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Natural Hazards and Earth System Sciences
Discussions

Impact of large wildfires on PM10 levels and human mortality in Portugal

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Abstract.

Uncontrolled wildfires have a substantial impact on the environment, the economy and local populations. According to the European Forest Fire Information System (EFFIS), between the years 2000 and 2013 wildfires burnt about 170,000-740,000 ha of land annually on the south of Europe (Portugal, Spain, Italy, Greece and France). Although most southern European countries have been impacted by wildfires in the last decades, Portugal was the most affected, having the highest percentage of burned area comparing to its whole territory. For this reason, it deserves a closer attention. However, there is a lack of knowledge regarding the impacts of the wildfire-related pollutants on the mortality of the population. All wildfires occurring during the fire seasons (June-July-August-September) from 2001 and 2016 were identified and those with a burned area above 1000 ha were considered for the study. To assess the spatial impact of the wildfires, these were correlated with PM10 concentrations measured at nearby background air quality monitoring stations, provided by the Portuguese Environment Agency (APA). Associations between PM10 and all-cause (excluding injuries, poisoning and external causes) and cause-specific mortality (circulatory and respiratory), provided by Statistics Portugal, were studied for the affected populations, using Poisson regression models. During the studied period (2001-2016), more than 2 million ha of forest were burned in mainland Portugal and the 48% of wildfires occurred were large fires. A significant correlation between burned area and PM10 have been found in some NUTS III (regions) on Portugal, as well as a significant correlation between burned area and mortality. North, centre and inland of Portugal are the most affected areas. The high temperatures and long episodes of drought expected on the future will increase the probabilities of extreme events and therefore, the occurrence of wildfires.

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1 Introduction

The existence of wildfires constitutes a considerable impact on the environment and humans living in numerous regions worldwide. Climate change has lately been identified as a very important variable to be considered in this matter and global warming scenarios are forecasting an increase of the number and intensity of wildfires during the next years (Bowman et al., 2017). Global warming will produce changes in temperature and precipitation patterns which will increase the prevalence and severity of wildfires (Settele et al., 2015), consequently impacting future air quality (Schär et al., 2004). In fact, an increase on the number of droughts, heat waves and dry spells is suggested by climate change projections, which could not only extend the burnt area in chronically impacted areas, but also affect new ones (Gillett et al., 2004), as was the case of Sweden in the summer of 2018 (Lidskog et al., 2019). One of the areas of the world most fustigated by wildfires is the Mediterranean basin (Portugal being the most impacted country), which needs to be studied carefully to address the concerns of local populations.

Although there has been a slight decreasing trend in the burnt area in this region since 2000 after an increasing period in the previous 20 years (European Environment, Agency, https://www.eea.europa.eu/data-and-maps/indicators/forest-fire-danger-3/assessment), recent extreme events like the 2017 fires in Portugal and the 2018 fires in Greece which even resulted in a severe loss of human lives are confirming the worst projections. In fact, a recent study by Turco et al. (2019) showed a relationship between drought and the occurrence of wildfires and suggested an increase of both due to future climate change. But already some years before, the PESETA (Projection of Economic impacts of climate change in Sectors of the EU based on bottom-up Analysis) study estimated an increase of the burnt area in southern Europe in the future (Ciscar et al., 2014).

Uncontrolled wildfires emit numerous pollutants derived from the incomplete combustion of biomass fuel, which cause damage to human health, particularly the respiratory system (World Health Organization, 2010). Examples include particulate matter (PM), carbon monoxide, methane, nitrous oxide, nitrogen oxides, volatile organic compounds (VOCs), and other secondary pollutants (Cascio, 2018) that are released mainly into the atmosphere but can be transported to many other environmental compartments. Moreover, they can affect the physicochemical properties of the atmosphere, as for instance the interaction of PM with solar radiation which can prompt a modification of the temperature depending on the characteristics of the aerosol (Trentmann et al., 2005). Consequently, some of these chemicals are regulated by the European Directive 2008/50/EC of 21 May 2008 of the European Parliament and of the Council on Ambient Air Quality and Cleaner Air for Europe, which establishes threshold values for a safe air quality. But although wildfire emissions are a crucial parameter for the local air quality (Knorr et al., 2016), where in some cases there are already chronically-exposed populations due to the frequency and dimension of the events, they are not contained by political borders and can also affect areas far from the ignition points due to the atmospheric transport of the pollutant plumes. A number of studies (e.g. Lin et al. (2012); Im et al. (2018); Liang et al. (2018); Augusto et al. (2020), among others) report the influence of natural and anthropogenic emissions on air quality composition across different countries, especially PM and tropospheric O_3. For wildfires it is also important to take into account some factors which influence the plume dispersion, such as the duration and space evolution of the fire event and the meteorological conditions associated (Lazaridis et al., 2008). An increase of cardiovascular and respiratory morbidity and mortality are some of the impact these contaminants can have on humans (Johnston et al., 2012; Tarín-Carrasco et al., 2019).

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For instance, there is a strong evidence of the relationship between PM in general and mortality, especially from cardiovascular diseases, for both long-term and short-term exposure (Anderson et al., 2012). Although some studies corroborate the existence of a link between the exposure to wildfire-related air pollutants and hospital admissions, visits to emergency clinics or even respiratory morbidity (Liu et al., 2015; Reid et al., 2016), the impacts on human health are difficult to quantify and the real effects still poorly known.

