



# Health and economic burden of wildland fires PM<sub>2.5</sub>-related pollution in Portugal – A longitudinal study

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## ABSTRACT

Portugal has been affected by wildland fires that destroy thousands of hectares of forest, causing damage to the environment and to the exposed populations. This study aims to assess the influence of wildland fire emissions on air quality, its effect on population health and the related costs, between 2015 and 2018 in Portugal.

The cause-specific mortality due to PM<sub>2.5</sub> was calculated considering the exposure for five endpoints in adults, twelve age groups for adults and considering children under five years old. The contribution of wildfire emissions to PM<sub>2.5</sub> concentrations in Portugal was assessed through EMEP-MSC/W model.

Results showed that the average annual fire emissions of PM<sub>2.5</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and NO<sub>2</sub> a significant and continuous increase was observed during the first three years (2015, 2016 and 2017) for all pollutants, followed by a decrease in 2018, with values lower than those observed in 2015.

Regarding the long-term exposure to PM<sub>2.5</sub> emitted by fires a total of 32, 93, 189 and 31 deaths, corresponding to a cost of 59, 174, 360 and 60 million EUR in 2015, 2016, 2017 and 2018, respectively, were estimated.

On the other hand, in the first three years an increase in years of life lost (YLL) values of 496, 1608 and 3092 was observed, corresponding to a cost of 16, 54 and 105 million EUR, respectively, followed by a decrease in 2018 with a YLL of 480, corresponding to a cost of 17 M€.

## 1. Introduction

In recent years, the number of wildland fires has dramatically intensified across the world, affecting biodiversity, livelihoods, air quality, and public health, causing damage to the environment, animal life and, in some cases, human life. The occurrence of wildland fires has been largely attributed to climate changes, human negligence, gaps in the management and planning of fires and extreme weather phenomena. Specifically, deliberate human ignitions, including cleaning or land management, fuel characteristics, weather conditions (involving the combination of very high temperatures or heat waves), low relative humidity, strong winds, prolonged dry period and lack of soil moisture are the main risk factors assigned to these catastrophes (Castagna et al., 2021; Majdi et al., 2018; Marques et al., 2011). These are increasingly frequent and transversal to different regions of the globe, such as the USA, Australia, Amazon (Brazil) and Mediterranean Europe (southern France, Greece, Italy, Portugal and Spain) (Bowman et al., 2019;

Castagna et al., 2021).

In Mediterranean Europe, in the last decade, about 2,800,286 ha burned, being approximately 42% related to the burned area in Portugal (San-Miguel-Ayanz and Et, 2021). Between 2015 and 2018, more than 819,500 ha were consumed in Portugal (Pordata, 2022), where in 2016, 2017 and 2018 were the years with the largest burned area in the Mediterranean Europe (San-Miguel-Ayanz and Et, 2021). The year of 2017, with severe fires in June and October, was the most devastating, either in burned area, 539.921 ha (the largest burned area since 1980, year from which there are records), and in number of fatalities (112) with no record of such a high number among the civilian population (Pordata, 2022; Viegas et al., 2019).

Wildland fires emit significant amounts of pollutants, including carbon monoxide (CO), nitrogen dioxide (NO<sub>2</sub>), particulate matter (PM), formaldehyde and benzene, that increase air pollution and consequently contribute to the deterioration of health (Domitrovich et al., 2017; Ravi et al., 2019). The scientific community grew interest on this issue given

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the known impacts of air pollution on health, affecting vulnerable populations such as children, pregnant women and elderly, and has been associated to all-cause, cardiovascular and respiratory mortality (Chen and Hoek, 2020; Hvidtfeldt et al., 2019).

Several studies have reported the impact of short-term exposure to PM<sub>2.5</sub> emitted by fires on health, namely mortality, cardiorespiratory effects and hospital admissions (Arriagada et al., 2020; Haikerwal et al., 2015; Henn et al., 2019; Huang et al., 2019; Jones et al., 2020; Ravi et al., 2019; Shi et al., 2019; Stowell et al., 2019; Wettstein et al., 2018). Wettstein et al. (2018) described an association between emergency room (ER) visits due to cardiovascular, cerebrovascular, and respiratory diseases and wildfire smoke density in California, while Arriagada et al. (2020) estimated the number of hospitalisations related to cardiovascular and respiratory diseases, deaths and asthma-related ER visits, related to short-term exposure to PM<sub>2.5</sub> due to wildland fire smoke in Australia. Jones et al. (2020) analysed the association between exposure to PM due to wildland fires and out-of-hospital cardiac arrest in California (USA). Stowell et al. (2019) estimated the link among PM<sub>2.5</sub> short-term exposure and cardiorespiratory acute events in Colorado, using an exposure model that relates emergency department visits and hospitalizations for acute cardiorespiratory outcome. Ravi et al. (2019) used BenMAP to calculate the additional all-cause mortality caused by exposure to PM<sub>2.5</sub> from prescribed fires in the Pacific Northwest region of the United States, estimating that only prescribed fires caused 280 to 700 additional deaths. Huang et al. (2019) quantified the impact of prescribed fires on human health, in Georgia (USA) during the fire seasons of 2015–2018, through the asthma-related ER visits, estimating an increase in the number of ER for asthma due to fire impacts. Shi et al. (2019) evaluated the impact on air quality of wildfires that occurred in December 2017 in Southern California, using the Weather Research and Forecasting model with Chemistry, combined with satellite and surface observations. The results showed that PM<sub>2.5</sub> concentrations increased significantly, exceeding the U.S. air quality limits, indicating that this fire contributed to the acute and cumulative exposure of PM<sub>2.5</sub> in this region, which can cause premature death and cardiovascular effects in the exposed population (Shi et al., 2019). Zhang et al. (2023) also evaluated the effect of wildland fire-related PM<sub>2.5</sub> exposure, but in pregnant women, indicating an increase in the number of preterm birth or low birth weight.

Specifically in Portugal, few studies evaluated the impact of wildland fire smoke on air quality either considering prescribed fires (Miranda et al., 2010) or real episodes (Martins et al., 2012; Monteiro et al., 2013; Slezakova et al., 2013; Vicente et al., 2011). Moreover, as far as known, only three of these studies evaluated their impact on health (Esteves et al., 2021; Miranda et al., 2012; Oliveira et al., 2016, 2020). Oliveira et al. (2020) estimated the impact of PM<sub>10</sub> short-term exposure on asthmatic symptoms in asthmatic children, and to PM<sub>2.5</sub> on the number of hospital admissions due to cardiovascular diseases, as well as mortality in adults (all natural causes), showing an increase during these episodes. Augusto et al. (2020) evaluated the long-range transport of PM<sub>10</sub> and its association to the mortality of the exposed population, only due to the October 2017 wildland fires, suggesting that PM<sub>10</sub> concentrations had a significant effect on the number of natural deaths and cardiorespiratory mortalities. Finally, a previous study performed by Barbosa et al. (2022), evaluated long-term exposure of 2017 wildland fires on asthmatic children, through the effect of long-term exposure to PM<sub>10</sub> and NO<sub>2</sub> concentrations on postneonatal mortality, bronchitis symptoms and their prevalence and associated costs. The results obtained showed that the wildfires smoke considerably impacted lung function of children, both on morbidity and mortality (Barbosa et al., 2022).

