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# Smoke emissions from the extreme wildfire events in central Portugal in October 2017

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## ABSTRACT

In the last decades, numerous large forest fires have been recorded in Portugal. On 15 and 16 October 2017, seven extreme wildfires events (EWEs) took place in the central region of Portugal. Aiming to contribute to the assessment of the smoke impact of these EWEs, this study estimates their atmospheric emissions using a bottom-up approach with high spatial and temporal resolution. To this end, fire data were used, such as ignition location and time, propagation, burned area, and fuel load and emission factors according to forest species. A particular fire – EWE in Lousã with a high fuel load – emitted ~50% of the sum of the emissions of the six other case studies. The spatial distribution of the EWE emissions indicates that fuel load is an important component of emissions estimation. The obtained results were compared with remote sensing data, showing good agreement in terms of total values. During these EWEs, particulate matter and carbon monoxide emissions were higher than Portuguese anthropogenic emissions in 2017. This approach contributes to the state of the art on forest fire emissions, reducing uncertainty and obtaining the best possible and detailed quantification of the temporal and spatial variability of EWE emissions.

**Keywords:** bottom-up approach, emissions, extreme events, high resolution, Mediterranean conditions, satellite data, smoke, wildland fire.

## Introduction

Wildfires can produce substantial emissions of carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), volatile organic compounds (VOCs) and particulate matter (PM) (Crutzen *et al.* 1979; Miranda *et al.* 1994, 2005; Andreae and Merlet 2001; Reddington *et al.* 2016). These emissions affect global atmospheric chemistry (Spracklen *et al.* 2007; Jaffe *et al.* 2008; Monks *et al.* 2012), impact radiative transfer in the atmosphere (Clinton *et al.* 2006) and reduce visibility (Wade and Ward 1973; Valente *et al.* 2007). Moreover, they strongly degrade air quality (Valente *et al.* 2007; Miranda *et al.* 2009; Bytnerowicz *et al.* 2010; Carvalho *et al.* 2011; Martins *et al.* 2012; Turquety *et al.* 2014; Keywood *et al.* 2015), with significant effects on human health (Miranda *et al.* 2010, 2012; Johnston *et al.* 2012; Knorr *et al.* 2012; Martins *et al.* 2012; Akagi *et al.* 2014; Dennekamp *et al.* 2015; Reid *et al.* 2016; Apte *et al.* 2018).

San-Miguel-Ayanz *et al.* (2013) estimated that 2% of 'mega-fires' contribute to 80% of the total area burned in Europe. These extreme wildfire events (EWEs) are usually clusters of fires that burn simultaneously and propagate rapidly owing to critical meteorological conditions, such as hot and dry conditions with strong winds (Pereira *et al.* 2005), and are particularly difficult to control. There are several examples in which the yearly national emissions of EWE exceed those of anthropogenic activities, despite the former being concentrated in both time and space. Such are the cases of the Portuguese fires in 2003, 2015 and 2017 or the Greek fires in 2007 or the Russian fires in 2010 (Hodzic *et al.* 2007; Turquety *et al.* 2009; Konovalov *et al.* 2011; Hodnebrog *et al.* 2012; Martins *et al.* 2012). The fires that occurred in 2017 in central Portugal are the most recent example of large (and deadly) wildfires in Europe, and have not yet been sufficiently investigated (Solomos et al. 2019).

Most forest fire emission studies rely on the model proposed by Seiler and Crutzen (1980) and Ward and Hardy (1991), which is based on information about burned area extent, the amount and type of vegetation burned (fuel types, fuel loads) and the conditions under which fires take place (combustion efficiencies). Emission factors are also used to estimate the amount of emissions of each species (gases and particles). More recently, global satellite-derived burned area information has become available. Thus, the scientific community has put considerable effort into quantifying the impact of wildland fires by remote-sensing approaches to improve these estimates (Giglio et al. 2006; Mouillot et al. 2006; Reid et al. 2009; Mieville et al. 2010; Wiedinmyer et al. 2011; Kaiser et al. 2012; Ichoku and Ellison 2014; Monteiro et al. 2014; Darmenov and da Silva 2015; Chuvieco et al. 2016; van der Werf 2017). Furthermore, instantaneous fire radiative power (FRP) is used nowadays as a measure of the rate of radiant energy emission from the fire to derive the amount of fuel burned directly (Freeborn et al. 2008), in particular, to facilitate real-time applications (Sofiev et al. 2009; Kaiser et al. 2012).

Although much progress has been made over the last couple of decades in improving the quality of vegetation fire emission datasets (e.g. Pereira et al. 2009; van der Werf et al. 2010, 2017; Sofiev et al. 2013; Rémy et al. 2017; Prichard et al. 2020), uncertainties are still an issue but are poorly estimated and considered in modelling, mainly at regional and local levels (e.g. Liousse et al. 2010; Kaiser et al. 2012; Petrenko et al. 2012; Bond et al. 2013; Zhang et al. 2014; Ichoku et al. 2016; Pereira et al. 2016; Reddington et al. 2016; Pan et al. 2020). They are mainly associated with fire characteristics (vegetation burned and fuel load consumed) and emission factors (EFs) (Miranda et al. 2008; Ottmar et al. 2008; Langmann et al. 2009). Regarding EFs, the majority of the available information is for United States of America (USA) forest (Urbanski 2013), and it is not a suitable proxy for wildfires in Europe, owing to vegetation cover and the differences in combustion characteristics (e.g. flaming and smouldering phases). Efforts to narrow the uncertainties in the EFs are ongoing in the form of numerous field campaigns and laboratory studies (e.g. Alves et al. 2011; Vicente et al. 2012, 2017; van der Werf et al. 2017).

Thus far, no forest fire emission inventory delivers data with high enough spatial (e.g. ~5 km or better) and temporal (e.g. approximately hourly or better) resolution (e.g. Reid et al. 2009; Shi et al. 2015; Pereira et al. 2016; Reddington et al. 2016). The accuracy and high resolution of fire emissions inventories are particularly important for air quality modelling studies at regional- and local-scale (Miranda et al. 2005; Valente et al. 2007; Akagi et al. 2011; Martins et al. 2012; van Marle et al. 2017; Mota and Wooster 2018).

