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 2000 and 2013 wildfires burnt up to 740,000 ha of land annually on the south of Europe, being Portugal the country with the highest percentage of burned area per km^2. However, there is still a lack of knowledge regarding the impacts of the wildfire-related pollutants on the mortality of the country’s population. All wildfires occurring during the fire season (June-July-August-September) from 2001 and 2016 were identified and those with a burned area above 1,000 ha (large fires) were considered for the study. During the studied period (2001-2016), more than 2 million ha of forest (929,766 ha from June to September alone) were burned in mainland Portugal. Although large fires only represent less than 1% of the number of total fires, in terms of burned area their contribution is of 46% (53% from June to September). To assess the spatial impact of the wildfires, burned areas in each region of Portugal were correlated with PM10 concentrations measured at nearby background air quality monitoring stations. Associations between PM10 and all-cause (excluding injuries, poisoning and external causes) and cause-specific mortality (circulatory and respiratory) were studied for the affected populations, using Poisson regression models. A significant positive correlation between burned area and PM10 was found in some regions of Portugal, as well as a significant association between PM10 concentrations and mortality, being these apparently related to large wildfires in some of the regions. The north, centre and inland of Portugal are the most affected areas. The high temperatures and long episodes of drought expected in the future will increase the probabilities of extreme events and therefore, the occurrence of wildfires.

1 Introduction

Wildfires have a considerable impact on the environment and humans worldwide. Climate change has lately been identified as a very important variable in this matter (Gillett et al., 2004) since the future projections suggest an increase of the number of droughts, heat waves and dry spells (Turco et al., 2019). Global warming will produce changes in temperature and precipitation patterns leading to a higher prevalence and severity of wildfires (Settele et al., 2015; Bowman et al., 2017) and consequently impacting future air quality (Schär et al., 2004). In fact, this could not only extend the burnt area in chronically impacted areas (Ciscar et al., 2014), but also affect new ones, like Sweden in the summer of 2018 (Lidskog et al., 2019). According to the 2016 European Forest Fire Information System (EFFIS) report (San-Miguel-Ayanz et al., 2017), the south of Europe (Portugal, Spain, France, Italy and Greece) is the area most affected by wildfires since 1980 until today, considering Europe, Middle East and North Africa. 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). 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 resulted in a severe loss of human lives are confirming the worst projections.

Uncontrolled wildfires emit numerous pollutants derived from the incomplete combustion of biomass fuel, which cause damage to human health, particularly the cardiovascular and respiratory systems (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). 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.

Concerning 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 burned area of large wildfires and PM10 and this same pollutant and mortality was 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 exposure to pollutants due to wildfires on human mortality were quantified. The forest fire pollutant emissions were estimated for the period 2001-2016 during the summer months (June-July-August-September) in mainland Portugal (23 NUTS III and more than 10 million people). In Portugal, large forest fires usually occur during the months of June, July, August, and September, which correspond to the time of the year with the highest temperatures and driest conditions. By focusing our study only on these 4 months, we can have enough data to perform a valid statistical treatment, while avoiding a strong influence of PM10 from other sources in colder months (such as home heating or traffic). At the same time, we do not include in the analysis the deaths due to, for instance, cold and flu that could become confounding factors.

For the quantification, two steps were 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 were correlated through linear regression, while the mortality data and PM10 were 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 different causes of mortality during the period 2001-2016 for the summer months was studied. The study is focused on 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 focuses 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 1,993 metres above sea level 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, combined with high temperatures in the summer months, represents a potential fire hazard, which unfortunately has been often proved almost every summer for many years.

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. The geocode is divided in three levels (I, II, III) which are established by each EU member country. NUTS III from mainland Portugal (in total, 23) at a 1:60 million scale were retrieved from the Eurostat web page (Eurostat, 2019) and treated with QGIS3 software.