On the other hand, studies combining health impact and their associated costs are even scarcer. Johnston et al. (2020) compared the wildland fire smoke related health costs in Australia during 20 fire seasons (2000–2020), while Fann et al. (2018) calculated the economic cost of wildland fire PM<sub>2.5</sub> impacts associated to premature deaths and

to respiratory hospital admissions in US over 5 years (2008–2012). Matz et al. (2020) estimated the health impacts and the associated costs attributable to wildland fires-PM<sub>2.5</sub> in Canada, during 2013–2015 and 2017–2018. Recently, (Wu et al., 2023) quantified the costs of premature deaths due to PM<sub>2.5</sub> associated to wildland fires in Brazil between 2000 and 2016.

While the majority of the aforementioned studies described the health effects of short-term exposure to smoke from wildland fires, as far as known only one study has evaluated these long-term effects in Portugal (Barbosa et al., 2022). Nevertheless, this study was only performed for one year, and the health outcomes considered were only for children. Moreover, only this study performed their valuation. To overcome this gap, the present study aims to evaluate the effect of emissions from wildfires on air quality, its effect on population health and their related costs, between 2015 and 2018 in Portugal.

## 2. Methods

### 2.1. Study area

Portugal is placed in the extreme southwest of continental Europe, by the Atlantic Ocean on the north, west, and southwest (MNE, 2023). It is organised into 18 Districts that represent a total area of around 90,000 km<sup>2</sup>.

In Portugal the fire season usually occurs between June and October, a period when high temperatures and low relative humidity are usually recorded. Usually, the most affected regions are those located inland, which typically reach very high temperatures at this time of the year.

Environmental conditions oscillate significantly from north to south of the country, and according to the season. The maximum average annual temperatures and the total annual precipitation recorded were 21.5 °C and 599.6 mm (2015), 21.3 °C and 991.6 mm (2016), 22.5 °C and 541.3 mm (2017) and 20.9 °C and 939.9 mm (2018) (Pordata, 2020, 2021). The year of 2017 was recorded as the warmest and driest in most regions between 2015 and 2018 (Pordata, 2021).

### 2.2. PM<sub>2.5</sub> fire-related concentrations

The influence of fire emissions in the concentrations of PM<sub>2.5</sub> in Portugal in 2015, 2016, 2017, and 2018 was performed using EMEP/ MSC-W, the open-source chemistry transport model (version rv4.17). This model was already used successfully to estimate the health and economic costs of fire emissions in Portugal and was validated in a previous study by Barbosa et al. (2022). Additionally, information about EMEP/ MSC-W can be found in Simpson et al. (2012). The potential impact of wildfire emissions was evaluated for each year, and the model was run for the two scenarios considered by Barbosa et al. (2022), i.e., one scenario including wildfire emissions, anthropogenic emissions, and other natural emissions (F-SCN) and a reference scenario, excluding wildfire emissions (B-SCN). The fire emissions for the different years were obtained from the Fire INventory from NCAR (FINN) (Wiedinmyer et al., 2010). EMEP's emissions database, WebDab, was used to obtain data on emissions from industry, road traffic, public power, and other sectors, for the same years as the fire emission inventories (EMEP/CEIP, 2018). For the simulations for the year 2018, the emissions of other sources from the year 2017 were used, as the emissions for this year were not available. Sahara dust emissions and NO<sub>x</sub> from lightning were also considered (Simpson et al., 2012). The meteorological data for each year was generated with the Weather Research & Forecast (WRF) atmospheric model.

### 2.3. Health impact evaluation

The health impacts of wildland fires were calculated based on the two scenarios mentioned above. Detailed information on the two scenarios can be found in Barbosa et al. (2022). The increased number of

deaths associated with long-term exposure to PM<sub>2.5</sub> emitted by wildfires, was evaluated using the integrated exposure–response functions (IERs) designed by Burnett et al. (2014) based on Arden et al. (2011, 2009). This methodology was chosen because to date, the IERs are the approach that provides most guarantees considering the epidemiological findings regarding the effects of PM<sub>2.5</sub> on mortality (Nunes et al., 2021). Thus, the mortality associated with specific causes, attributed to PM<sub>2.5</sub>, was calculated using the following approach: i) assessing exposure for five health endpoints in adults (stroke, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), and lung cancer (LC)); ii) considering 12 age groups (specifically for IHD and stroke); and iii) considering children under 5 years old (acute respiratory lung infection (ALRI)). The methodology employed to determine the relative risks for IERs, which were used to estimate cause-specific mortality due to PM<sub>2.5</sub>, as well as the excess mortality measured by the increase in the number of deaths and years of life lost (YLLs), can be found in Nunes et al. (2021). Population data for Portugal, categorized by year of age and local administrative units (LAU2) level (civil parish), was obtained from the Eurostat 2011 Census database hub (European Statistical System Census Hub, 2011 Census Database, 2018).

### 2.4. Evaluation of external socio-economic costs

The health burdens were evaluated by multiplying the IERs (Incremental Exposure Risks) with the respective unit health costs (cost per death or YLL). The costs associated with exposure-related deaths and YLLs were calculated for 2015, 2016, 2017, and 2018 using the methodology described by Barbosa et al. (2022). Similar to the Barbosa et al. (2022) study, mortality was assessed using the value of statistical life (VSL), while the value of a life year (VOLY) was used to assess the YLL. The Portuguese VSL value for 2015 was obtained from health economic assessment tools and updated for 2016, 2017, and 2018. The unit values employed are summarized in Table 1.

For the economic assessment of mortality due to air pollution in Europe the VOLY was used according to the study described by Desaiques et al. (2011) and updated to 2015, 2016, 2017 and 2018 using the same methodology used by Barbosa et al. (2022).

## 3. Results

### 3.1. Contribution of wildland fire emissions to PM<sub>2.5</sub> concentrations

Table 2 shows the annual mean emissions of PM<sub>2.5</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and NO<sub>2</sub> from wildland fires obtained in Portugal between 2015 and 2018. Comparing the first three years, a significant and continuous increase (approximately double from year to year) was observed until 2017 for all pollutants, followed by an accentuated decrease in 2018, with values lower than those observed in 2015.

The annual mean emissions were in line with the burned area in Portugal (Fig. S1 Supplementary Material), which also maintained the same increase profile.

Fig. 1 shows the spatial distribution of total annual fire emissions for Portugal in 2015, 2016, 2017 and 2018. As can be seen through the spatial distribution, the total fire emissions increased from year to year, except during 2018, which decreased significantly.

In general, the geographic areas with the highest emission of

**Table 1**  
Unit cost values for value of statistical life (VSL) and value of a life year (VOLY).

Parameter	Value of Statistical Life (VSL)	Value of Life Year (VOLY)
Unit value for 2015	1.83	32,611
Unit value for 2016	1.87	33,280
Unit value for 2017	1.90	33,946
Unit value for 2018	1.94	34,609
Units	Million €/death	€/life lost year

**Table 2**

Annual mean emissions of PM<sub>2.5</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and NO<sub>2</sub> from Portuguese wildland fires between 2015 and 2018.