The main objective of the present study is to estimate the atmospheric emissions from the October 2017 Portuguese EWEs with a high-resolution methodology. We rely on a combination of burned area maps and land cover maps, forest inventory data, statistical growth models for forests and shrublands, and EFs updated according to recently published data. We also compare these emissions with satellite data and with Portuguese anthropogenic emissions.

## Emissions estimation methodology

On the morning of 15 October, at 6:00 hours in the central region of Portugal, a serious wildfire situation started and developed into seven EWEs that lasted until 8:00 hours on 16 October. The dry vegetation and soil due to the hot and dry season throughout 2017, combined with the strong and persistent southerly winds caused by the close passage of hurricane Ophelia to the Portuguese mainland, increased the intensity of the EWEs (Turco et al. 2019; Augusto et al. 2020). Fig. 1 shows the location of the seven EWEs.

Atmospheric emissions during these EWEs were estimated using a bottom-up methodology based on the following equations that should be well known (e.g. Wiedinmyer et al. 2006; Carvalho et al. 2011):

$$E_i = EF_i \times FC \times A \quad (1)$$

$$FC = \beta \times B \quad (2)$$

where $E_i$ is the emission of compound i (g), $EF_i$ the EF for compound i ($g\,kg^{-1}$), FC is fuel consumption ($kg\,m^{-2}$), $\beta$ the burning efficiency, $B$ the fuel load ($kg\,m^{-2}$), and $A$ the burned area ($m^2$) (Wiedinmyer et al. 2006; Carvalho et al. 2011).

The hourly fire progression (burned area) was estimated based on detailed data collected by the Associação para o Desenvolvimento da Aerodinâmica Industrial (Viegas et al. 2019) (see *Burned area* below), while fuel load data over the study areas were obtained using the National Forest Inventory (ICNF 2019) and Portuguese land use data (DGT 2018) with a high horizontal spatial resolution (see *Fuel load*). A literature review was performed to obtain the burning efficiency values (*Burning efficiency*) and the most suitable EFs (*Emission factors*) to be considered for the 2017 EWEs.

The uncertainty for the estimated emissions was quantified applying the Monte Carlo approach. Random values were generated for each input parameter (i.e. EF, burning efficiency and fuel load) assuming a normal distribution and taking their coefficient of variation into account.

According to Ottmar et al. (2008), the coefficient of variation for the EFs is 16%, for the burning efficiency, 30% and for the fuel load, 83%. Notwithstanding the focus of the analysis of Ottmar et al. (2008) on a region in the USA, these coefficients of variation were considered in the present study assuming that methods for the quantification of EFs, burning efficiency and fuel load parameters were similar

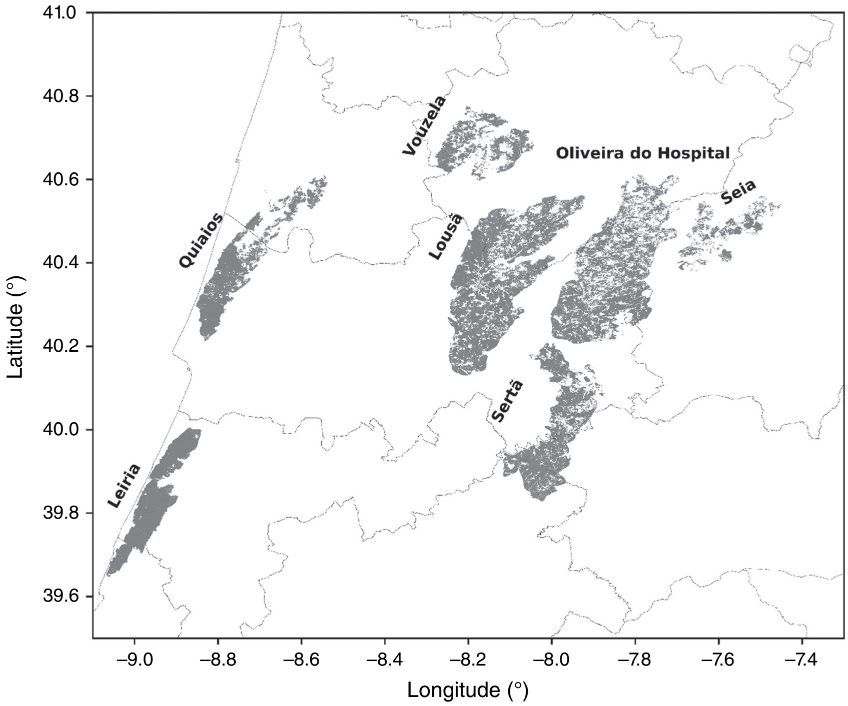


**Fig. 1.** Location of the Portuguese areas (Quiaios, Vouzela, Lousã, Oliveira do Hospital, Seia, Sertã and Leiria) affected by the extreme wildfire events between 15 and 16 October 2017.

**Table 1.** Information about burned area, ignition time and wildfire duration for the seven EWEs (Leiria, Lousã, Oliveira do Hospital, Quiaios, Seia, Sertã and Vouzela) recorded between 15 and 16 October 2017 (Viegas *et al.* 2019).

| Extreme wildfire event (EWE) | Burned area (ha) | Start time (day – hours) | Finish time (day – hours) | Duration (hh:mm) |
|---|---|---|---|---|
| Leiria | 20 014 | 15 – 13:51 | 16 – 01:00 | 10:50 |
| Lousã | 54 407 | 15 – 08:41 | 16 – 03:00 | 17:45 |
| Oliveira do Hospital | 51 429 | 15 – 10:26 | 16 – 05:00 | 18:00 |
| Quiaios | 23 844 | 15 – 13:34 | 16 – 00:00 | 12:10 |
| Seia | 17 003 | 15 – 06:03 | 16 – 08:00 | 26:00 |
| Sertã | 30 977 | 15 – 12:02 | 16 – 01:00 | 13:10 |
| Vouzela | 15 959 | 15 – 17:21 | 16 – 03:00 | 09:30 |

to those used in Portugal. Multiple runs (maximum of 500 iterations) were performed until results converged (i.e. an average difference less than 0.3% between multiple runs).