2.2.2 Wildfires data

The wildfire data, collected for the period from 2001 and 2016, was obtained from the Portuguese Institute for Nature Conservation and Forests (https://www.icnf.pt/). For this study only forest fires were considered, and from them, only those with more than 1,000 ha of total burned area (which we denominated *large fires*) were selected. In total, there were 323 events under that category (less than 1% of the number of total fires), which were responsible for 46% of the total burned area. Table 1 shows the yearly variability during the studied period of the number of the occurrences, total burned area or the contribution of large fires to the burned area in mainland Portugal. Although other studies have shown a relationship with high temperatures and

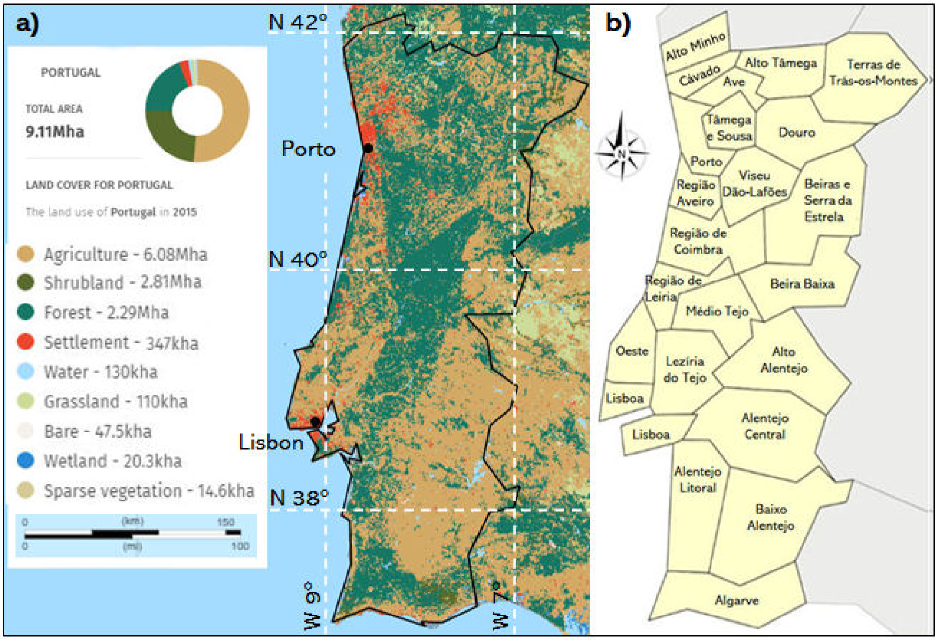

Figure 1. (Left) Land cover in mainland Portugal in 2015 (Global Forest Watch, https://www.globalforestwatch.org; (Right) Mainland Portugal NUTS III regions.

drought periods (Turco et al., 2019), the data in Table 1 suggests that it is not possible to perceive a yearly pattern of wildfires in the country. For instance, in 2008 no large fires occurred, whereas 2003 accounted for the highest number of occurrences (81), which were responsible for 80% of the total burned area in that year. But the latter contribution was as low as 12% in 2011 and had a mean percentage for the whole period of 34%.

Considering only June, July, August and September 2001-2016 (the months with highest temperatures and drier conditions when more than 86% of the total fires and 311 of the 323 large fires -96%- occurred), this data was divided by month and year and the respective monthly and yearly sums were considered for each NUTS III level region. All NUTS III had at least one large fire during the study period. In terms of burned area 929,766 ha of forest were lost in mainland Portugal from June to September (2001 to 2016), with about 53% due to large fires (>1,000 ha). Figure 2 represents the number of large fires and the burned area they were responsible for, by NUTS III.

The north and centre of Portugal present the most extensive forest cover in the country (Nunes et al., 2019), particularly abundant in pine and eucalyptus trees, two highly combustible species that have been associated with extreme wildfire events (Maia et al., 2014). Consequently, both areas show the highest number of large fires and respective burned area (being Beiras e Serra da Estrela and Médio Tejo the most affected NUTS III), but with also Alto Alentejo and Algarve (more to the south, see Figure 1) among the NUTS III with a higher incidence. 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. Algarve, despite

Table 1. Number of wildfires and burned area (BA) by year for the period 2001-2016 in mainland Portugal. From left to right: number of occurrences (Occ.) when the burned area is larger than 1000 ha; sum of the burned area for fires larger than 1000 ha; total burned area caused by all fires; percentage of burned are caused by large fires; and index between burned area and the number of occurrences.