	PM <sub>2.5</sub> (ton/ year)	CO (ton/ year)	CH <sub>4</sub> (ton/ year)	CO <sub>2</sub> (ton/ year)	NO <sub>2</sub> (ton/ year)	Total (ton/ year)
2015	10,841	86,371	3,521	1,732,821	2,188	1,835,742
2016	22,750	179,101	7,196	3,667,549	4,594	3,881,191
2017	40,011	305,191	12,041	6,514,194	7,883	6,879,320
2018	6,558	54,367	2,205	1,141,159	1,445	1,205,733

pollutants corresponded to the locations where wildland fires occurred in higher number (largest burned area).

Although more significant in 2016, the spatial distribution of fire emissions in 2015 and 2016 were almost focused in the North region. On the other hand, in 2017 it was clearly verified, that the emission of pollutants was almost exclusively on the Centre region, near the area where the two major wildland fires occurred (on June and October). Generally, the regions most devastated by wildland fires in the years analysed were the North and Centre regions.

The spatial distribution of the cause-specific mortality (five health-endpoints) and the contribution of wildland fire emissions to the annual mean concentrations of PM<sub>2.5</sub> for the four years is shown in Fig. 2.

In 2015, the increase in PM<sub>2.5</sub> concentrations ranged between 0.0 and 0.4 µg m<sup>-3</sup>, between 0.0 and 0.70 µg m<sup>-3</sup> in 2016, between 0.0 and 1.4 µg m<sup>-3</sup> in 2017 and between 0.0 and 0.5 µg m<sup>-3</sup> in 2018, following the trend observed for the emissions.

Fig. 2 also shows the cause-specific mortality spatial distribution (five health-endpoints) due to PM<sub>2.5</sub> wildland fire for 2015, 2016, 2017 and 2018 in Portugal at parish level. Once again, as can be seen by the spatial distribution, the regions most affected by wildland fires were the North and Centre regions, being the health impact due to fire-related PM<sub>2.5</sub> worse for more severe fires.

The estimated years of life lost (YLL) and associated costs related to wildland fires that occurred during 2015, 2016, 2017 and 2018 are shown in Table 3. The results were also estimated based on the above-referred five health end-points (IHD, stroke, COPD, LC and ALRI).

Comparing with the previous results, and as expected, the estimated values showed that YLL increased during the first three years 496, 1608 and 3092, corresponding to a cost of 16, 54 and 105 M€, respectively, followed by a decrease in 2018 with a YLL of 480, corresponding to a cost of 17 M€.

## 4. Discussion

This longitudinal study (between 2015 and 2018) estimated the impacts of Portuguese wildland fires on human health and their associated costs. The results showed that the average annual emissions of PM<sub>2.5</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and NO<sub>2</sub>, increased significantly and continuously during the first three years (2015–2017) for all pollutants, followed by a decrease in 2018, with values lower than those observed in 2015. The same trend was observed for PM<sub>2.5</sub> concentrations. In 2018, the number of wildland fires vs burned area was considerably lower, since, after the tragic year of 2017, there was a greater consciousness and implementation of preventive measures imposed by the government, such as the obligation to clean land and charges for non-compliant landowners. It is important to mention that in 2018 the annual mean maximum temperatures were slightly lower and the average relative humidity during the fire season were higher (ranging between 60 and 75%) than in the other years, which probably also contributed to the lower number of wildland fires and consequently, lower burned area (IPMA, 2018; Pordata, 2021).

On the other hand, the results confirmed that fires tend to occur in inland areas of Portugal, which, unlike coastal areas that are more populated, are usually rural areas, with lower population density

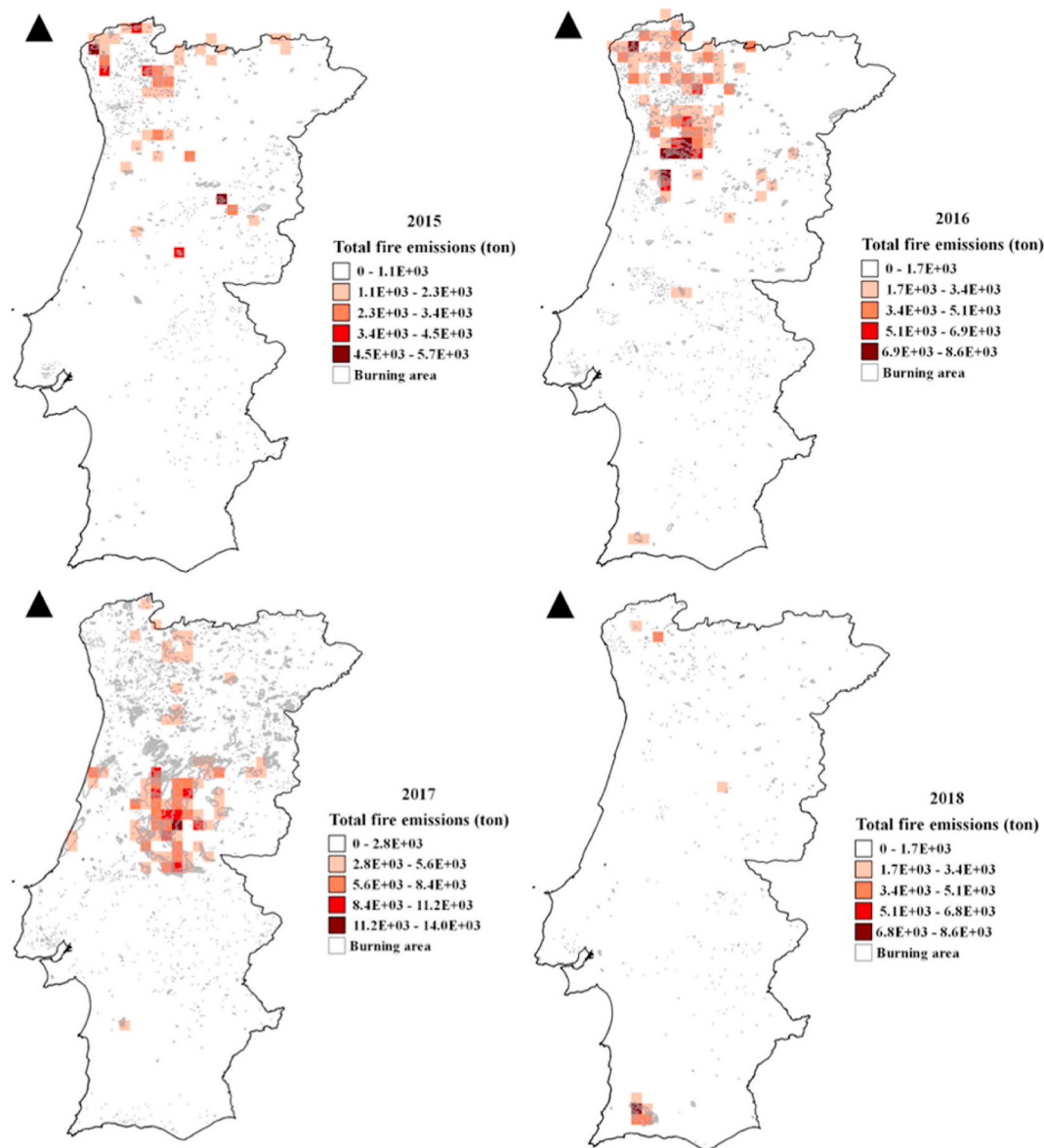


Fig. 1. Spatial distribution of total annual fire emissions in the study domain for 2015, 2016, 2017 and 2018 in Portugal. Total fire emissions are in ton. The burnt area is represented in grey.