## Burned area

Fire data, such as ignition location and time and burned area, for each EWE were acquired from the report delivered by the Associação para o Desenvolvimento da Aerodinâmica Industrial (Viegas *et al.* 2019). This report resulted from a careful and detailed study based on fire data collected in the field, namely on many interviews with operational and affected people, among others who experienced the fire first-hand. These interviews enabled the identification of a set of thousands of georeferenced points with an associated time. In many cases, the time information was confirmed by registration on mobile phones, as people tried to call when the fire reached the surroundings of their homes. Further, several photographs and videos of fire progression were considered. Notwithstanding the great effort to obtain a rigorous determination of fire spread, owing to the extent of the burned area and the complexity of the EWEs, slight deviations are still expected. This detailed information allowed the different ignition points and how the fires spread and affected the territories to be inventoried and therefore estimation of the burned area with a high spatial and temporal resolution. Table 1 shows a summary of the information on burned area, ignition time and wildfire duration considered in this work to estimate the emissions for each EWE (Viegas *et al.* 2019).

According to the information provided by the report of ADAI on these EWEs (Viegas *et al.* 2019), the first forest fire warning was issued in Seia, where 17 003 ha of forest and shrubland were burned. Four hours later, a second occurrence was registered in Lousã, where 54 407 ha were burned. The fire in Oliveira do Hospital started at 10:26 hours and resulted in the destruction of several houses and industrial facilities as well as burning a vast area (51 429 ha). In Sertã, the fire started at ~12:00 hours on 15 October (30 977 ha burned). In the coastal zone of Portugal, the first forest fire ignition occurred at ~14:00 hours in Leiria and Quiaios with burned areas of 20 014 and 23 844 ha, respectively. The last forest fire alert was registered at 17:21 hours in Vouzela, with the smallest burned area (15 959 ha).

### Fuel load

Fuel load was obtained from the sixth Portuguese Forest Inventory (ICNF 2019), which is based on data collection from aerial images and vegetation measurements on the ground (~12 000 measurement sites) across the Portuguese mainland in 2015. This inventory provides surface fuel load by land-use type (trees, under vegetation cover, standing trees, fallen trees, stump and foliage) and forest species (acacia, carob, chestnut, cork oak, eucalyptus, holm oak, oaks, other hardwoods, other resinous, *Pinus pinaster* and stone pine) for the Portuguese Nomenclature of Territorial Units for Statistical Purposes (NUTS) III.

To improve the spatial distribution of the fuel load data over the study areas, values were spatially disaggregated using the Portuguese land use data (Carta de Uso e Ocupação do Solo – COS) (DGT 2018) and applying an area-weighting technique. The COS dataset was produced based on visual interpretation of orthorectified aerial images with a spatial resolution of 0.5 m. Other sources of information, including satellite images, were also used during the production process as well as in quality control. This database provides information on the areas covered by different forest species (acacia, chestnut, eucalyptus, holm oak, oaks, other hardwoods, other resinous, *Pinus pinaster* and stone pine) with a minimum cartographic unit, minimum distance between lines and minimum polygon width of 1 ha, 20 and 20 m, respectively.

In addition, measurement datasets (7964 sites across the Portuguese mainland) provided by the Portuguese Institute for Nature Conservation and Forests were also used to improve the accuracy of the estimated fuel load as well as the identification of the forest species in the study area. This joint compilation of data allowed reduction in the uncertainty of the fuel load considered, as well as producing fuel load maps per forest species with a high spatial horizontal resolution.

### Burning efficiency

Burning efficiency was introduced to the emissions study community at least as early as 1991 by Ward and Hao (1991). Usually, burning efficiency is defined as the ratio of carbon released as carbon dioxide ($CO_2$) to the total carbon present in the fuel (Miller 2011). In field and laboratory experiments, burning efficiency can be expressed as the fraction burned relative to the total available biomass. Many researchers relate burning efficiency with fire type (surface fire, crown fire or ground fire), fire phase (smouldering or flaming), and other factors such as wind speed, month of occurrence (vegetation has different water contents in spring and summer), soil moisture and even different slope aspect (Kauffman *et al.* 2003; Miranda *et al.* 2005; Chang and Song 2010; van der Werf *et al.* 2010; Akagi *et al.* 2011; Guo *et al.* 2017). Despite the difficulty in accurately estimating it, there is a wide range of burning efficiency data (e.g. PNAC 2002; Miranda *et al.* 2005; Wiedinmyer *et al.* 2006; Martins *et al.* 2012; Urbanski 2013) for shrubs and forest species. In the present study, for shrubs, a burning efficiency value of 0.8, suggested by the National Program for Climate Changes (PNAC 2002), was selected because it represents Portuguese conditions for understorey vegetation as well as fine fuel from other vegetation species. Regarding forest, a burning efficiency value of 0.25 was taken from the EEA (2019) guidance document as representing southern European forest species, namely communities of eucalyptus, and resinous and deciduous trees.

### Emission factors

Emission factors for southern European conditions were chosen based on a bibliographic review taking into consideration Portuguese land-use types, as well as considering values selected by previous studies (Miranda 2004; Alves *et al.* 2011; Martins *et al.* 2012; Vicente *et al.* 2012, 2017; van der werf *et al.* 2017). Most of the studies reported in the literature provide EFs for American fuels (e.g. McMeeking *et al.* 2009; Akagi *et al.* 2011) and savannas or pastures, tropical and extratropical forests (van der Werf *et al.* 2017), with few studies for Mediterranean species. Table 2 lists the average EFs (in $g\,kg^{-1}$ fuel burned, dry basis) for the relevant air pollutants. All reported values were obtained from experimental forest fires.

The EFs listed for eucalyptus, acacia and *Pinus pinaster* species express the average of the EFs obtained experimentally in Portugal by Alves *et al.* (2011) and Vicente *et al.* (2012, 2017). These averages were calculated using the harmonic mean (Fujioka 1985). The EFs reported by van der Werf *et al.* (2017) were used for the other hardwoods species. The EFs for other resinous, oak, chestnut, cork oak and stone pine species were obtained from Miranda (2004). Emission factors still are one of the main uncertainty sources in emissions estimations, and it is important to work on this topic with more field measurements, in particular for southern European conditions.