Regarding PM, a recent study focusing on 10 southern European cities revealed that cardiovascular and respiratory mortality associated to PM10 (particles with aerodynamic diameter below 10 μm) was higher on days affected by wildfires' smoke than in smoke-free days (Faustini et al., 2015). The authors also found that PM10 from forest fires increased mortality more than PM10 from other sources. So, the estimation of mortality due to exposure to wildfire-generated pollutants is key to manage health resources and the necessary public funds towards prevention and remediation, setting up appropriate policies and protocols (Rappold et al., 2012).

The two main factors to take into account for the wildfire's effects are the location and, most importantly, the size of the fire event (characterised by the respective burnt area). When the wildfire occurs close to a large conurbation, the population exposed is higher. But as Analitis et al. (2012) showed in their study, small fires do not seem to have an effect on mortality, whereas medium and large episodes (with burnt areas >1000 ha) have a significant impact on human health, which increases with the size of the fire. Aiming to enhance the knowledge on the effects of wildfires on human health, this study describes the pattern of wildfires in Portugal for 16 years (2001-2016) and assesses the impact of those events on the country's population mortality during the fire season (June, July, August and September). In this work, the focus is placed on indirect effects of pollutants emitted by wildfires, namely assessing the influence of wildfire-generated PM10 on the Portuguese population mortality. The relationship between the size of the wildfire (characterised by the respective burned area) and PM10 and this same pollutant and mortality has been studied. The Nomenclature of Territorial Units for Statistics (NUTS) level 3 (NUTS III) geographical division has been used to be able to compare the effects of the fires in different parts of the country. Finally, monthly deaths due to all-cause (excluding injuries, poisoning and external causes) and cause-specific mortality (cardiovascular and respiratory) for all ages for each NUTS III has been studied. These causes have been selected due to their well-known connection with air pollution.

2 Methodology and data

In this study, the effects of short-term pollutants exposure due to wildfires on human mortality are quantified. The forest fire pollutant emissions were estimated for the period 2001-2016 during the summer months (June-July-August-September) in Portugal mainland (23 NUTS III and more than 10 million people). For this quantification, two steps have been followed.

First, an assessment of the incidence, patterns and variations of burned area on a large time frame and spatially integrated by NUTS III was done on the levels of air pollutants. PM10 and burned area has been correlated through linear regression, while the mortality data and PM10 was correlated with Poisson regression. Data was processed and ordered by NUTS and by month and year. Finally, the correlation between the pollutants emitted by forest fires, the wildfires burned area and the

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different causes of mortality during the period 2001-2016 for the summer months was studied. The study is focused in PM since it is one of the main pollutants emitted by wildfires, which can increase PM concentrations up to 50% and more (Lazaridis et al., 2008). Moreover, there is a clear relation with several effects on human health (including mortality), in particular with respiratory and circulatory diseases (Kollanus et al., 2016; Reid et al., 2016; Liang et al., 2018). There was not enough PM2.5 data collected from the Portuguese air quality management network to establish a correlation (only 20 stations measure PM2.5 in the mainland). For all these reasons this study is focused on PM10.

2.1 Target area

With 89 015 km^2 (9.11 Mha) mainland Portugal accounts for over 96% of the country's area and hosts over 10 million inhabitants in the west Iberian Peninsula (southwestern Europe). With the largest urban areas along the west Atlantic coast, particularly around the capital Lisbon more to the south and the second largest city (Porto) in the north (see Figure 1,left), the country has most of its mountain ranges in the north, reaching 1993 m in Serra da Estrela. Although showing a Mediterranean climate, this topographic display leads to various climate patterns along the country, with increasing temperature and decreasing rainfall from northwest to southeast (Moreira et al., 2011; Oliveira et al., 2017). In terms of land cover, Figure 1,left shows a predominance of agriculture by 2015 (over 50% and mainly in the south), followed by forests and shrublands, which comprise 43% of the territory (mainly in the north and southwest). This allied with high temperatures in the summer months represent a potential fire hazard, which unfortunately has been often verified almost every summer for many years.

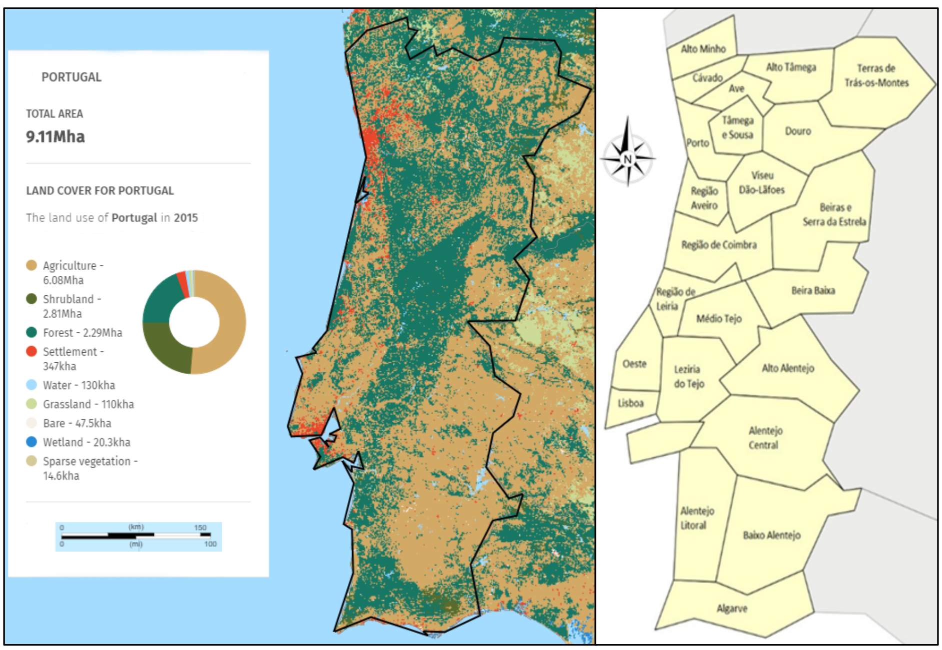

Figure 1. (Left) Land cover in mainland Portugal in 2015 (Global Forest Watch, https://www.globalforestwatch.org; (Right) Mainland Portugal NUTS III regions as included in this contribution.