(Fig. S2), Fig. S1, but with a greater extension of forest and wood.

Sometimes, some air pollution events can occur (such as natural phenomena as wildfires or Sahara Desert), characterized by high levels of pollutants, with variable duration, which often exceed the daily limit concentrations and can affect human health. Several studies indicated that  $PM_{2.5}$ ,  $PM_{10}$  and CO concentrations increased substantially during fire episodes, most often exceeding the legislated levels (Haikerwal et al., 2015; Henn et al., 2019; Larsen et al., 2018). Also, Oliveira et al. (2020) and Augusto et al. (2020) reported that  $PM_{10}$  and  $PM_{2.5}$  concentrations increased enormously during the 2017 major fires in Portugal, thus putting the health of the exposed population at increased risk. It is well known that exposure to  $PM_{2.5}$  has an adverse effect on health and depending on its toxicology can have different consequences, and in the worst case scenario can cause death (Augusto et al., 2020; Stowell et al., 2019). According to Stowell et al. (2019), smoke from fires produces higher amounts of  $PM_{2.5}$  than urban environments (without contribution from fires). On the other hand, the presence of methanol and formaldehyde has been detected in smoke from fires, in higher amounts than in particles from urban environments (Liu et al., 2017). In

the present study, the increase in the annual mean concentrations of  $PM_{2.5}$  was assigned to the evolution and to the severity of wildland fires (Pordata, 2022). The increase in the severity of wildland fires observed in recent years is not exclusive to Portugal, but a global issue, often associated with climate change and extreme weather phenomena (Aguilera et al., 2021; Asbi et al., 2020; Castagna et al., 2021; EEA, 2021). Climate change models predict that the effect of climate change will bring forward the start of the fire season and that it will end later, leading to a significant increase in the number of days with meteorological conditions favourable to the occurrence of high-intensity wildland fires (Aparício et al., 2022). In addition, and depending on the global warming scenario (1.5, 2 or 3 °C), Costa et al. (2020) estimated an increase in the number of days with high to extreme fire danger from around 10 to more than 40 days per year for Portugal and Spain. Moreover, one of the most used measure to manage the extent of the wildfire is the use of prescribed fire, and its feasibility, according to Davim et al. (2022), is being affected by climate change which elevates the apparent need to scale-up fuel management efforts.

Regarding the results obtained for the YLL and related costs due to

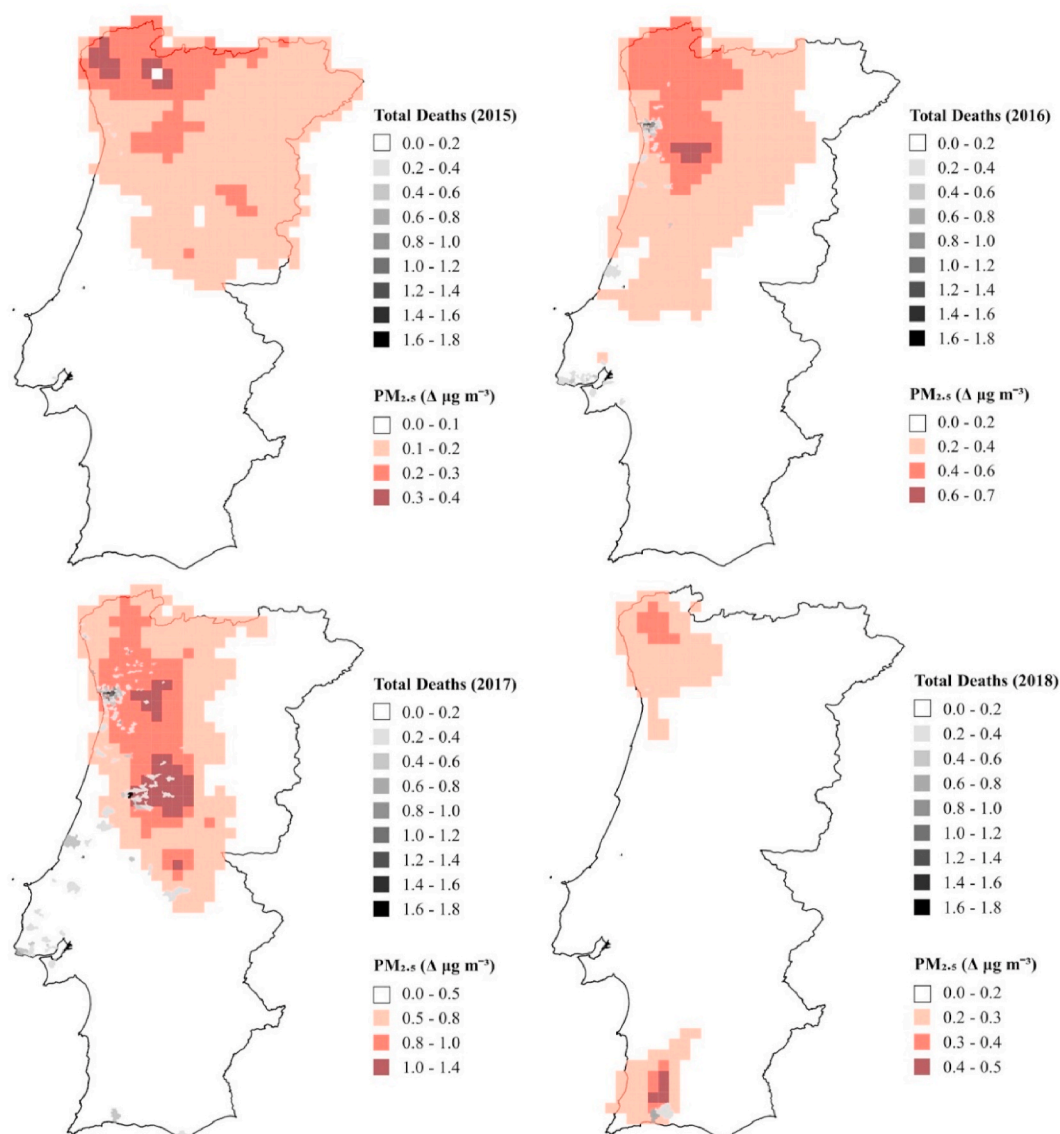


Fig. 2. Spatial distribution of the cause-specific mortality (five health-endpoints) and of the contribution of wildland fire emissions to annual mean concentrations of PM<sub>2.5</sub> for 2015, 2016, 2017 and 2018 in Portugal (Δ = S-SCN – B-SCN). Concentrations were calculated in μg m<sup>-3</sup>.