## Results

The methodology considered for analysing the obtained atmospheric emissions was based on approaches used in similar previous studies (e.g. Giglio *et al.* 2006; Mouillot *et al.* 2006;

**Table 2.** Averaged emission factors (g $kg^{-1}$ fuel burned, dry basis) of the main smoke pollutants per vegetation type.

| Species | Eucalyptus[A,B,C] | Other resinous[D] | Oak, chestnut, cork oak[D] | *Acacia*[A,B,C] | Other hardwoods[E] | *Pinus pinaster*[A,B,C] | Stone pine[D] |
|---|---|---|---|---|---|---|---|
| PM10 | 21 | 10 | 13 | 11 | 8.3 | 13 | 10 |
| PM2.5 | 19 | 9 | 11 | 10 | 6.3 | 11 | 9 |
| $NO_x$ | 5 | 3 | 3 | 5 | 3.11 | 3 | 5 |
| CO | 170 | 100 | 128 | 232 | 102 | 204 | 91 |
| $SO_2$ | 0.8 | 0.8 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 |
| $NH_3$ | 0.6 | 0.6 | 0.6 | 0.6 | 2.17 | 0.6 | 0.6 |
| $CO_2$ | 1408 | 1497 | 1393 | 1561 | 1585 | 1398 | 1487 |
| $CH_4$ | 6 | 6 | 6 | 4.7 | 5.82 | 6 | 5 |

[A]Vicente *et al.* (2012).
[B]Vicente *et al.* (2017).
[C]Alves *et al.* (2011).
[D]Miranda (2004).
[E]van der Werf *et al.* (2017).

Reid *et al.* 2009; Mieville *et al.* 2010; Wiedinmyer *et al.* 2011; Kaiser *et al.* 2012; Ichoku and Ellison 2014; Monteiro *et al.* 2014; Darmenov and da Silva 2015; Chuvieco *et al.* 2016; van der Werf *et al.* 2017). In *Emission data and maps*, the spatial distribution and hourly total atmospheric emissions of the main smoke pollutants are shown and discussed. The impact of each EWE (e.g. Leiria and Lousã) and forest species (e.g. eucalyptus and other resinous) on total emissions was analysed. The results were also compared with data from other approaches (*Comparison with satellite data*), and with emissions from anthropogenic sectors in mainland Portugal (*Smoke vs anthropogenic emissions*). The main purpose of these comparisons was to understand the accuracy and magnitude of the atmospheric emissions during the study period.

## Emission data and maps

The analysis of the atmospheric emissions (particles with an aerodynamic diameter smaller than 10 μm – PM10 – and 2.5 μm – PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$) from the seven EWEs between 15 and 16 October 2017 was based on their spatial and hourly distributions, as well as on the total emissions by case (Quiaios, Vouzela, Lousã, Oliveira do Hospital, Seia, Sertã and Leiria) and by burned species (acacia, chestnut, cork oak, eucalyptus, oak, other hardwoods, other resinous, *Pinus pinaster* and stone pine).

Fig. 2 shows the spatial distribution ($500 \times 500\,m^2$) of the atmospheric pollutant emissions (in kt) during the EWEs.

The spatial correlation coefficient between the different atmospheric pollutants (e.g. PM10 vs PM2.5) ranged from 0.81 to 0.99, showing that the analysed pollutants have a similar spatial distribution. The lowest correlation values (0.81–0.90) were calculated when comparing the spatial distribution of $NH_3$ with the other atmospheric pollutants. As the $SO_2$ and $NH_3$ EFs are the same for the most representative species (except other hardwoods) in the study areas (Table 1) and their spatial distributions are similar to those from the remaining pollutants (PM10, PM2.5, $NO_x$, CO, $CO_2$ and $CH_4$), fuel load is the main parameter that affects the spatial distribution of the estimated emissions.

The highest emission values were estimated for the Lousã EWE, where the available fuel load was higher mainly owing to the high percentage of acacia covering the area (41.1%), with a fuel load of 6238.5 kt. Based on spatial distribution, it was possible to quantify the maximum emissions (over space) of the different EWEs in relation to the Lousã event: 88.1% (in Quiaios), 95.6% (in Vouzela), 60.0% (in Oliveira do Hospital), 95.8% (in Seia), 58.0% (in Sertã) and 71.1% (in Leiria). The lowest maximum value was obtained in Vouzela, which is an area mainly covered by *Pinus pinaster* (83.5%), with an average fuel load of 364.7 kt (87.2% less than the average Lousã fuel load).

To understand the temporal distribution of PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ atmospheric emissions from each EWE, Fig. 3 presents hourly emissions (in kt) during the study period.

Fig. 3 shows that the Lousã, Leiria and Sertã EWEs were the largest contributors, with emissions from the Lousã EWE predominating. The period with the highest total emission values lasted for 12 h, between 15:00 hours on 15 October and 02:00 hours on 16 October. The time with highest emission values was 21:00 hours on 15 October, with the biggest contribution from the Lousã EWE (61.38%) and Leiria EWE (21.58%). Furthermore, the temporal distribution profiles of the pollutants were similar, but with different absolute values, because for each pollutant, the burned area, burning efficiency and fuel load values considered varied the same way.

The total emissions (in space and in time) of PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ were estimated for each case study and are presented in Fig. 4.

For $NH_3$, the estimated highest total emissions were in the Lousã EWE ($5.22 \pm 0.91$ kt), followed by Sertã