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2.2 Datasets

2.2.1 NUTS III boundary data

The target domain was divided by NUTS (Nomenclature of Territorial Units for Statistics) level 3 (Figure 1,right) for Portugal mainland. NUTS is a geocode standard for referencing the subdivisions of countries for statistical purposes developed by the European Union, and are divided in three levels, established by each EU member country. The boundaries of the NUTS III files from mainland Portugal (in total, 23) were retrieved from the Eurostat web page (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts) with QGIS3 software. The downloaded data are for the 14 March 2019 version at a 1:60 million scale.

2.2.2 Wildfires data

The wildfire data, collected in the period from 2001 and 2016, was obtained from the Portuguese Institute for Nature Conservation and Forests (https://www.icnf.pt/). For this study, forest fires occurring in the months of June, July, August and September 2001-2016 (the months with highest temperatures and drier conditions when more than 65% of fires happened) with more than 1000 ha of total burned area were selected and considered *large fires*. In total, there were 331 events under that category. This data was divided by month and year and the respective monthly and yearly sums were considered for each NUTS III level region. Ave, Alto Tâmega, Tâmega e Sousa, Oeste, Médio Tejo and Alentejo Litoral are the NUTS III where large fires during the study period were not found.

2.2.3 Pollution data

The information available on the levels of pollutants was obtained from the Portuguese Environment Agency air quality network (https://qualar.apambiente.pt/qualar/index.php), established to monitor the concentrations of pollutants according to the European Legislation requirements (European Directive 2008/50/EC of 21 May 2008). The network is irregularly scattered throughout the country, with a stronger presence in the most populated areas. The isolation of pollutant emissions due to burnt biomass is quite complicated as it depends on parameters, such as vegetation type, the weather conditions on the burnt moment or the contribution of other sources, among others. For this reason, in this study, background stations (specifically urban, suburban and rural background) were selected, so that the direct impact of other urban and industrial sources such as road traffic, building heating and manufacturing combustions was avoided. Considering all the pollutants measured on the background stations, PM was the one with a potentially higher link to forest fires. And although some stations also measured PM2.5, the coverage was insufficient to draw any significant correlations, so PM10 was chosen in the end.

As for the wildfires data, also here the time range was from 2001 to 2016 and only the months of June to September were considered, with monthly means used for the correlations. Concentrations of PM10 were obtained for mainland Portugal in all types of background stations (a total of 91 which cover 17 NUTS III, as shown in Figure 2)- Given the uneven coverage of the target domain, most stations are located in the metropolitan areas of Oporto (14 stations) and Lisbon (24 stations) and in the

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rest of the coastal areas, where the higher population (NUTS III commonly above 250,000 inhabitants, Figure 2) demands a tighter control of the air quality, but where, in turn, not a lot of large wildfires occur due to the urbanized land use.

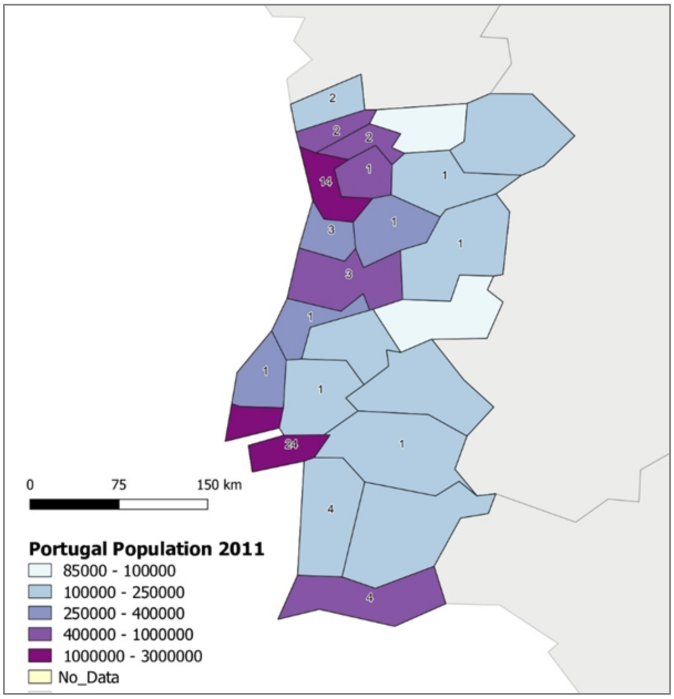

Figure 2. Population of each NUTS III according to the 2011 Census (https://www.ine.pt) and respective number of monitoring stations for PM10.