**Table 3**  
Years of life lost (YLL) and related costs due to wildland fires for Portugal in 2015, 2016, 2017 and 2018.

Health Endpoint		YLL		2016		2017		2018	
		2015	Costs (M€ <sup>a</sup> )	(95% CI)	Costs (M€ <sup>a</sup> )	(95% CI)	Costs (M€ <sup>a</sup> )	(95% CI)	Costs (M€ <sup>a</sup> )
PM <sub>2.5</sub>	Cause-specific Total <sup>b</sup>	496	16	1608	54	3092	105	480	17

<sup>a</sup> M€ - Million.

<sup>b</sup> Cause-specific total calculated based on IHD, Stroke, COPD, LC and ALRI.

wildland fires an increase during the first three years, followed by a decrease in 2018 were also observed. Similar results were achieved by Matz et al. (2020) who evaluated the costs associated with health impacts, both acute and chronic, due to wildfire-PM<sub>2.5</sub> smoke exposure in Canada during 2013–2015 and 2017–2018, estimating values of €388M-€1.7B and €4.1B-\$18B per year, respectively, during the study period. The estimates made for the five years showed that the greatest health impacts were also estimated for 2017 (Matz et al., 2020). The same trend was found by Johnston et al. (2020), who compared the wildland fire smoke related health costs in Australia during 20 fire

seasons (2000–2020), concluding that the health costs were highest (€1.19 billion) in 2019–2020 season when the concentrations of PM<sub>2.5</sub> were also higher. On the other hand, Fann et al. (2018) calculated the economic costs of wildland fire PM<sub>2.5</sub> associated to premature deaths and respiratory hospital admissions in US over 5 years (2008–2012), estimating a long-term exposure value between €70 and €119 billion per year.

In the present study, the health costs related to premature deaths from wildland fire smoke exposure represented approximately 0.35%, 0.99%, 1.97% and 0.31% of Portugal’s GDP (allocated to health

expenditure) in 2015, 2016, 2017 and 2018, respectively, evidencing a huge increase in 2017, when compared to the other years. These results are in accordance with those mentioned above, as all showed that the health economic burden related to wildland fire smoke costs are greatest in the most severe wildfire seasons, as happened in Portugal in 2017. On the other hand, compared to the results reported by Wu et al. (2023), who calculated the costs related to premature deaths due to PM<sub>2.5</sub> exposure from wildland fires in Brazil between 2000 and 2016, estimating a total of €75.11 billion in economic losses (€4.70 billion per year), representing 0.68% of economic losses which is equivalent to approximately 0.14% of Brazil's GDP, the values were considerably higher for the 4 years.

In Portugal, after the catastrophic fires of 2017, the government, public and private entities, and the general population became more aware of the issues related to the wildland fires. In the following years, awareness-raising actions were carried out and prevention and mitigation measures were implemented, such as the obligation to clean forests and private land (subject to fines in case of non-compliance), and more recently, operational teams were reinforced during fire seasons.

## 5. Limitations

There are limitations and uncertainties inherent to methodology followed that should be discussed (WHO Regional Office for Europe, 2016; World Health Organization, 2014). The EMEP-MSC/W model was already used successfully to estimate the health and economic impact of wildland fire emissions in Portugal, providing a good spatial correlation for PM<sub>2.5</sub> concentration due to wildfires in Portugal (Barbosa et al., 2022). However, using multiple factors to calculate emissions, such as active fires, burned area, biomass loading and emission factors to calculate daily open burn emissions with a spatial resolution of 1 km (Wiedinmyer et al., 2010), increases uncertainties. Thorough information can be found in Barbosa et al. (2022).

Another limitation pertains to the distribution of the population being studied at the parish level and the availability of baseline incidences, which were only accessible at the country level. However, to reduce uncertainty regarding concentrations at parish level, an assumption was made to evenly distribute the population among the parishes. Regarding population data, the latest data available refer to 2021 (censuses 2021), however, it was decided to perform the analysis based on the 2011 censuses, as it was assumed that for the period studied (2015–2018) the population was better represented by the 2011 censuses. Additionally, residential mobility was not considered, which may increase the inaccuracies.

The methodology used in health impact assessment has limitations and uncertainties that should be discussed (WHO Regional Office for Europe, 2016; World Health Organization, 2014). Concerning the choice of pollutants, PM<sub>2.5</sub> was evaluated in the present study, since due to its small size and composition (determinants in its toxicity), it was identified as the best individual indicator of the health risks due to smoke from biomass combustion sources. There are some evidence that the emission of particulate matter existing in smoke from vegetative biomass is essentially composed by smaller particles (aerodynamic diameter of 0.1–2 µm), which easily penetrate deeper into the lungs (Domitrovich et al., 2017). PM is one of the most used and accepted indicators by the scientific community, however it is difficult to understand which of its components (sulfate, nitrate, black carbon, metals and organic components) is more toxic, and which has a greater impact on health. Anyway, using them as a group rather than individually, may provide more consistent results (Chen et al., 2022).

The associations between PM<sub>2.5</sub> exposure and mortality from IHD, stroke, lung cancer, COPD and ALRI were estimated using the IERs developed by Burnett et al. (2014). Those were developed by the GBD (Global Burden of Disease) initiative and pool evidence from different studies of long-term exposure to PM<sub>2.5</sub> (including exposure to outdoor air pollution, to passive and active smoking and to household air

pollution), to estimate the risk of environmental air pollution (Burnett et al., 2014; World Health Organization, 2014). As far as known, IERs represents the best available method to estimate PM<sub>2.5</sub> mortality impacts, however, cause-specific IERs may not be suitable for PM<sub>2.5</sub> emitted by wildland fires. Moreover, PM<sub>2.5</sub> annual average concentration may not adequately represent the regions exposed to wildland fires during fire season, inducing residual confounding (Roberts and Wooster, 2021). Finally, although the toxicity of PM<sub>2.5</sub> may vary according to the different sources of combustion (leading to different compositions), in this approach this was not considered to assess the toxicity, only the magnitude of exposure was considered.

Undoubtedly, there were inherent uncertainties associated with the assumptions made regarding the costs associated with health impacts. The estimation of VOLY and VSL values relied on the Willingness to Pay (WTP) technique. However, it is important to note that the effectiveness of this technique relies on the sensitivity of each individual, as it involves conducting personal interviews to gauge the amount that individuals are willing to pay to mitigate the risk of premature death. This factor introduces an element of increased uncertainty. To mitigate this uncertainty, the values were adjusted using the benefit transfer approach, which, among others, adjusts the values based on income differences between countries, inflation and income growth over time, considering the differences for each year (WHO, 2017). The VSL default values were calculated based on the OECD report (OECD, 2012), internationally recognized as offering the most evidence, and was adapted based on agreed values for Portugal.