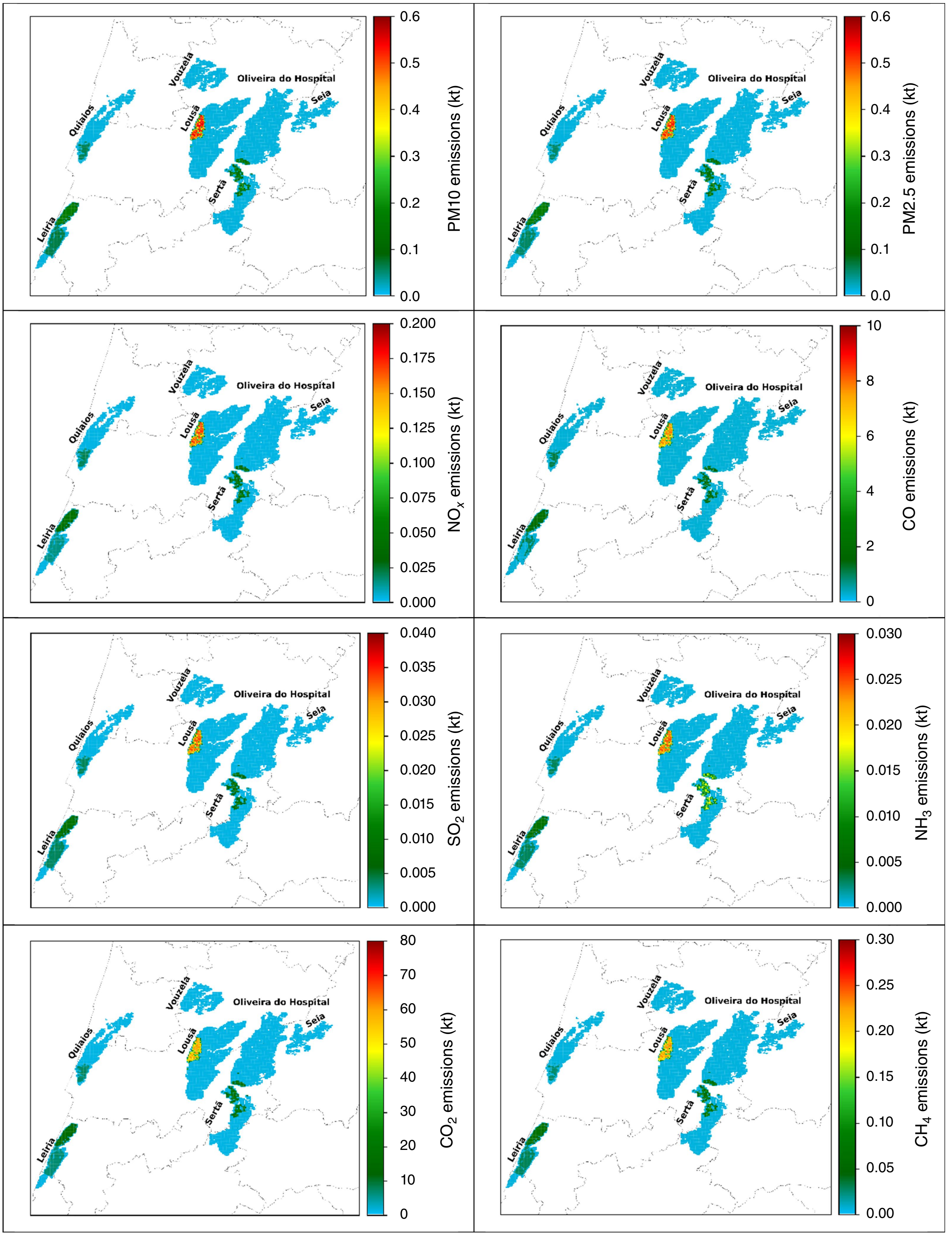


**Fig. 2.** Spatial distribution (500 × 500 $m^2$) of atmospheric emissions for PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ (kt) in Quiaios, Vouzela, Lousã, Oliveira do Hospital, Seia, Sertã and Leiria, over combustion time from 15 to 16 October 2017.

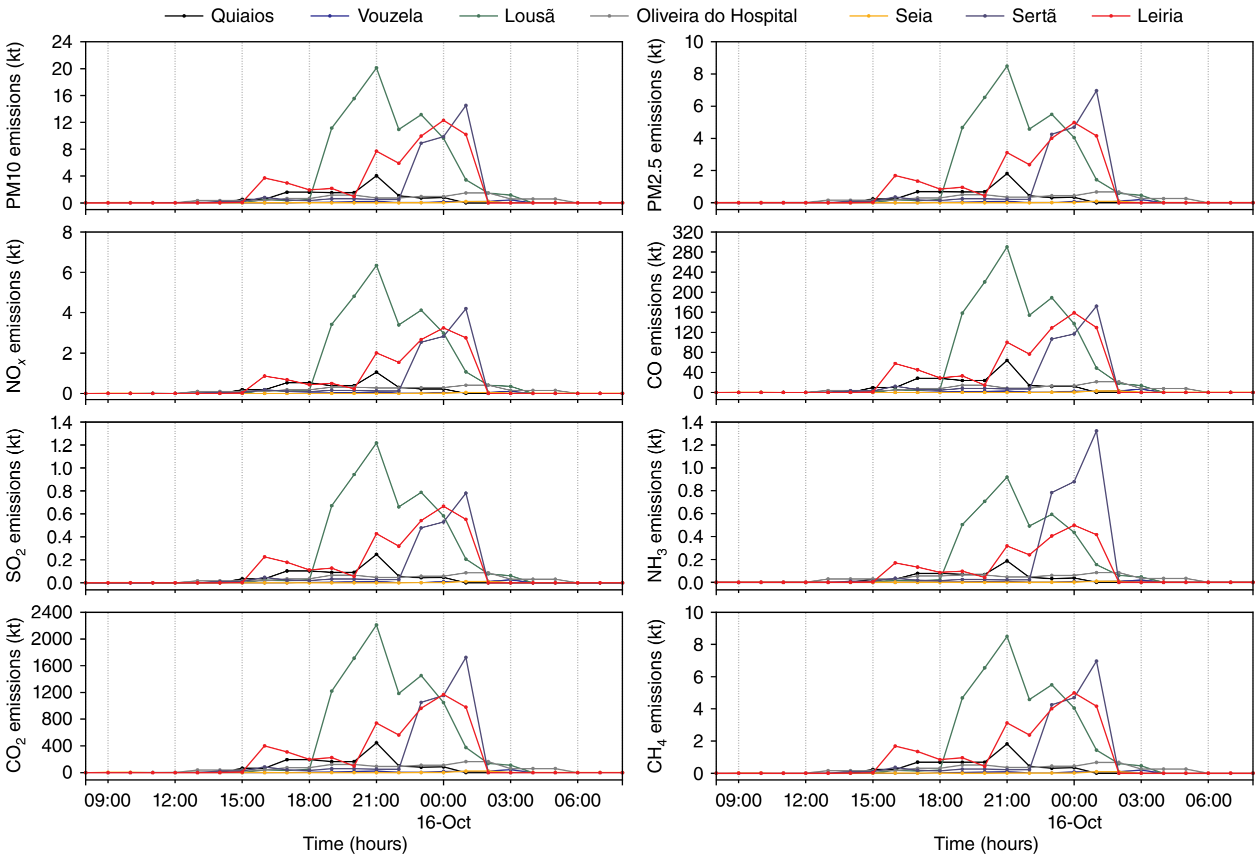


**Fig. 3.** Hourly total atmospheric emissions of PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ (in kt) for the Quiaios, Vouzela, Lousã, Oliveira do Hospital, Seia, Sertã and Leiria EWE, from 15 to 16 October 2017.