Year	Occ. (N) with BA>1000 ha	BA>1000 ha	Total BA	%BA>1000 ha	BA/Occ. (ha/N)
2016	22	85166	138884	61	3871
2015	8	16629	63227	26	2078
2014	3	5560	19771	28	1853
2013	26	66633	152181	44	2563
2012	11	41884	108965	38	3808
2011	6	8694	72006	12	1449
2010	25	54901	131753	42	2196
2009	9	18018	86478	21	2002
2008	0	0	16662	0	-
2007	2	4623	32595	14	2312
2006	7	19008	75513	25	2715
2005	61	167133	338262	49	2740
2004	24	56088	129715	43	2337
2003	81	338486	425742	80	4179
2002	17	29414	124408	24	1730
2001	21	32509	112166	29	1548

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), leading to a burned area of 112,764 ha, the second highest at the NUTS III level. Beiras e Serra da Estrela is the region which presented the largest burned area in the summer months from 2001 to 2016, (almost 117,000 ha) and the highest number of large fires (50). On the other hand, Oeste and A.M. Lisboa (mainly non-forested areas) are the NUTS III with a smaller number of large fires, only one during the target timeframe. More detailed information can be found in Supplementary Material (Table SM1).

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 location of the air quality stations is irregularly scattered throughout the country, with a stronger presence in the most populated areas (Figure 3). 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 moment the fire is taking place or the contribution of other sources, among others.

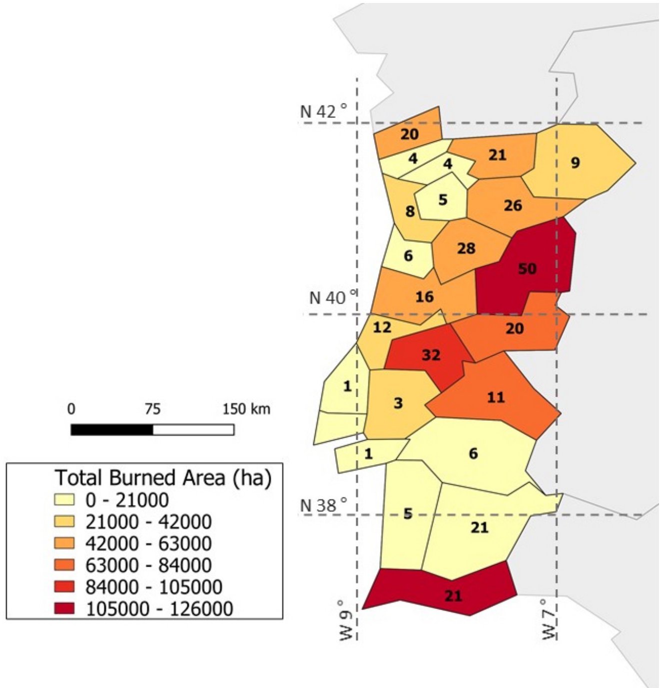

Figure 2. ~~Burned~~ Total burned area ~~caused by large fires and~~ per NUTS III from June to September in the period 2001-2016. The numbers inside each NUTS III represent the respective number of large fires (>1,000 ha) ~~per NUTS III from June to September~~ in the same period~~2001-2016~~.

Considering all the pollutants measured on the background stations, PM10 was the one with a potentially higher link to forest fires. Although some stations also measured PM2.5, the coverage in this case was insufficient to draw any significant correlations. The main anthropogenic sources of PM10 include road traffic, industrial activities, and home heating. In this study, to minimize the influence of non-wildfire causes for the PM10 concentrations, we selected only background stations (encompassing urban and semi-urban ones, which are located within urban areas but with minimum influence of road traffic; and rural stations). Therefore, urban stations with road traffic influence and stations close to industrial complexes were not selected. The influence of home heating was already minimized by selecting the summer period as our target timeframe.

As done before for the wildfires data, also here the time range considered was from 2001 to 2016 and only the months of June to September, 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 3). 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 rest of the coastal areas, where the higher population (NUTS III commonly above 250,000 inhabitants, Figure 3) 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. For the NUTS III with more than one station a mean between all the PM10 concentrations in each NUTS was done.