2.2.4 Mortality data

Mortality data covering the period from 2001 to 2016 was obtained from Statistics Portugal (https://www.ine.pt). Monthly death counts due to all-cause (International Classification of Diseases (ICD-10), codes A00-R99) excluding injuries, poisoning and external causes; and cause-specific mortality: cardiovascular (codes I00-I99) and respiratory (J00-J99) were collected for each NUTS III region of Portugal, comprising all-age residents. These mortality causes were selected since they have been reported previously in literature as important in their connection with air pollution (Hoek et al., 2013; Liu et al., 2015; Kollanus et al., 2016; Münzel et al., 2018), in particular with particulate matter (PM). Other relevant mortality causes, such as Chronic Obstructive Pulmonary Disease (COPD, codes J40-J45) and asthma (ICD-10, code J47), were also considered, however the reduced number of deaths due to these diseases in the study period prevented the establishment of correlations.

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2.3 Statistical analysis

2.3.1 Correlations between PM10 and burned area

Correlations between PM10 and the total burned area per month by NUTS III were estimated using Pearson correlations coefficients (Pearson and Galton, 1895). Pearson correlation is used to correlate two continuous variables having a normal distribution, while Poisson coefficients are used to correlate a count variable with a continuous variable. These methodologies are widely used in studies covering the topic of health impacts of air pollution (e.g. Islam and Chowdhury (2017); Pallarés et al. (2019); Rahman et al. (2019); Rovira et al. (2020); among many others). Results were considered statistically significant if the p-value was $p<0.05$. Correlations were performed using the detrended data series of burned area and PM10 in order to remove the strong seasonal cycle of these variables and avoid spurious correlations. The detrending method follows Tarín-Carrasco et al. (2019), using the first-time difference time series.

2.3.2 Associations between burnt area, PM10 and mortality

The associations of monthly average PM10 levels, and the size of the wildfires (burnt area >1000 ha and burnt area <1000 ha) with mean monthly mortalities (all-cause, respiratory and cardiovascular causes) were studied for the months June, July, August and September for the period between 2001 and 2016. The effect estimates were obtained for each NUTS III region using Pearson regression models. The results were expressed as the Relative Risk (RR) of all-cause, cardiovascular and respiratory mortalities with a 95% confidence interval (95% CI). All regression models were performed using IBM SPSS Statistics 25.0 software.

3 Results and discussion

The results obtained in the study are presented as follows. First, the description of the situation in Portugal in terms of geographical distribution of the burned area is presented. Then, a summary of the PM10 concentrations during the summer months of the years 2001-2016 is presented. Finally, the correlations between burned area and PM10 and the potential associations of wildfire-derived PM10 and all-cause mortality is presented in this section.

3.1 Spatio-temporal patterns of wildfires

3.1.1 Burned area

From 2001 to 2016 period more than 2 million ha of forest were burned in mainland Portugal. Around 48% due to large fires (>1000 ha). During this period, the wildfires occurred on different areas in Portugal, as shown in Figure 3.

The north, centre and inland of Portugal are the areas with the highest number of wildfires and the highest burned area, being Beiras e Serra da Estrela and Beira Baixa. Also Lezíria do Tejo (in Alentajo) and Algarve (in the south) (Figure 1) can be found among the most affected areas (in number of wildfires and burned area). As seen in Figure 3, the north and centre of

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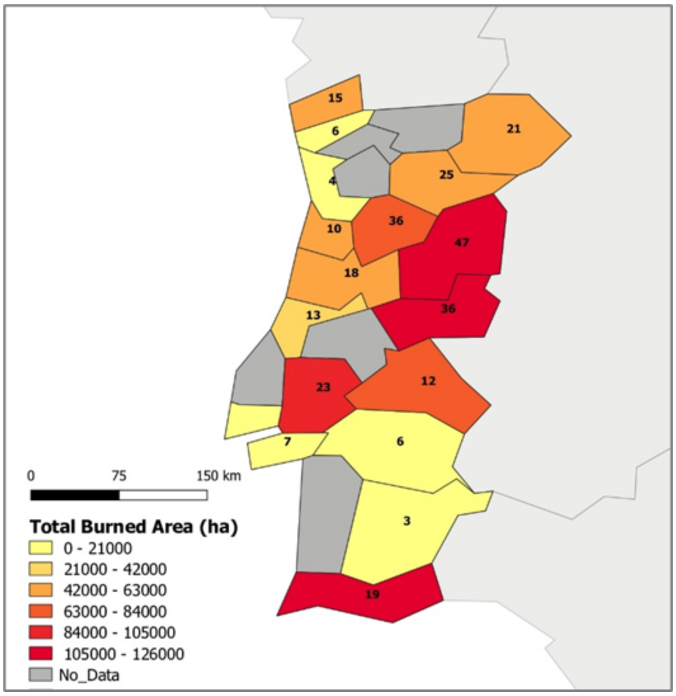

Figure 3. Burned area and number of fires (>1000 ha) per NUTS III from June to September in the period 2001-2016.

Portugal is where the most extensive forests in the country (Nunes et al., 2019), particularly abundant in pine and eucalyptus trees, two species that have been associated with extreme wildfire events (Maia et al., 2014). Additionally, dense Mediterranean forests over hard-to-reach mountains can also be found in these areas, which combined enhance the difficulty of the firefighting efforts. The Algarve, which despite being located in the south coast, also has some mountains with forests, surrounded by a considerably dry and arid terrain, especially in the summer (Nunes et al., 2019). Beira Baixa is the region which presented the most burned area during the period 2001-2016, with almost 124,000 ha in total. But Beira e Serra da Estrela is the area where the highest number of wildfires was found, 47 in total. On the other hand, Lezíria do Tejo is the NUTS III region most affected by wildfires, considering the number of large fires and burned area together. Oeste and Area Metropolitana de Lisboa are the areas with a smaller number of large fires, only one during the target timeframe (since these are mainly non-forested areas). Table 1 presents an overview of the burned area and occurrences of large fires by NUTS III areas in mainland Portugal.

