FIRE-RES

Innovative technologies & socio-ecological-economic solutions for fire resilient territories in Europe

D5.10 - Quantifying impacts of exposure to air pollutants from wildfires

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Abstract: Health effects of aerosols emitted by wildfires remain poorly quantified due to uncertainties on wildfire emissions assessment. Exposure to air pollutants from wildfires is linked to serious health effects such as respiratory and cardiovascular problems This issue is particularly pronounced for firefighters, who, while performing fire control and extinguishing operations, firefighters are exposed to smoke that contains substantial amounts of known harmful pollutants. A deeper understanding of the concentrations of air pollutants from wildfires is essential to developing effective mitigation strategies. This will help protect firefighters from the harmful effects of these pollutants and enhance public health and safety.

Key words: Source apportionment, black carbon, particulate matter, wildland fire, aerosols.

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1. Introduction

A comprehensive understanding of exposure concentrations and exposure scenarios is crucial for developing mitigation strategies aimed at enhancing occupational and public health and safety. The main objectives of the IA5.7 – Quantifying impacts of exposure to air pollutants from wildfires, are as follows:

- Characterize personal exposures: Identify and quantify the specific exposure concentrations experienced by firefighters.
- Validate the use of portable monitors: Assess the reliability and accuracy of portable monitoring devices for monitoring personal exposure during wildfires and prescribed burns.
- Communicate the health impacts of firefighters' exposure to smoke: Raise awareness of the potential health risks associated with repeated or prolonged exposure to fire smoke, emphasizing the importance of protective measures.
- Quantify impacts on air quality: Study the impacts of wildfire smoke plumes on ambient air quality.

To achieve these objectives, two complementary approaches are employed:

(i) Personal exposure monitoring, by employing portable monitors that firefighters can carry throughout their shifts. The exposure data collected provides deeper insights into emissions and their impact on exposure profiles. This information becomes the foundation for developing occupational health and safety strategies, aiming to reduce the health risks associated with prolonged exposure to harmful pollutants. By implementing protective measures based on real-time exposure data, the firefighter community can proactively enhance worker safety, minimize health impacts, and provide novel information for developing protocols and decision support systems.

(ii) Air quality monitoring, focused on assessing ambient air quality in areas impacted by fire smoke using static sensors strategically placed in locations vulnerable to smoke dispersion. These sensors provide data about the environmental concentrations of smoke-related pollutants in a fixed area, providing ambient air quality data over time. This data is essential for validating and refining smoke dispersion models, which predict how smoke will move and settle in different environmental conditions. Accurate smoke dispersion models allow for better understanding of the broader impact of fire events on air quality, offering valuable insights for public health advisories and environmental safety protocols. By improving predictive capabilities through model validation, authorities and researchers can more effectively manage air quality impacts, identify high-risk areas, and issue timely warnings to the public in affected regions.

Together, these approaches provide a robust framework for reducing health risks, promoting safety and improving both occupational and public health responses to exposure scenarios.

2. Methodology

Between 2022 and 2024, pollutant measurement campaigns have been conducted with portable monitors for **(i) Personal exposure** and with static sensors for **(ii) Air quality**. Below are the details of the campaigns for each of these approaches.

2.1 Personal exposure

2.1.1 Study locations

Exposure monitoring was conducted between 2022 and 2024 during 15 prescribed burns across Catalonia, Spain. The sampling locations included various sites in the provinces of Barcelona, Girona, Tarragona, and Lleida, each with different vegetation types such as Mediterranean vegetation, shrubs, young trees, and grass. Burn areas varied in size from 0.3 to 4 hectares.

Prescribed burns (PB), performed annually as a management tool, follow specific guidelines based on meteorological conditions, fuel types, and terrain. These burns aim to control vegetation, prevent wildfires, and support plant regeneration. They occur in two main periods: PB1 (summer-autumn) with temperatures between 24°C and 30°C, and PB2 (winter) with colder conditions below 15°C. Logistically, the monitoring for PB1 and PB2 varied; during PB1, researchers had no direct access to burn sites, whereas PB2 allowed for easier access and more data collection.

For sampling, portable monitors were given to firefighters, and post-shift questionnaires were used to gather data on burn activities such as lighting, holding (also referred to as perimeter controlling), and mopping-up. Lighting involves the fire ignition process with a drip-torch fuelled by a mix of gasoil and diesel (torcher). Holding involves the management of fire within the perimeter and use of manual tools to prevent fire spread (line operator). Mopping-up entails the extinguishing of smouldering fire after the major burning phase, by stirring the top-soil layer, using handheld tools (e.g. spades). In prescribed burns, firefighters are assigned two primary roles: Torcher and Line operator.