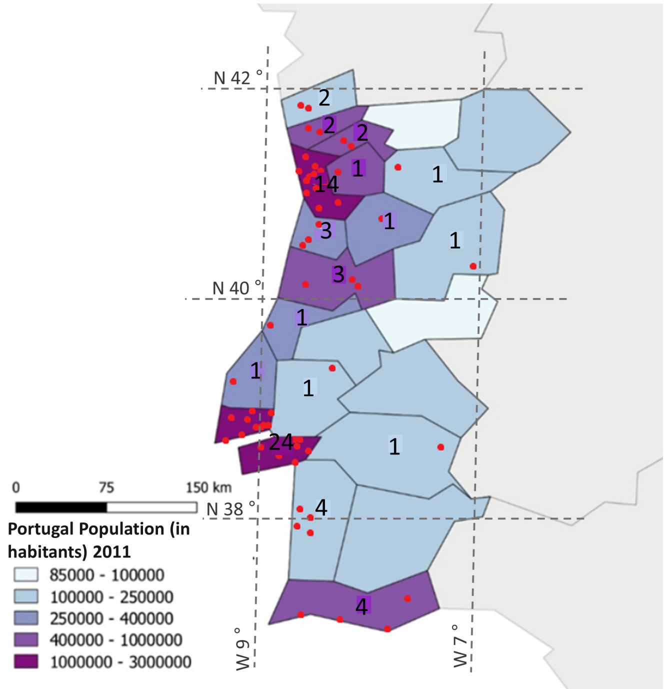

Figure 3. Population of each NUTS III according to the 2011 Census (https://www.ine.pt) and respective number of monitoring stations for PM10. Red dots indicate the location of the air quality monitoring stations used in this study.

Figure 4 shows the mean concentration of PM10 by NUTS III from June to September in the period of 2001-2016 in the stations available in mainland Portugal. The highest mean concentrations of PM10 during the period 2001-2016 (June to September only) were observed in Oporto, with 31 μg m^{-3}; followed by Lisbon, Alentejo Central and Ave, with levels ranging from 26 to 29 μg m^{-3} (Figure 4). Conversely, the NUTS III which present the lowest mean values, between 14-17 μg m^{-3}, are Oeste, Alto-Minho and Viseu Dão-Lafões. Despite these values, no NUTS in Portugal exceed the threshold value of PM10 (40 μg m^{-3} per year) established by the European Directive 2008/50/EC.

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, since

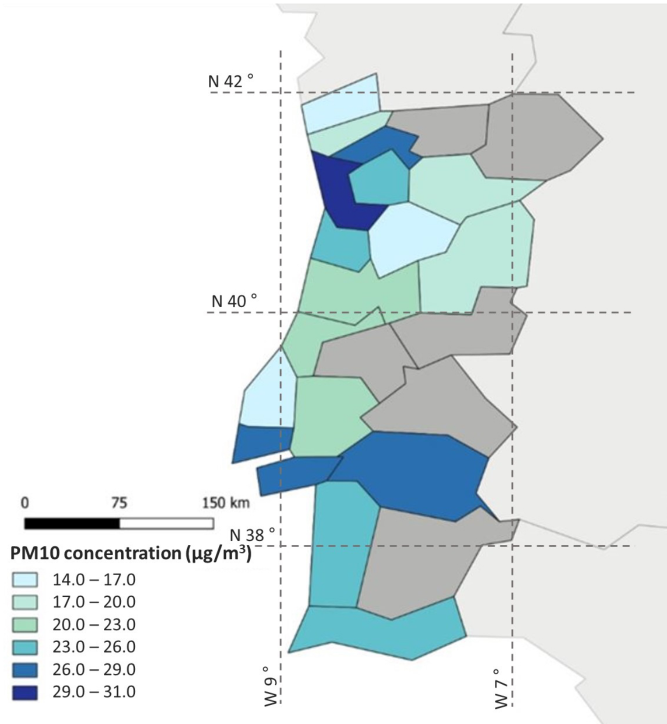

Figure 4. Mean concentration of PM10 ~~(μg m^{-3})~~ by NUTS III from June to September in the period of 2001-2016 in mainland Portugal.

in many months and NUTS III in the target time period there were no deaths for COPD and asthma, it was not possible to obtain a data series large enough to correlate with PM10 and wildfires series.