On the other hand, Table 2 shows the yearly variability during the studied period of the number of the occurrences and burned area. In 2008 no wildfires over 1,000 ha of burned area occurred, whereas 2003 accounted for 81 of occurrences of large fires, which were responsible for 80% of the total burned area in that year. The data in Table 2 suggests that it is not possible to perceive a yearly pattern of wildfires in Portugal regarding the occurrences, burned area or the contribution of large fires to the burned area, but other studies have shown a relationship with high temperatures and drought periods (Turco et al., 2019).

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Table 1. Total burned area and occurrences of *large fires* by NUTS III areas in mainland Portugal in the period 2001-2016 in the months of June, July, August and September (total of 64 target summer months).

	NUTS	Months with large fires (N)	Number of large fires (N)	Total burned area (ha)
North	Alto Minho	7	14	53918
	Cávado	3	4	7731
	Ave	4	4	5410
	Alto Tâmega	10	21	48415
	Terras de Trás-os-Montes	7	10	28050
	A. M. Porto	5	8	40840
	Tâmega e Sousa	4	4	5706
	Douro	14	27	48907
Centre	Aveiro	3	6	17481
	Viseu Dão-Lafões	11	31	60744
	Coimbra	8	16	45673
	Beiras e Serra da Estrela	17	49	115503
	Leiria	6	13	28347
	Médio Tejo	11	31	96947
	Beira Baixa	7	14	59032
	Oeste	1	1	1700
A.M.Lisboa		1	1	2756
Alentejo	Leizíria do Tejo	2	3	24404
	Alto Alentejo	4	12	70657
	Alentejo Central	3	6	1970
	Alentejo Litoral	3	5	16176
	Baixo Alentejo	2	2	9240
Algarve		9	19	107273

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Table 2. Number of wildfires and burned area (BA) by year for the period 2001-2016. From left to right: number of occurrences when the burned area is larger than 1000 ha; sum of burned area for fires lager than 1000 ha; percentage of burned area caused by large fires; and index between burned area and the number of occurrences.

Year	Occ. (N) with BA>1000ha	BA>1000ha	Total BA	%BA>1000ha	BA/Occ. (ha/N)
2016	22	85166	160458	53	3871
2015	8	16886	64978	26	2111
2014	3	6451	21114	31	2150
2013	26	71391	156688	46	2746
2012	11	48035	116204	41	4367
2011	6	9102	74686	12	1517
2010	25	60738	138797	44	2430
2009	9	21467	90541	24	2385
2008	0	0	17393	0	-
2007	2	6203	34036	18	3102
2006	7	21197	79536	27	3028
2005	61	172723	344554	50	2832
2004	32	75168	148194	51	2349
2003	81	375783	470617	80	4639
2002	17	30786	129731	24	1811
2001	21	34856	116706	30	1660

According to the 2016 EFFIS report, the south of Europe (Portugal, Spain, France, Italy and Greece) is the area most affected by wildfires since 1980 until today. In the last decades, Portugal was by far the country with the largest burned area, almost 50% between the southern European countries (Parente et al., 2018). But not only the south of Europe seems to be affected by wildfires, as areas in north of Europe which never had relevant wildfires are now suffering from these extreme episodes, as was the case of Sweden in the summer of 2018 (Lidskog et al., 2019).

3.1.2 Particulate matter (PM10)

Regarding particulate matter, air quality monitoring stations are unequal spatial distributed. As mentioned previously, most of them are located near the coast, particularly in the in metropolitan areas of Lisbon and Oporto, the two most densely populated in the country; and only a few monitoring stations can be found inland. The mean highest concentrations of PM10 during the period 2001-2016 (June to September only) were observed in Oporto, with 31 μm m^{-3}; followed by Lisbon, Alentejo Central and Ave, with levels ranging from 26 to 29 μm m^{-3} (Figure 4) Conversely, the NUTS III which present the lowest mean values, between 14-17 μm m^{-3}, are Oeste, Alto-Minho and Viseu Dão-Lafões. Despite these values, no NUTS in Portugal exceed the threshold value of PM10 (40 μm m^{-3} per year) established by the European Directive 2008/50/EC.