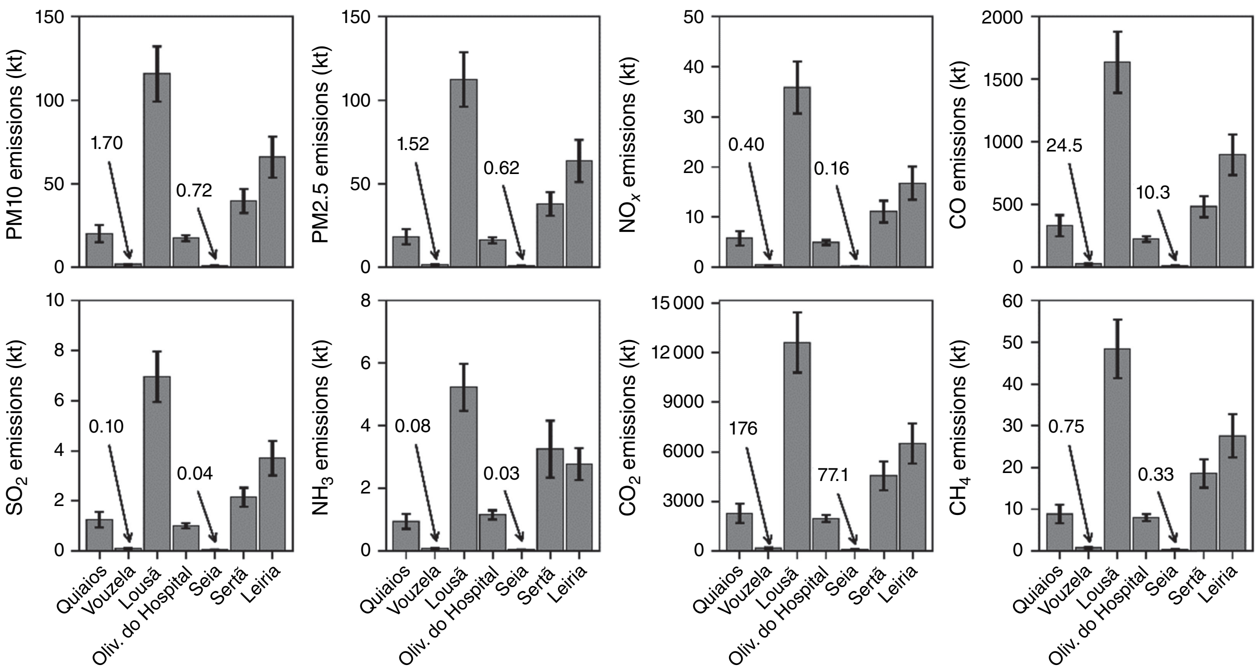


**Fig. 4.** Total emissions of PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ (in kt) in Quiaios, Vouzela, Lousã, Oliveira do Hospital, Seia, Sertã and Leiria on 15 and 16 October 2017.

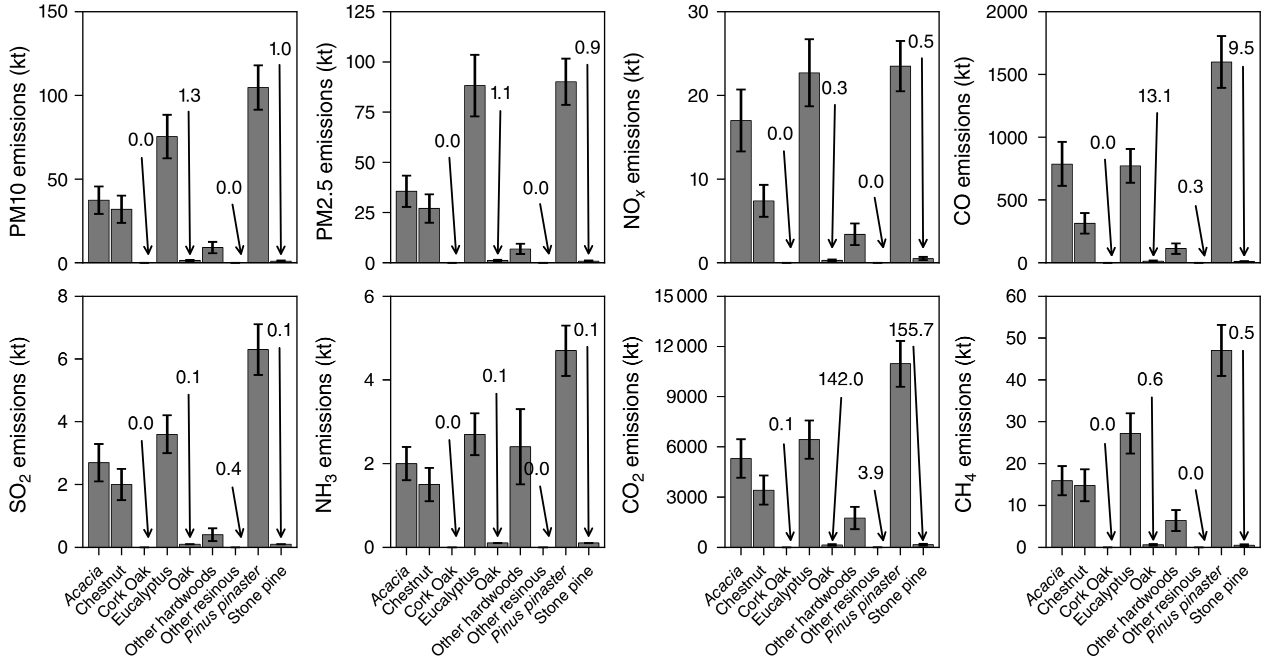


**Fig. 5.** Total emissions of PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ (in kt) by forest species (acacia, chestnut, cork oak, eucalyptus, oak, other hardwoods, other resinous, *Pinus pinaster* and stone pine), from 15 to 16 October 2017.