## 6. Conclusions

This study is the first attempt to perform a longitudinal study (2015–2018) estimating the impacts of Portuguese wildland fires on human health and their economic burden. Regarding the annual mean fire emissions of PM<sub>2.5</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and NO<sub>2</sub> a significant and continuous increase during the three first years (2015, 2016 and 2017) was observed for all pollutants, followed by a decrease in 2018, with values lower than those observed in 2015. In 2018, the burned area was considerably lower, the lowest of the 4 years studied, probably due to the annual average maximum temperatures that were slightly lower, but also because after the tragic year of 2017, there was a greater awareness and implementation of preventive measures imposed by the government.

The long-term exposure to PM<sub>2.5</sub> from wildfires impacted human health, and estimated to have caused a total of 31–189 deaths, corresponding to a cost of 59–360 million €, in the studied years, considering the five health end-points (IHD, stroke, COPD, LC and ALRI). In future studies it would be interesting to include other health end-points associated with morbidity and mortality due to exposure to smoke from wildland fires, as for example heart failure which is growing and is costly.

Scientific knowledge about wildland fires along with climate change suggests that wildland fires may occur with greater frequency and severity. Thus, developing strategies that promote fire prevention, the awareness and action of the local population and land owners and other stakeholders are of huge importance, in order to implement sustainable management measures that allow, among others, a reduction in the intensity of fires, and their health consequences.

## Credit author statement

J.V.B.: Conceptualization, Investigation, Formal analysis, Writing - original draft; R.A.O.N. Data curation, Formal analysis; M.C.M.A.-F. and F.G.M.: Writing - review & editing; S.I.V.S.: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation; Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2023.117490>.