Monitoring was also conducted during eight wildfires in 2022 and 2023, with varying burn intensities and areas. Exposure records varied greatly based on the specific conditions of each burn and the firefighter's shift, ranging from 1 to 8 hours for prescribed burns and 1 to 13 hours for wildfires.

2.1.2 $PM_{2.5}$ and BC monitors

At each site, the goal was to monitor the personal exposure of 4 to 8 firefighters to Black Carbon (BC) and Particulate Matter ($PM_{2.5}$). Lightweight, non-invasive portable monitors were used to track their exposure. Firefighters wore the monitors on their bodies (Figure 1), with the sampling inlet positioned near their breathing zone without disrupting their tasks. BC aerosols were measured using two types of portable Aethalometers: the AE51 (single-wavelength) and the MA200 (multi-wavelength). These monitors collected data on BC concentrations at 880 nm, with the MA200 estimating the BC contributions from both fossil fuel and biomass burning emissions. A total of four MA200 and five AE51 units were used, with data recorded at 1-minute intervals and a flow rate of 100 mL/min.

Figure 1: Firefighter carrying the monitoring instruments during a prescribed burn.

For $PM_{2.5}$, ten portable AirBeam2 sensors were deployed. These devices, which use Plantower PMS7003 particle sensing units, operate independently with their own battery and can transmit data via Bluetooth or WiFi to a mobile phone. The sensors also include a GPS to map the recorded $PM_{2.5}$ concentrations, with data averaged over 1-minute intervals.

Before each sampling campaign, the devices were calibrated and compared for consistency. They were also compared to high-end instruments at an EU-reference air quality monitoring station in Barcelona. BC concentrations from the Aethalometers were compared to those from a stationary Multi-Angle Absorption Photometer (MAAP), while $PM_{2.5}$ concentrations were cross-checked with an environmental dust monitor (GRIMM180). The $PM_{2.5}$ sensor data were adjusted based on these reference measurements. The authors note that the sensors were calibrated using urban aerosols, which may differ from the wildfire smoke aerosols targeted in this study.

2.1.3 Source apportionment of BC

Source apportionment was conducted on the multi-wavelength BC datasets to separate the contributions of fossil fuel and biomass burning contributions. Equations from the Aethalometer model were employed to calculate the contribution of fossil fuel combustion (BC_{ff}) and biomass burning (BC_{bb})to BC (Sandradewi et al., 2008b).

2.2 Air quality

Three wildfire campaigns were conducted during the summers of 2022, 2023 and 2024. Here, the impacts of the wildfires from the 2022 campaign will be specifically analyzed, which took place in Galicia. Analyses of the subsequent campaigns can be found in the annual reports.

2.2.1 Study area

The study area covered the Galicia region (lat. 42° 45'N, long. 7° 41'W) (Figure 2), located in the northwest of the Iberian Peninsula. It is one of the regions in Europe with the highest activity of forest fires and, consequently, the most affected by the emissions from this source (Alonso-Betanzos et al., 2003).