(3.25 ± 0.75 kt), Leiria (2.77 ± 0.51 kt), Oliveira do Hospital (1.15 ± 0.24 kt), Quiaios (0.94 ± 0.15 kt), Vouzela (0.08 ± 0.1 kt) and Seia (0.03 ± 0.01 kt), whereas for the remaining atmospheric pollutants, the largest total emissions were in the Lousã EWE, followed by Leiria, Sertã, Quiaios, Oliveira do Hospital, Vouzela and Seia.

The emissions in Lousã were 43.4–45.8% higher than the sum of emissions from all the other case studies. This EWE was responsible for the largest burned area (54 407 ha – Table 1) and also had the highest available fuel load (15 188.8 kt). The lowest emissions were calculated for the Seia EWE (17 003 ha – Table 1) and Vouzela EWE (15 959 ha – Table 1), which are the regions with the smallest burned area, representing 0.19–0.32% and 0.61–0.63%, respectively, of the total emissions in the study region.

The contribution of each forest species considered in this work for the total emissions of PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$ is also shown in Fig. 5.

According to Fig. 5, the forest species that contributed the largest emission values were *Pinus pinaster* (37.49–42.47%) and eucalyptus (22.65–23.12%), followed by acacia (13.87–19.56%), chestnut (10.76–12.40%) and other hardwoods (4.45–6.77%). That contribution profile was obtained for all pollutants considered (PM10, PM2.5, $NO_x$, CO, $SO_2$, $NH_3$, $CO_2$ and $CH_4$).

## Comparison with satellite data

To compare the obtained results with data from other approaches, Fig. 6 shows the PM10 and PM2.5 emissions from the wildfires events between 15 and 16 October 2017 (~24 h) from MODIS (Moderate Resolution Imaging Spectroradiometer) and SEVIRI (Spinning Enhanced Visible and InfraRed Imager) sensors. To facilitate comparison between the results obtained by the different approaches (SEVIRI vs bottom-up vs MODIS), Fig. 6 presents the PM10 and PM2.5 emission values with a horizontal spatial resolution of 10 × 10 $km^2$ for the study period.

MODIS is onboard the polar-orbiting satellite platforms Terra and Aqua. It provides data with 1 × 1 $km^2$ horizontal resolution and typically makes two to four overpasses per day over each specific region of the globe (Sofiev *et al.* 2013). SEVIRI is onboard the Meteosat Second Generation (MSG) geostationary satellite, supplying measurements at 15-min temporal resolution; however, the pixel size of 3 km is coarser than for MODIS (Turquety *et al.* 2014). The high temporal coverage of the SEVIRI observations increases the probability of detecting a fire, but the coarse spatial horizontal resolution (3 × 3 $km^2$) increases the limit of detection and small fires may be missed (Turquety *et al.* 2020). Detailed information on the methodology applied to estimate the atmospheric emissions of wildfires using the SEVIRI and MODIS sensors is presented in Sofiev *et al.* (2013).

The ratios between the PM2.5 and PM10 emissions were on average 0.99 (SEVIRI), 0.94 (bottom-up) and 0.99 (MODIS). Table 1 shows that the PM2.5/PM10 EF ratios for the main vegetation species in the study area ranged from 0.76 to 0.91 (average 0.87). In this bottom-up study, the spatial distribution of PM10 and PM2.5 emissions covered the seven EWEs, whereas with the MODIS and SEVIRI

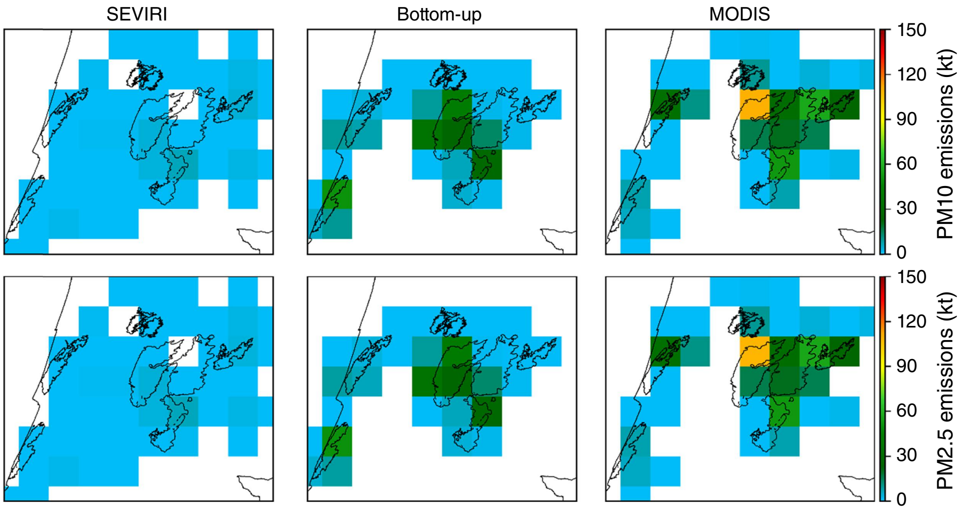


**Fig. 6.** PM10 (top panel) and PM2.5 emissions (bottom panel) (in kt) from extreme wildfire events in October 2017 quantified using SEVIRI, present study and MODIS approaches with a horizontal spatial resolution of $10 \times 10\,km^2$.

**Table 3.** Summary of the SEVIRI, bottom-up and MODIS results.

| Parameter | Pollutant | SEVIRI | Bottom-up | MODIS |
|---|---|---|---|---|
| Maximum (kt) | PM10 | 6.13 (Sertã) | 50.8 (Lousã) | 109 (Lousã) |
| | PM2.5 | 6.08 (Sertã) | 50.3 (Lousã) | 108 (Lousã) |
| Total (kt) | PM10 | 57.5 | 261 | 428 |
| | PM2.5 | 57.0 | 250 | 425 |

approaches, some burned areas did not show atmospheric emissions. These results are probably due to the coarse spatial ($3 \times 3\,km^2$) and temporal (two to four overpasses per day) resolutions of the SEVIRI and MODIS sensors, respectively. Table 3 summarises the SEVIRI, bottom-up and MODIS results presented in Fig. 6.