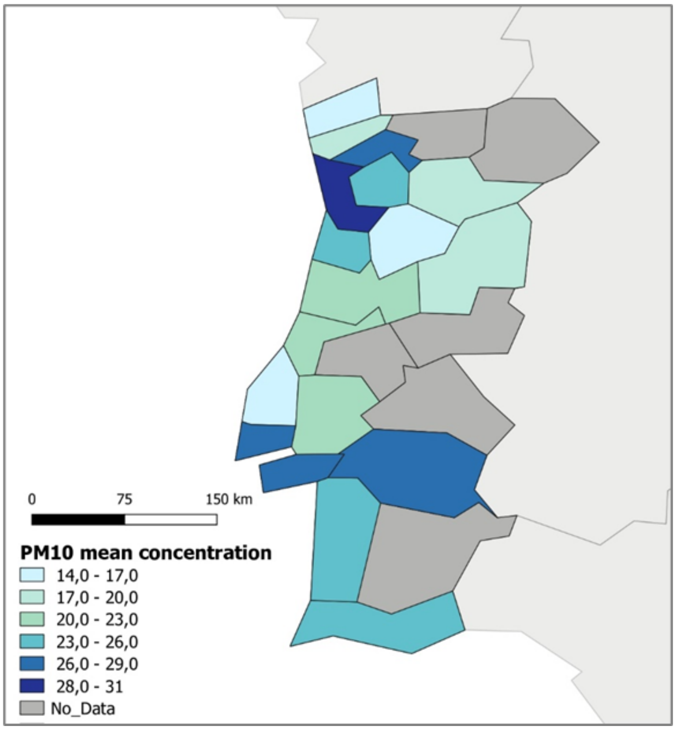

Figure 4. Mean concentration of PM10 per NUTS III from June to September in the period 2001-2016.

3.2 Relationship between burned area and particulate matter

Regarding correlation between burned area and PM10, a significant positive correlation was found for most of the studied NUTS III, represented by black dots in the map of Figure 5. The correlation is weaker for Alto Minho, Cávado and Algarve but the rest of studied NUTS present a strong correlation between both variables, peaking in Lisbon and Leiria with more than 0.98 at a confidence level of 0.95. Obviously, the location of the air monitoring stations may play a role in these correlations, especially when they are scarcer, but for these NUTS this is a good indication where the influence of wildfires on the emissions of PM10 is likely to be stronger. In fact, some authors have reported a contribution of wood burning to the PM10 load even in urban environments, where the presence of other PM sources tends to be higher (Fuller et al., 2014; Perrino et al., 2019).

3.3 Impact of wildfires on all-cause mortality

The mortality counts for the period 2001-2016 (for the months June to September, 64 months) in mainland Portugal are presented in Table 3, for each NUTS III region and all-cause, cardiovascular and respiratory-related deaths. Results show that almost 30% of all-cause and cardiovascular mortality occur during the extended summer (June, July, August and September), as do 26% of the respiratory mortality.

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Table 3. Mean number of deaths occurring during months affected by large fires (LF) in the period 2001-2016 in the months of June, July, August and September (total of 64 target summer months) in the 23 NUTS III sub-regions of mainland Portugal.

	NUTS III	All	Months w./ LF	All	Months w./ LF	All	Months w./ LF	Inhabitants (2016)
North	Alto Minho	44434	13213	16586	4731	4975	1293	233813
	Cávado	44307	12832	14136	3931	5964	1471	404664
	Ave	49068	14153	15736	4421	5754	1363	415617
	Alto Tâmega	20527	5324	6687	1864	2298	576	87941
	Terras de Trás-os-Montes	24664	7190	8083	2312	2623	633	109409
	A. M. Porto	221105	64366	67239	18660	24914	6252	1719021
	Tâmega e Sousa	50971	14623	18038	4847	6504	1574	420854
	Douro	39670	11648	13162	3642	4511	1143	193202
Centre	Aveiro	53380	15440	17705	4945	6664	1647	363752
	Viseu Dão-Lafões	48379	14170	17700	4918	6474	1679	256928
	Coimbra	81397	23648	28146	7718	10898	2807	439507
	Beiras e Serra da Estrela	53414	15699	17816	5036	6108	1558	218961
	Leiria	45190	13259	14294	4015	5507	1426	287770
	Médio Tejo	49769	13908	16666	4595	5417	1444	236256
	Beira Baixa	22545	6624	8063	2306	2267	562	82731
	Oeste	60896	17819	22467	6285	6539	1660	358029
A.M.Lisboa		399704	118206	147172	41599	38931	10117	2821349
Alentejo	Leizíria do Tejo	45762	13505	16241	4491	5025	1397	239977
	Alto Alentejo	29145	8622	10391	2957	3690	923	108588
	Alentejo Central	33134	9602	12171	3252	2979	765	156207
	Alentejo Litoral	19241	5681	6916	1972	2294	635	94291
	Baixo Alentejo	30823	8988	11955	3317	3190	875	119024
Algarve		71445	21715	22591	6482	7926	2307	441469

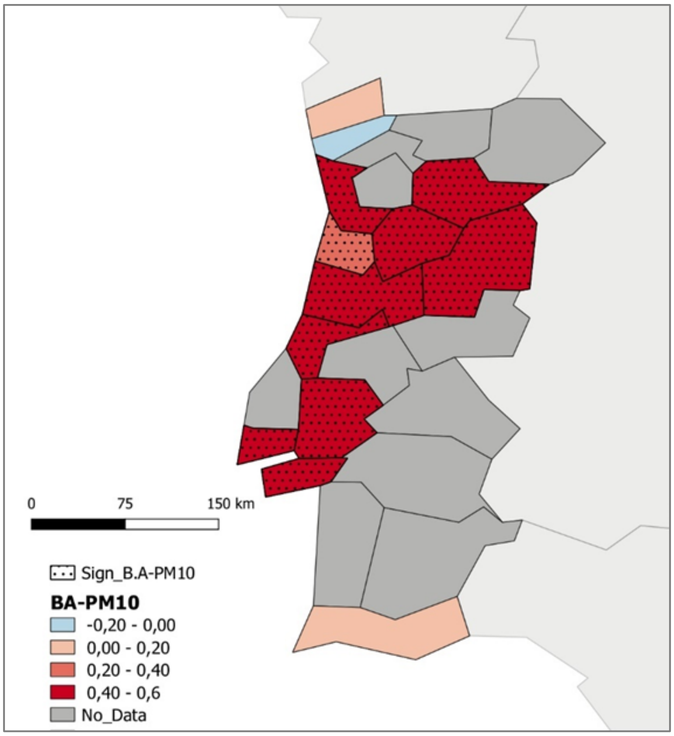

Figure 5. Significance of Pearson correlations between burned area and PM10 for each NUTS III in the period 2001-2016 (from June to September; dots represent significant correlations at 95%).