## References

- Aguilera, R., Corringham, T., Gershunov, A., Benmarhnia, T., 2021. Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nat. Commun.* 12 <https://doi.org/10.1038/s41467-021-21708-0>.
- Aparício, B.A., Santos, J.A., Freitas, T.R., Sá, A.C.L., Pereira, J.M.C., Fernandes, P.M., 2022. Unravelling the effect of climate change on fire danger and fire behaviour in the Transboundary Biosphere Reserve of Meseta Ibérica (Portugal-Spain). *Clim. Change* 173, 1–20. <https://doi.org/10.1007/s10584-022-03399-8>.
- Arriagada, N.B., Palmer, A.J., Bowman, D.M.J.S., Morgan, G.G., Jalaludin, B.B., Johnston, F.H., Arriagada, N.B., Palmer, A.J., Bowman, D.M.J.S., Morgan, G.G., Jalaludin, B.B., Johnston, F.H., 2020. Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia - supporting information. *Med. J. Aust.* 2019–2020. <https://doi.org/10.5694/mja2.50545>.
- Asbi, A., Ramiah, V., Yu, X., Wallace, D., Moosa, N., Reddy, K., 2020. The determinants of recovery from the Black Saturday bushfire: demographic factors, behavioural characteristics and financial literacy. *Account. Finance* 60, 15–46. <https://doi.org/10.1111/acfi.12575>.
- Augusto, S., Ratola, N., Tarín-Carrasco, P., Jiménez-Guerrero, P., Turco, M., Schuhmacher, M., Costa, S., Teixeira, J.P., Costa, C., 2020. Population exposure to particulate-matter and related mortality due to the Portuguese wildfires in October 2017 driven by storm Ophelia. *Environ. Int.* 144, 106056 <https://doi.org/10.1016/j.envint.2020.106056>.
- Barbosa, J.V., Nunes, R.A.O., Alvim-ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2022. Health and economic burden of the 2017 Portuguese extreme wildland fires on children. *Int. J. Environ. Res. Publ. Health* 19 (1), 593. <https://doi.org/10.3390/ijerph19010593>.
- Bowman, D.M.J.S., Moreira-Muñoz, A., Kolden, C.A., Chávez, R.O., Muñoz, A.A., Salinas, F., González-Reyes, Á., Rocco, R., de la Barrera, F., Williamson, G.J., Borchers, N., Cifuentes, L.A., Abatzoglou, J.T., Johnston, F.H., 2019. Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires. *Ambio* 48, 350–362. <https://doi.org/10.1007/s13280-018-1084-1>.
- Burnett, R.T., Arden Pope, C., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Ross Anderson, H., Smith, K.R., Balmes, J.R., Bruce, N.G., Kan, H., Laden, F., Prüss-Ustün, A., Turner, M.C., Gapstur, S.M., Diver, W.R., Cohen, A., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* 122, 397–403. <https://doi.org/10.1289/ehp.1307049>.
- Castagna, J., Senatore, A., Bencardino, M., D'Amore, F., Sprovieri, F., Pirrone, N., Mendicino, G., 2021. Multiscale assessment of the impact on air quality of an intense wildfire season in southern Italy. *Sci. Total Environ.* 761, 143271 <https://doi.org/10.1016/j.scitotenv.2020.143271>.
- Chen, J., Hoek, G., 2020. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. *Environ. Int.* 143, 105974 <https://doi.org/10.1016/j.envint.2020.105974>.
- Chen, J., Hoek, G., de Hoogh, K., Rodopoulou, S., Andersen, Z.J., Bellander, T., Brandt, J., Fecht, D., Forastiere, F., Gulliver, J., Hertel, O., Hoffmann, B., Hvidtfeldt, U.A., Verschuren, W.M.M., Jöckel, K.-H., Jørgensen, J.T., Katsouyanni, K., Ketzel, M., Méndez, D.Y., Leander, K., Liu, S., Ljungman, P., Faure, E., Magnusson, P.K.E., Nagel, G., Pershagen, G., Peters, A., Raaschou-Nielsen, O., Rizzato, D., Samoli, E., van der Schouw, Y.T., Schramm, S., Severi, G., Stafoggia, M., Strak, M., Sørensen, M., Tjønneland, A., Weinmayr, G., Wolf, K., Zitt, E., Brunekreef, B., Thurston, G.D., 2022. Long-term exposure to source-specific fine particles and Mortality—A pooled analysis of 14 European cohorts within the ELAPSE Project. *Environ. Sci. Technol.* <https://doi.org/10.1021/acs.est.2c01912>.
- Costa, H., de Rigo, D., Libertà, G., Houston Durrant, T., San-Miguel-Ayanz, J., 2020. European Wildfire Danger and Vulnerability in a Changing Climate: towards Integrating Risk Dimensions. <https://doi.org/10.2760/46951>.
- Davim, D.A., Rossa, C.G., Pereira, J.M.C., Fernandes, P.M., 2022. Evaluating the effect of prescribed burning on the reduction of wildfire extent in Portugal. *For. Ecol. Manage.* 519.
- Domitrovich, J.W., Broyles, G.A., Ottmar, R.D., Reinhardt, T.E., Naeher, L.P., Kleinman, M.T., Navarro, K.M., Mackay, C.E., Adetona, O., 2017. Wildland fire smoke health effects on wildland firefighters and the public. *Final Rep 1–11*.
- EEA, 2021. European Environment Agency. <https://www.eea.europa.eu/ims/forest-fire-s-in-europe>.
- EMEP/CEIP, 2018. <https://www.ceip.at/the-emep-grid/gridded-emissions>.
- Esteves, F., Madureira, J., Teixeira, J.P., Costa, S., 2021. Assessment of Potential Health Risks of Portuguese Wildland Firefighters' Occupational Exposure: Biomonitoring Approach, pp. 31–36.
- European, 2018. Statistical System Census Hub 2011 Census Database. <https://ec.europa.eu/CensusHub2/query.do?step=selectHyperCube&qhc=false>.
- Haikerwal, A., Akram, M., Monaco, A., Del, Smith, K., Sim, M.R., Meyer, M., Tonkin, A. M., Abramson, M.J., Dennekamp, M., 2015. Impact of fine particulate matter (PM<sub>2.5</sub>) exposure during wildfires on cardiovascular health outcomes. *J. Am. Heart Assoc.* 4, 1–10. <https://doi.org/10.1161/JAHA.114.001653>.
- Henn, S.A., Butler, C., Li, J., Sussell, A., Hale, C., Broyles, G., Reinhardt, T., 2019. Carbon monoxide exposures among U.S. wildland firefighters by work, fire, and environmental characteristics and conditions. *J. Occup. Environ. Hyg.* 16, 793–803. <https://doi.org/10.1080/15459624.2019.1670833>.
- Huang, R., Hu, Y., Russell, A.G., Mulholland, J.A., Odman, M.T., 2019. The impacts of prescribed fire on PM<sub>2.5</sub> air quality and human health: application to asthma-related emergency room visits in Georgia, USA. *Int. J. Environ. Res. Publ. Health* 16. <https://doi.org/10.3390/ijerph16132312>.
- Hvidtfeldt, U.A., Sørensen, M., Geels, C., Ketzel, M., Khan, J., Tjønneland, A., Overvad, K., Brandt, J., Raaschou-Nielsen, O., 2019. Long-term residential exposure to PM<sub>2.5</sub>, PM<sub>10</sub>, black carbon, NO<sub>2</sub>, and ozone and mortality in a Danish cohort. *Environ. Int.* 123, 265–272. <https://doi.org/10.1016/j.envint.2018.12.010>.
- IPMA, 2018. Apoio Meteorológico Na Prevenção E Combate Aos Incêndios Florestais.
- Jones, C.G., Rappold, A.G., Vargo, J., Cascio, W.E., Kharrazi, M., McNally, B., Hoshiko, S., 2020. Out-of-hospital cardiac arrests and wildfire-related particulate matter during 2015–2017 California wildfires. *J. Am. Heart Assoc.* 9, 19–22. <https://doi.org/10.1161/JAHA.119.014125>.
- Larsen, A.E., Reich, B.J., Ruminiski, M., Rappold, A.G., 2018. Impacts of fire smoke plumes on regional air quality, 2006–2013 article. *J. Expo. Sci. Environ. Epidemiol.* 28, 319–327. <https://doi.org/10.1038/s41370-017-0013-x>.
- Liu, X., Huey, L.G., Yokelson, R.J., Selimovic, V., Simpson, I.J., Müller, M., Jimenez, J.L., Campuzano-Jost, P., Beyersdorf, A.J., Blake, D.R., Butterfield, Z., Choi, Y., Crouse, J.D., Day, D.A., Diskin, G.S., Dubey, M.K., Fortner, E., Hanisco, T.F., Hou, W., King, L.E., Kleinman, L., Meinardi, S., Mikoviny, T., Onasch, T.B., Palm, B.B., Peischl, J., Pollack, I.B., Ryerson, T.B., Sachse, G.W., Sedlacek, A.J., Shilling, J.E., Springston, S., St Clair, J.M., Tanner, D.J., Teng, A.P., Wennberg, P.O., Wisthaler, A., Wolfe, G.M., 2017. Airborne measurements of western U.S. wildfire emissions: comparison with prescribed burning and air quality implications. *J. Geophys. Res.* 122, 6108–6129. <https://doi.org/10.1002/2016JD026315>.
- Majdi, M., Turquet, S., Sartelet, K., Legorgeu, C., Menut, L., Kim, Y., 2018. Impact of wildfires on particulate matter in the Euro-Mediterranean in 2007: sensitivity to the parameterization of emissions in air quality models. *Atmos. Chem. Phys. Discuss.* 1–32. <https://doi.org/10.5194/acp-2018-309>.
- Marques, S., Borges, J.G., Garcia-Gonzalo, J., Moreira, F., Carreiras, J.M.B., Oliveira, M. M., Cantarinha, A., Botequim, B., Pereira, J.M.C., 2011. Characterization of wildfires in Portugal. *Eur. J. For. Res.* 130, 775–784. <https://doi.org/10.1007/s10342-010-0470-4>.
- Martins, V., Miranda, A.I., Carvalho, A., Schaab, M., Borrego, C., Sá, E., 2012. Impact of forest fires on particulate matter and ozone levels during the 2003, 2004 and 2005 fire seasons in Portugal. *Sci. Total Environ.* 414, 53–62. <https://doi.org/10.1016/j.scitotenv.2011.10.007>.
- Matz, C.J., Eged, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., Henderson, S.B., Stieb, D.M., 2020. Health impact analysis of PM<sub>2.5</sub> from wildfire smoke in Canada (2013–2015, 2017–2018). *Sci. Total Environ.* 725, 138506 <https://doi.org/10.1016/j.scitotenv.2020.138506>.
- Miranda, A.I., Martins, V., Cascão, P., Amorim, J.H., Valente, J., Borrego, C., Ferreira, A. J., Robalo, C., Viegas, D.X., Ottmar, R., Isabel, A., Martins, V., Cascão, P., Amorim, J. H., Valente, J., Borrego, C., Ferreira, A.J., Cordeiro, C.R., Casco, P., Amorim, J.H., Valente, J., Borrego, C., Ferreira, A.J., Cordeiro, C.R., Viegas, D.X., Ottmar, R., 2012. Wildland smoke exposure values and exhaled breath indicators in firefighters. *J. Toxicol. Environ. Health Part A Curr. Issues* 75, 831–843. <https://doi.org/10.1080/15287394.2012.690686>.
- Miranda, A.I., Martins, V., Cascão, P., Amorim, J.H., Valente, J., Tavares, R., Tchepel, O., Borrego, C., Cordeiro, C.R., Ferreira, A.J., Viegas, D.X., Ribeiro, L.M., Pita, L.P., 2010. Monitoring fire-fighters' smoke exposure and related health effects during Gestosa experimental fires. *WIT Trans. Ecol. Environ.* 137, 83–94. <https://doi.org/10.2495/FIVA100081>.
- MNE, 2023. Permanent mission of Portugal to the united nations. Ministry of Foreign. <https://onu.missaoportugal.mne.gov.pt/en/about-portugal/general-information>.
- Monteiro, A., Corti, P., San Miguel-Ayanz, J., Miranda, A.I., Borrego, C., 2013. The EFFIS forest fire atmospheric emission model: application to a major fire event in Portugal. *Atmos. Environ.* 84, 355–362. <https://doi.org/10.1016/j.atmosenv.2013.11.059>.
- Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Peñuelas, A.L., Durán-Grados, V., Moreno-Gutiérrez, J., Jalkanen, J.P., Hannuniemi, H., Sousa, S.I.V., 2021. Estimating