2.3 Statistical analysis

2.3.1 Correlations between PM10 and burned area

The correlations between PM10 and the total burned area by large fires per month for each NUTS III were estimated using Pearson correlations coefficients (Pearson and Galton, 1895). The Pearson approach, used to correlate two continuous variables having a normal distribution, is widely found in studies of air pollution (e.g. 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 occurrence of large wildfires (burnt area >1,000 ha), with mean monthly mortalities (all-cause, respiratory and cardiovascular causes) were studied for the months of June, July, August and September for the period between 2001 and 2016. The estimates of the effects were obtained for each NUTS III region using Poisson regression models (Faustini et al., 2015; Islam and Chowdhury, 2017). Poisson coefficients can correlate a count variable (such as the number of deaths) with a continuous variable. 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

3.1 Relationship between burned area and particulate matter

For the correlation between the burned area from large fires and PM10, a significant positive correlation was found for 7 (out of 13 with available data) of the studied NUTS III, represented by the dotted areas in the map of Figure 5. For Oeste, Região de Leiria, Beira Baixa, Médio Tejo, Cávado, Ave, Terras de Trás-os-Montes and Alto Tâmega and the four Alentejo NUTS (Alto Alentejo, Alentejo Central, Alentejo Litoral and Baixo Alentejo), there was not enough pollutant and/or burned area data enough to establish statistical relationships. The correlations are strongest for Cávado, Ave, Tâmega e Sousa, Região de Aveiro and Viseu Dão-Lafões, with correlation coefficients above 0.75 at a confidence level of 0.95, followed by Alto Tâmega and Beiras e Serra da Estrela, between 0.5 and 0.74. As expected, all these areas are in the north and center of mainland Portugal, in line with the denser forest cover.

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Finally, in Alto Minho, A.M. Porto, Douro, Região de Coimbra, Região de Leiria and Algarve no significant correlations were found. The limited number of stations in those areas (which means fewer data to correlate), their location (closer or farther from the large wildfire spots) and uneven distribution, and the contribution of other sources for the PM10 levels can be some of the explanations. The location of the air monitoring stations may play a key 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).

3.2 Impact of wildfires on mortality

3.2.1 Mortality overview

The mortality counts for the period 2001-2016 (for the months June to September, 64 months) in mainland Portugal are presented in Table 2, for each NUTS III region and all-cause, cardiovascular and respiratory-related deaths. Results show that

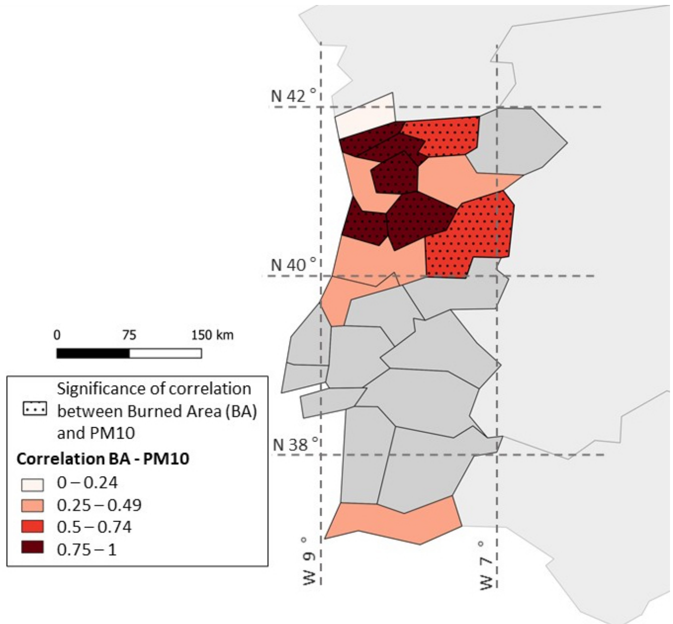

Figure 5. Significance of Pearson correlations between burned area and PM10 for each NUTS III in the period of 2001-2016 (from June to September; dots represent significant correlations at 95% confidence).

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.

Algarve, Alto Minho, Alto Alentejo and A.M. 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.

With respect to cardiovascular mortality, the NUTS III 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, Leizíria do Tejo and Alentejo Litoral are the NUTS III 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). In addition, the aforementioned regions suffer from a considerable afflux of tourists that increase their population in the same period, particularly in 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 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).

Table 2. Mean number of deaths occurring in months affected by large fires (LF) from June to September in the period of 2001-2016 (total of 64 target summer months) in the 23 NUTS III sub-regions of mainland Portugal.