Considering that this period corresponds to one third of the year, the mortality in these months is slightly below what would be a regularly distributed percentage for a 12-month timeframe (33%). This is in line with the evidence that cold temperatures are in general more responsible for all cause deaths then warm ones (Lee et al., 2018; Scovronick et al., 2018).

Algarve, Alto Minho, Alto Alentejo and Lisbon are the NUTS with the higher percentage of all-cause mortality for the studied months, but the NUTS with more per capita incidence are Beira Baixa, Alto Alentejo, Baixo Alentejo and Beiras e Serra da Estrela, areas with lower population density and with mean higher age than the rest of the country.

Regarding cardiovascular mortality, the NUTS which present a high incidence are Algarve, Terras de Trás-os-Montes and Beira Baixa, with the latter, Baixo Alentejo and Alto Alentejo having a higher percentage of population affected.

Finally, the results obtained for respiratory mortality show that Algarve, Lezíria do Tejo and Alentejo Litoral are the NUTS which top the ranking in the summer months, whereas Alto Alentejo is the region with most population affected. Alentejo and Algarve suffer from high temperatures in the summer, which may also be an indicator that contribute for a higher mortality in general (Basu and Samet, 2002) but also due to cardiovascular and respiratory diseases (Pinheiro et al., 2014). As is the considerable afflux of tourists that increase their population in the same period, particularly in the Algarve. In Alentejo, the combination of high temperatures with an aged population and less health care resources available may be the justification to have the most population affected by mortality (Chen et al., 2019). In fact, this is a tendency that has been becoming stronger

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since the beginning of the XXI century, as the percentage of population over 65 years-old changed in Alentejo from 22.5% in 2001 to 25.4% in 2018, higher than the percentages in the whole of Portugal (from 16.4% in 2001 to 21.7% in 2018) (as derived from PORDATA, https://www.pordata.pt).

The negative impact particulate matter can bring to human health is well established and can be translated into several types of diseases (Kim et al., 2015). Wildfires are an important source of this pollutant and the associations between wildfires and mortality were assessed in this work.

As shown in Figure 6,a, four NUTS (Beiras e Serra da Estrela, Viseu Dão-Lafões, Coimbra and Lezíria do Tejo) present associations between wildfire-generated PM10 and all-cause mortality during the studied period, being these related to large fires in two of the NUTS, namely Lezíria do Tejo and Região de Coimbra. The wildfire origin of PM10 is corroborated by the positive significant correlations between PM10 and burnt area obtained for these four NUTS (Figure 5).

It is an evidence that particulate matter can enter the human body, arrive to the bloodstream and damage some organs or even provoke death due to cardiovascular afflictions like stroke or heart attack, among others, representing a clear hazard to public health (Brook et al., 2010; Hamanka and Mutlu, 2018). Regarding cardiovascular mortality, five NUTS present associations with PM10: Alto Minho, Douro, Região de Aveiro, Lezíria do Tejo and Beiras e Serra da Estrela, with only the last one being associated with the occurrence of large fires (Figure 6,b). This NUTS region was the most affected by these events during the studied period, both in number ($\approx$ 50) and respective burned area ($>$100 000 ha).

Beiras e Serra da Estrela counts with almost 50 large fires during 2001-2016, which involves high levels of PM10 in a short period of time, which might provoke damage in human health, particularly in an aged population (23.8 and 28.7% over 65 years-old in 2001 and 2018, respectively; PORDATA, https://www.pordata.pt)).

Particulate matter also can damage the human respiratory system. The risk depends on the size of the particle, which if very small can even reach the alveolus (Neuberger et al., 2004; Jo et al., 2017). For respiratory mortality, four NUTS present associations with PM10: Área Metropolitana do Porto, Douro, Região de Aveiro and Viseu Dão-Lafões, all located in the north of the country (Figure 6,c). The majority had a correlation with the presence of large fires, except Viseu Dão-Lafões.

Aveiro and Oporto regions are urbanized areas with considerable industrial presence and a cooler and rainier climate year-round than in the south, and the chronic exposure to these conditions suggests that people may be more susceptible to have their respiratory tract affected by acute PM-releasing events like large fires.

In some NUTS III regions like Tâmega e Sousa and Área Metropolitana de Lisboa no correlations were expected since there was not a high number of large fires. In addition, these fires did not spread through a very large area. On the other hand, for Alentejo NUTS (Alto Alentejo, Alentejo Central, Alentejo Litoral and Baixo Alentejo), Oeste, Leiria, Beira Baixa, Médio Tejo, Cávado, Ave, Terras de Trás-os-Montes and Alto Tm̂ega pollutant data were missing or there was only one station for the whole region. Viseu Dão-Lafões is one of the NUTS with less PM10 concentration for the whole Portugal mainland. Finally, for Alto Minho and Algarve no correlation was found between wildfires and PM10.

