) in *Algarve*, Forests (+16%) and Urban fabric (+8%) in *Alentejo*, Industrial, commercial and transport units (+48%), Mine, dump and construction sites (+14%) in *AML* and Open spaces with little or no vegetation (+9%) in *Centro*.

We believe that the findings of this study contribute to close gaps and a better knowledge of the fire regime in Portugal, especially in what concerns to the fire incidence regional patterns and to the specificities of both the intentional and negligent fires. The results of this study help to identify the areas in each region where forest fires are most likely to be ignited intentionally and by negligence as well as where the largest areas burned by these fires occur. Therefore, the obtained results can also be used to better distribute resources for monitoring and fighting fires as well as to increase the efficiency of forest and fire management activities, including prevention, preparation, adaptation and suppression of fires in addition to the mitigation of their consequences.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.013.

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