	Natural Deaths (N)	Cardiovasc. deaths (N)	Respiratory deaths (N)					
	NUTS III	All Months	Months w./ LF	All Months	Months w./ LF	All Months	Months w./ LF	Inhabitants (2011)
North	Alto Minho	44434	13213	16586	4731	4975	1293	244149
	Cávado	44307	12832	14136	3931	5964	1471	411028
	Ave	49068	14153	15736	4421	5754	1363	425661
	Alto Tâmega	20527	5324	6687	1864	2298	576	93615
	Terras de Trás-os-Montes	24664	7190	8083	2312	2623	633	116713
	A.M. Porto	221105	64366	67239	18660	24914	6252	1758991
	Tâmega e Sousa	50971	14623	18038	4847	6504	1574	432946
	Douro	39670	11648	13162	3642	4511	1143	204121
Centre	Região de Aveiro	53380	15440	17705	4945	6664	1647	369287
	Viseu Dão-Lafões	48379	14170	17700	4918	6474	1679	266207
	Região de Coimbra	81397	23648	28146	7718	10898	2807	456871
	Beiras e Serra da Estrela	53414	15699	17816	5036	6108	1558	233478
	Região de Leiria	45190	13259	14294	4015	5507	1426	293941
	Médio Tejo	49769	13908	16666	4595	5417	1444	245940
	Beira Baixa	22545	6624	8063	2306	2267	562	88134
	Oeste	60896	17819	22467	6285	6539	1660	362311
A.M. Lisboa		399704	118206	147172	41599	38931	10117	2827050
Alentejo	Leizíria do Tejo	45762	13505	16241	4491	5025	1397	247857
	Alto Alentejo	29145	8622	10391	2957	3690	923	117357
	Alentejo Central	33134	9602	12171	3252	2979	765	165688
	Alentejo Litoral	19241	5681	6916	1972	2294	635	97878
	Baixo Alentejo	30823	8988	11955	3317	3190	875	125875
Algarve		71445	21715	22591	6482	7926	2307	446140

3.2.2 Associations between mortality and PM10

Wildfires are an important source of particulate matter and the associations between mortality, PM10, and the occurrence of large wildfires were assessed in this section. As shown in Figure 6,a, three NUTS III (Alto Tâmega, Beiras e Serra da Estrela, and Viseu Dão-Lafões) present associations between PM10 and all-cause mortality during the studied period. None showed a direct significant association with the occurrence of large fires, likely due to the fact that their contribution to the total burned area in each year from 2001 to 2016 (Table 1) was highly variable (from 12.1% in 2011 to 79.5% in 2003). However, the wildfire origin of PM10 is corroborated by the positive significant correlations obtained for these three NUTS between PM10 and burnt area (Figure 5), with Viseu Dão-Lafões displaying the highest correlations.

Beiras e Serra da Estrela is the NUTS region most affected by large wildfires during the studied period, both in number (50) and respective burned area (>100,000 ha), and Viseu Dão-Lafões is the third in occurrences (28) corresponding to over 58,000 ha burned. This involves high levels of PM10 in a short period of time, which might provoke damage in human health, particularly in an aged population (e.g., for Beiras e Serra da Estrela, 23.8 and 28.7% over 65 years-old in 2001 and 2018, respectively; PORDATA, https://www.pordata.pt)).

In terms of types of diseases, for cardiovascular mortality five NUTS presented associations with PM10: Alto Minho, A.M. Porto, Região de Aveiro, Região de Coimbra, and Algarve (Figure 6,b). Again, no direct significant associations were obtained with the occurrence of large fires. From these five NUTS, only Região de Aveiro showed a significant correlation between PM10 and burned area, revealing the impact of wildfires in the origin of the PM10. For respiratory mortality, only Viseu Dão-Lafões present associations with PM10, for which a strong correlation between PM10 and burned area was found, suggesting again the impact of wildfires on the presence of PM10 (Figure 6,c).