With the different approaches, the highest PM10 and PM2.5 emissions were obtained at different EWEs: for SEVIRI in Sertã, PM10, 6.13 kt; PM2.5, 6.08 kt; present study in Lousã: PM10, 50.8 kt, PM2.5, 50.3 kt; MODIS in Lousã, PM10, 109 kt; PM2.5, 108 kt (Table 3). The difference between the maximum values from the current study and the other two approaches ranged between −44.7 kt (SEVIRI) and +58.2 kt (MODIS) for PM10 and from −44.3 kt (SEVIRI) to +57.7 kt (MODIS) for PM2.5. The same type of differences were also estimated for the PM10 and PM2.5 total emissions over the study area. For example, calculated PM10 values with the bottom-up approach were on average 4.5 times higher than SEVIRI values and 1.7 times lower than MODIS values.

## Smoke vs anthropogenic emissions

To understand the magnitude of the atmospheric pollutant emissions during the study period, Fig. 7 shows PM10, PM2.5, $NO_x$, CO, $SO_2$ and $NH_3$ emissions (in kt) by anthropogenic sector in mainland Portugal for the year 2017 (European Monitoring and Evaluation Programme (EMEP); http://www.emep.int/). The Portuguese atmospheric emissions include the following Selected Nomenclature for Air Pollution (SNAP) activities: SNAP1 – energy production, SNAP2 – commercial, services and residential combustion, SNAP3&4 – industrial combustion and production processes, SNAP5 – extraction and distribution of fossil fuels, SNAP6 – solvents use, SNAP7 – road transport, SNAP8 – maritime transport, aviation and off-road transport, SNAP9 – waste treatment and disposal, and SNAP10 – agriculture.

During the EWEs in October 2017 (∼ 26 h), wildland fires emitted 2.7, 3.6 and 4.7 times more PM10, PM2.5 and CO, respectively, than Portuguese anthropogenic sources for the entire 2017 year. For $NO_x$, the EWEs emitted a total of 74.9 kt, which is higher than the annual emission from the Portuguese industrial (SNAP3&4 38.2 kt) and road transport (SNAP7 65.6 kt) sectors. The $SO_2$ (15.2 kt) and $NH_3$ (13.4 kt) emissions were lower (on average 4.8 times) than the total emissions from anthropogenic sectors. Notwithstanding these lower emissions, it is important to mention that EWEs emitted more $SO_2$ (15.2 kt) than the annual emissions from public power activity (SNAP1 14.1 kt) as well as more $NH_3$ (13.5 kt) than the Portuguese industrial sector for 2017 (SNAP3&4 5.6 kt).

# Conclusions

The present study focuses on estimating the atmospheric emissions resulting from the Portuguese wildfires of 2017

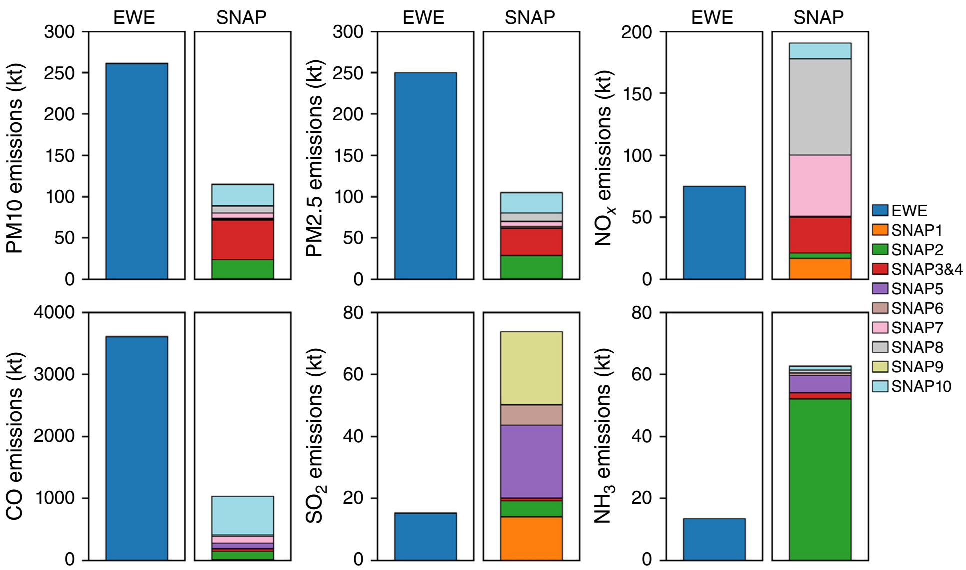


**Fig. 7.** PM10, PM2.5, $NO_x$, CO, $SO_2$ and $NH_3$ emissions (in kt) in 2017 over mainland Portugal for the analysed EWEs and SNAP activities.

with a high-resolution methodology. Burned area and land cover maps were used, together with forest inventory data for fuel load data and EFs updated for the Portuguese environment (as well as burning efficiency conditions).

Based on estimated emissions, a high-detail spatial analysis was done and the most affected areas were identified. Fuel load has an important role in the final spatial distribution of emissions. The contribution of each forest species tototal emissions, per pollutant, was also assessed, with *Pinus pinaster* having the highest impact (37.49–42.47%), followed by eucalyptus (22.65–23.12%).

The estimated emissions were then compared with satellite data (SEVIRI and MODIS), showing good agreement in terms of total values. Satellite-based data, however, did not allow detection of the spatial variability found with the current high-resolution approach. These emissions were also compared with the total national anthropogenic emissions throughout the Portuguese territory for the entire year 2017, confirming the extreme importance of this type of event in relation to air quality levels over the year.

This approach contributes to state-of-the-art knowledge on forest fire emissions, reducing the uncertainty level involved in this type of study and obtaining the best quantification – temporal and spatial – of the EWEs that occurred in Portugal in 2017. Unfortunately, it is impossible to fully validate the results by comparison with measured data, but quantitative values obtained indicate that fuel load has a very important role, and the spatial and temporal distributions provide further insights into smoke emission during EWEs. In the near future, these emissions will be used as input data in a chemical transport model and comparison between its results (atmospheric concentrations) and measured air quality data will contribute to validating the approach. Finally, the sample size is limited and is biased towards EWEs, so future work should use more fires across a broader range of severities.

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