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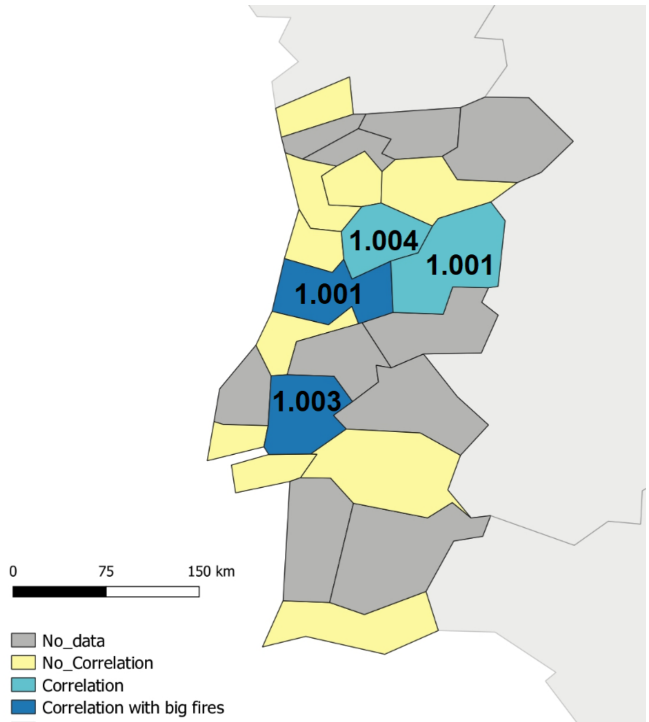

Figure 6. Relative risks (RR, numbers) obtained from Poisson regression for PM10 and (a) all-cause mortality; (b) cardiovascular mortality and (c) circulatory mortality from June to September in the period 2001-2016 (light blue NUTS III regions indicate a significant result, $p<0.05$); dark blue represents significant result, $p<0.05$, with fires >1000 ha; yellow NUTS III regions present no significant results for the variables studied; grey NUTS III regions indicate that no data was available for correlations). Only significant RR are displayed.

4 Conclusions

Portugal is a country that suffers constantly from serious wildfire incidents, which are bound to pose a risk not only to chronically affected populations but also from acute impacts of the pollutants released in such events. In this work, analysing the summer months (June to September) on a lengthy timeframe (2001-2016), it was possible to find significant associations between burned area and mortality in some NUTS III regions of mainland Portugal (mainly inland and in the north), as well as a significant correlation between burned area and PM10.

In particular, large fires (in this study considered above 1000 ha of burned area) have an impact on the health of the population in some areas due to the emission of particulate matter. Moreover, in such severe events, the population exposed to a high concentration of pollutants in a short period of time should be considered as a risk modifier of the impacts of air pollution exposure (Desikan, 2017; Rappold et al., 2017).

During the studied period (2001-2016), the 48% of wildfires occurred in Portugal were large fires, more than 2 million ha of forest were burned in mainland Portugal. The areas that are more affected by number and size of wildfires are north,

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centre and inland of Portugal. Wildfires do not follow a pattern in number of the occurrences or size during the years studied. These evidences were found despite the difficulties that the uneven scattering of the air monitoring stations analysing PM10 in Portugal posed, since the areas where wildfires are usually more frequent (inland) are far from the urban centres (mainly along the coast), and thus, not abundant in air quality data availability due to the shortage (or even lack in some NUTS III) of monitoring stations. These regions also have an aged population, poorer economy and less health care resources, which can lead to an increase in the mortality rates in general. The socio-economic status of the population affected and the health care facilities and measures existing in the communities have to be taken into account (Oliveira et al., 2017), adding to the countless parameters that may affect these estimations which contribute to considerable gaps identified in this type of studies (Black et al., 2017).

During the summer months occur almost 30% of the deaths of all diseases and cardiovascular while for respiratory diseases mortality is around a 26%, so we can conclude that cold temperatures are in more responsible for all cause deaths than warm ones.

These episodes occurred during the summer months (June-July-August-September), when high temperatures and long episodes of drought increase the probabilities of undergo one of these extreme events. On a future ruled by climate changes, the high temperatures and long periods of drought that usually fuel big fires are expected to increase, thus leading the way for more extreme and intense events to occur, even outside the typically affected regions. Thus, more population will be exposed more frequently to high pollutant levels, affecting their general health, and increasing chronic diseases and mortality. Hence, restrictive policies and protocols to improve the effectiveness of preventive and mitigation actions must be enforced to face this environmental and societal issue.

Data availability. Data is publicly available through the websites mentioned in the text:

- EFFIS (European Forest Fire Information System). Data and Services, 2019. Available at https://effis.jrc.ec.europa.eu/applications/data-and-services/ (last accessed 11/10/2019).
- ICNF (Instituto da Conservação da Natureza e das Florestas), 2019. Available at https://www.icnf.pt/(last accessed: 01/09/2019).
- INE (Instituto Nacional de Estatística). Statistics Portugal - Web Portal, 2019. Available at: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&contecto=pi&indOcorrCod=0008273&selTab=tab0 (last accessed 16/10/2019).
- GWF (Global Forest Watch), 2020. Available at https://www.globalforestwatch.org/map/?gfwfires=true (last accessed, 10/10/2020).
- PORDATA (Base de Dados Portugal Contemporâneo). População residente: total e por grandes grupos etários (in Portuguese), 2019. Available at https://www.pordata.pt (last accessed 31/03/2020).

All the compiled data is available upon contacting the corresponding author (pedro.jimenezguerrero@um.es)

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