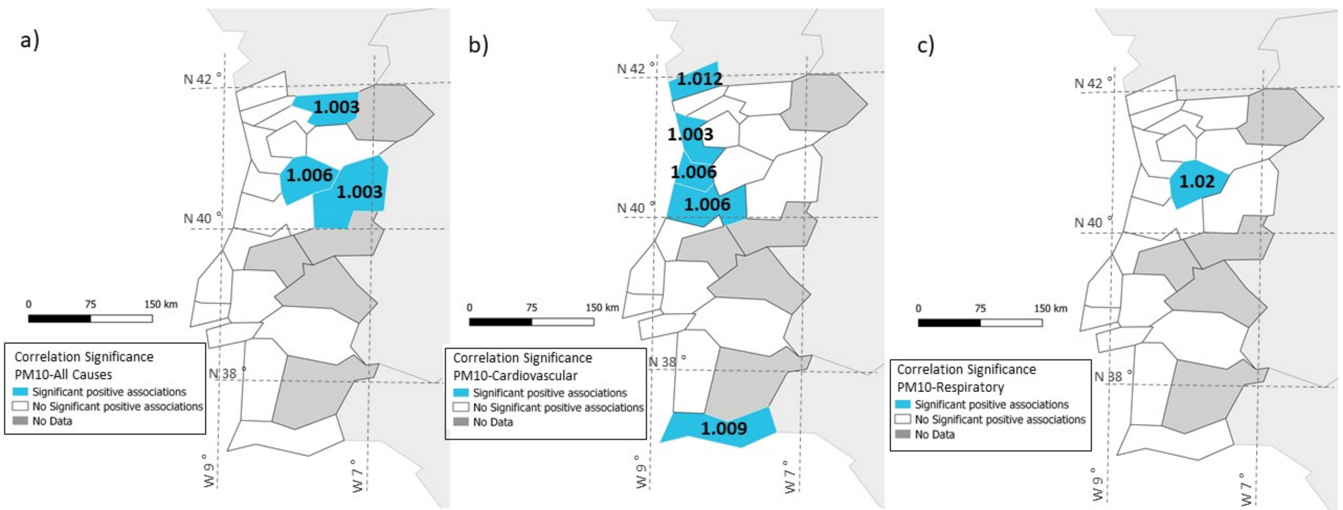

Figure 6. Relative risks (RR, numbers) obtained from Poisson regression for PM10 and (a) all-cause mortality; (b) cardiovascular mortality and (c) respiratory mortality from June to September in the period of 2001-2016 (light blue NUTS III regions indicate a significant result, $p<0.05$); white NUTS 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 shown.

4 Discussion

During the studied period (2001-2016), large fires were responsible for 46% of the more than 2 million ha of forest burned in mainland Portugal. The areas most affected by number and size of wildfires are north, center and inland of the country. Wildfires do not follow a pattern in number of the occurrences or size during the years studied. This evidence was found despite the difficulties that the uneven scattering of the air quality monitoring stations analysing PM10 in Portugal posed. In fact, 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). Unfortunately, the scarce data available and the lack of accuracy in the existing ones prevented us from estimating/including a correction regarding their influence.

Nevertheless, it was possible to find relationships between very relevant parameters. The significant positive correlation between PM10 and burned area found for 7 of the 13 NUTS III with available data is a good indication of where the influence of wildfires on the emission of PM10 is likely to be stronger. Although the location of the air quality monitoring stations may influence these correlations, especially when they are scarcer, for these NUTS it reveals the influence of wildfires on the local levels of PM10.

Large wildfires tend to be active for several days, releasing high amounts of pollutants to the atmosphere. In Portugal, such as in other Mediterranean countries, most of the wildfires are potentiated by strong winds, which may spread the fire smoke over large distances (Turco et al., 2019; Augusto et al., 2020). Thus, air quality monitoring stations located far from the ignition sites can still detect increases in the concentrations of, for instance, PM10. Augusto et al. (2020), while studying the impact of the uncontrolled wildfires of October 2017 in Portugal on the mortality, found that the PM10 and PM2.5 emitted reached the United Kingdom, as well as other northern European countries. Likewise, in Finland, where ambient PM levels are relatively low compared to other countries in Europe, most of the strongest PM pollution episodes are typically related to emissions from wildfires in eastern European countries (Russia, Belarus, Ukraine, Estonia, Latvia and Lithuania) at a distance of hundreds to thousands of kilometres from southern Finland (Niemi et al., 2009; Kollanus et al., 2016).

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). It is an evidence that it 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; Hamanaka and Mutlu, 2018). 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).