- the health and economic burden of shipping related air pollution in the Iberian Peninsula. *Environ. Int.* 156 <https://doi.org/10.1016/j.envint.2021.106763>.
- OECD, 2012. Mortality Risk Valuation in Environment, Health and Transport Policies. <https://doi.org/10.1787/9789264130807-en>.
- Oliveira, M., Delerue-Matos, C., Pereira, M.C., Morais, S., 2020. Environmental particulate matter levels during 2017 large forest fires and megafires in the center region of Portugal: a public health concern? *Int. J. Environ. Res. Publ. Health* 17, 10–13. <https://doi.org/10.3390/ijerph17031032>.
- Oliveira, M., Slezakova, K., Alves, M.J., Fernandes, A., Teixeira, J.P., Delerue-Matos, C., Pereira, M. do C., Morais, S., 2016. Firefighters' exposure biomonitoring: impact of firefighting activities on levels of urinary monohydroxyl metabolites. *Int. J. Hyg. Environ. Health* 219, 857–866. <https://doi.org/10.1016/j.ijheh.2016.07.011>.
- Pordata, 2022. <https://www.pordata.pt/portugal/area+ardida+e+incendios+rurais+em+portugal+continental-1192>.
- Pordata, 2021. [https://www.pordata.pt/Portugal/Temperatura+m%C3%A1xima+do+ar+\(m%C3%A9dia+anual\)-1068](https://www.pordata.pt/Portugal/Temperatura+m%C3%A1xima+do+ar+(m%C3%A9dia+anual)-1068).
- Pordata, 2020. <https://www.pordata.pt/Portugal/Precipita%C3%A7%C3%A3o+tota-1-1070>.
- Ravi, V., Vaughan, J.K., Wolcott, M.P., Lamb, B.K., 2019. Impacts of prescribed fires and benefits from their reduction for air quality, health, and visibility in the Pacific Northwest of the United States. *J. Air Waste Manag. Assoc.* 69, 289–304. <https://doi.org/10.1080/10962247.2018.1526721>.
- Roberts, G., Wooster, M.J., 2021. Global impact of landscape fire emissions on surface level PM2.5 concentrations, air quality exposure and population mortality. *Atmos. Environ.* 252, 118210 <https://doi.org/10.1016/j.atmosenv.2021.118210>.
- San-Miguel-Ayanz, J., Et, A., 2021. Forest Fires in Europe, Middle East and North Africa 2020. European Environment Agency, Luxembourg.
- Shi, H., Jiang, Z., Zhao, B., Li, Z., Chen, Y., Gu, Y., Jiang, J.H., Lee, M., Liou, K.N., Neu, J. L., Payne, V.H., Su, H., Wang, Y., Witek, M., Worden, J., 2019. Modeling study of the air quality impact of record-breaking southern California wildfires in december 2017. *J. Geophys. Res. Atmos.* 124, 6554–6570. <https://doi.org/10.1029/2019JD030472>.
- Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L.D., Fagerli, H., Flechard, C.R., Hayman, G.D., Gauss, M., Jonson, J.E., Jenkin, M.E., Nyíri, A., Richter, C., Semeena, V.S., Tsyro, S., Tuovinen, J.P., Valdebenito, A., Wind, P., 2012. The EMEP MSC-W chemical transport model – technical description. *Atmos. Chem. Phys.* 12, 7825–7865. <https://doi.org/10.5194/acp-12-7825-2012>.
- Slezakova, K., Morais, S., Pereira, M. do C., 2013. Forest fires in Northern region of Portugal: impact on PM levels. *Atmos. Res.* 127, 148–153. <https://doi.org/10.1016/j.atmosres.2012.07.012>.
- Stowell, J.D., Geng, G., Saikawa, E., Chang, H.H., Fu, J., Yang, C.E., Zhu, Q., Liu, Y., Strickland, M.J., 2019. Associations of wildfire smoke PM2.5 exposure with cardiorespiratory events in Colorado 2011–2014. *Environ. Int.* 133, 105151 <https://doi.org/10.1016/j.envint.2019.105151>.
- Vicente, A., Alves, C., Monteiro, C., Nunes, T., Mirante, F., Evtuygina, M., Cerqueira, M., Pio, C., 2011. Measurement of trace gases and organic compounds in the smoke plume from a wildfire in Penedono (central Portugal). *Atmos. Environ.* 45, 5172–5182. <https://doi.org/10.1016/j.atmosenv.2011.06.021>.
- Viegas, X., Almeida, M.F., Ribeiro, M., Almeida, M.A., Raposo, J., Viegas, M.T., Oliveira, R., Alves, D., Pinto, C., Rodrigues, A., Ribeiro, C., Lopes, S., Jorge, H., Viegas, C.X., 2019. Análise Dos Incêndios Florestais Ocorridos a 15 De Outubro De 2017 - Os Acidentes Pessoais 157–176.
- Wettstein, Z.S., Hoshiko, S., Fahimi, J., Harrison, R.J., Cascio, W.E., Rappold, A.G., 2018. Cardiovascular and cerebrovascular emergency department visits associated with wildfire smoke exposure in California in 2015. *J. Am. Heart Assoc.* 7 <https://doi.org/10.1161/JAHA.117.007492>.
- WHO, 2017. Health Economic Assessment Tool (HEAT) for Walking and for Cycling Methods and User Guide on Physical Activity, Air, vol. 86. Who.
- WHO Regional Office for Europe, 2016. Health Risk Assessment of Air Pollution, pp. 1–40.
- Wiedinmyer, C., Akagi, S.K., Yokelson, R.J., Emmons, L.K., 2010. The Fire INventory from NCAR (FINN) – a high resolution global model to estimate the emissions from open burning. *Geosci. Model Dev. Discuss. (GMDD)* 3, 2439–2476. <https://doi.org/10.5194/gmdd-3-2439-2010>.
- World Health Organization, 2014. WHO Expert Meeting: methods and tools for assessing the health risks of air pollution at local, national and international level. Meeting report 1–112.
- Wu, Y., Li, S., Xu, R., Chen, G., Yue, X., Yu, P., Ye, T., Wen, B., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Guo, Y., 2023. Wildfire-related PM2.5 and health economic loss of mortality in Brazil. *Environ. Int.* 174 <https://doi.org/10.1016/j.envint.2023.107906>.
- Zhang, Y., Ye, T., Yu, P., Xu, R., Chen, G., Yu, W., Song, J., Guo, Y., Li, S., 2023. Preterm birth and term low birth weight associated with wildfire-specific PM2.5: a cohort study in New South Wales, Australia during 2016–2019. *Environ. Int.* 174, 107879 <https://doi.org/10.1016/j.envint.2023.107879>.