In our study, the NUTS III where PM10 concentrations were found to be correlated with the burned area from large fires (Cávado, Ave, Tâmega e Sousa, Região de Aveiro, Viseu Dão-Lafões, Alto Tâmega and Beiras e Serra da Estrela) are indeed the ones where it would be expected to find the strongest influence of the wildfire originated PM10 on the population mortality. And although not for all, indeed associations between all-cause mortality and PM10 were found for three of these NUTS (Alto Tâmega, Viseu Dão-Lafões and Beiras e Serra da Estrela), with RR varying from 1.003 to 1.006; between cardiovascular mortality and PM10 for one (Região de Aveiro), with a RR of 1.006; and between respiratory mortality and PM10 also for one (Viseu Dão-Lafões) with a RR of 1.020. Associations between cardiovascular mortality and PM10 were found for four NUTS (Alto Minho, A.M. Porto, Coimbra and Algarve) where there was no significant correlation of PM10 with burned area. All these are located in the coast, where the population density in Portugal is clearly predominant (particularly in A.M. Porto), as well as considerable industrial presence. In these regions, cardiovascular disease may have many other sources, some of them derived from a more sedentary and stressed lifestyle.

The mortality increase associated with PM10 is consistent with the estimates reported in other European studies, such as APHEA2 (Katsouyanni et al., 2001), APHENA (Samoli et al., 2008), EpiAir (Faustini et al., 2011) and MED-PARTICLES (Faustini et al., 2015), which also reported higher PM10 effects on all-cause, cardiovascular, and respiratory mortalities.

However, some studies present uneven conclusions. Johnston et al. (2011) reported the highest effects on cardiovascular mortality, but Morgan et al. (2010) did not find any consistent effect with cardiovascular deaths in Australia, and Analitis et al. (2012) registered the highest effects on respiratory mortality in Greece. This high variability may be related to several factors, notably: i) different PM composition or varying gaseous emissions (CO, VOCs, NOx or SO_2) from wildfires, which may have different degrees of toxicity on cardiovascular and respiratory systems; or ii) increasing temperature during wildfires, which is known to enhance the effects of PM on more susceptible individuals (e.g., cardiac patients) (Qian et al., 2008). Therefore, the effects we found on all-cause, cardiovascular, and respiratory mortalities during the wildfire seasons may be due to different PM compositions or increasing temperature.

Region-specific associations between PM10 concentrations and mortality were also observed. These may have been influenced by the factors described above (different PM composition and increasing temperature), but also by the magnitude and duration of the exposure to PM from a given fire; the underlying health status of the population; and the size of the population. The age of the exposed individuals can also be important. In some studies, larger effect estimates in groups of 65 years and older have been reported. Analitis et al. (2012) mentioned that the effect of respiratory mortality in Greece was higher in adults of ages 75 and above during large fires, whereas Haikerwal et al. (2015) observed an increase in risk of cardiac arrests, especially in older adults in Australia, although not all resulted in death. In Brazil, Nunes et al. (2013) reported that older adults had the strongest association between exposure to biomass burning and circulatory disease mortality. In Portugal, the regions traditionally impacted by wildfires coincide with a larger percentage of aged population, which can help explaining the obtained associations.

In our analysis, to study the relationship between the burned area and PM10 concentrations, averaged monthly data were used, as the minimum temporal scale available for the burned area was one month. Other studies relating wildfire-originated PM and mortality are usually based on daily PM concentrations and daily death counts, since they do not account for the burned area as a measure of the wildfire size. Therefore, the monthly approach obviously reduced the number of data available and the possibility of finding more significant correlations, which may have diluted the effects of some wildfires on the population mortality. Moreover, some health effects may not have been detected because wildfires are episodic and local events. Nevertheless, the results provide an overall context, highlighting the strongest associations between wildfire generated PM10 and all-cause, cardiovascular, and respiratory mortalities. Being able to achieve them with this uneven distribution of available data is an indication that the approach can be very useful to at least uncover tendencies and, in regions with stronger monitoring capabilities and coverage, a way to find stronger and more accurate correlations. This will help legislators and other government bodies to propose ways to protect the population chronically exposed to wildfires or more susceptible to acute reactions to wildfire smoke.

5 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 relevant associations between PM10 (associated with large wildfires) 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, it was found that large fires (in this study considered above 1,000 ha of burned area) have an impact on the health of the population in some areas due to the emission of particulate matter. The lack of data or possible confounding factors likely prevented a higher number of NUTS III with significant correlations. 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).

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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