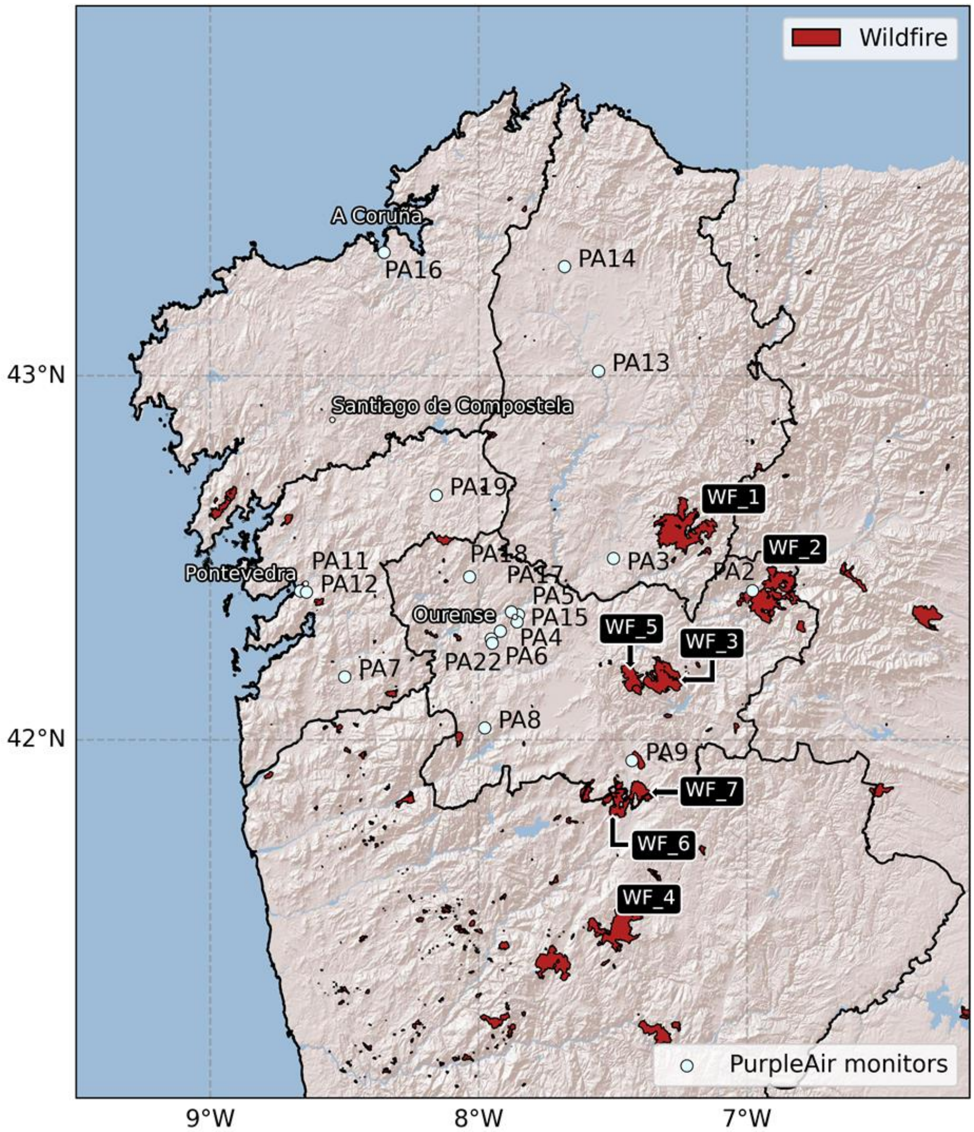

Figure 2. Map of the geographical distribution of PurpleAir (PA) monitors deployed in Galicia (NW Spain), major cities and wildfires during summer 2022. The seven largest wildfires considered in this study are labelled on the map (modified from Gili et al., 2024).

Historically, a number of extreme wildfires have affected Northern Portugal and Northwestern Spain. The 2017 Iberian wildfires were some of the most severe wildfires and had a significant impact on the region, resulting in human deaths and major economic damage (Chas-Amil et al., 2020). According to the European Forest Fire Information System (EFFIS), these wildfires burned an area of about 700,000 hectares in total. Another exceptional wildfire season was in summer 2022 in Spain, where the number of observed fires and the extent of burned area were higher than the average of 2006-2021.

Specifically, in Galicia, 50,000 hectares were burnt during this period. There are three key factors that make Galicia a fire-prone region. First, the regional climate promotes the accumulation of shrub biomass and consequently, the buildup of flammable forest fuels

(Aranha et al., 2020; Fernández-Alonso et al., 2022). As a result, the region exhibits a notable amount of available fuel leading to more intense, rapid combustion when ignited. Furthermore, the flora in Galicia is dominated by Eucalyptus plantations, which are linked to an elevated fire risk (Shakesby and Doerr, 2006; Taylor et al., 2017; Cordero et al., 2017). The third factor relates to unauthorized fire-setting activities for land management purposes, conducted without prior permissions from the administration. Given these characteristics, coupled with its notable historical fire incidence, Galicia emerged as a favorable study area from which findings may be extrapolated to analogous fire-prone regions.

2.2.2 Identification of NW Iberian Peninsula wildfires in summer 2022

Thirteen wildfires with >500 hectares in area were reported in Galicia during the summer of 2022. Table 1 presents the seven largest wildfires analyzed in this study. The largest of these was the Folgoso do Courel fire (referred to as WF_1), which burned 13,612 hectares. Ten other large fires occurred in the Ourense region.

Table 1. Main wildfire names and total acres burned (modified from Gili et al., 2024).

Fire Number	Name	Acres Burned	Initial date	Final date
WF_1	Folgoso do Courel	13,612	14/07/2022	23/07/2022
WF_2	Carballeda de Valdeorras	12,735	15/07/2022	22/07/2022
WF_3	Vilariño do Conso	7,090	15/07/2022	24/07/2022
WF_4	Tresminas *	7,641	17/07/2022	21/07/2022
WF_5	Laza	3,634	10/08/2022	15/08/2022
WF_6	Vilela Seca	3,127	15/07/2022	19/07/2022
WF_7	Verín	2,325	18/07/2022	21/07/2022

*Portugal wildfires

2.2.3 Site description and data validation

Between June 1 and August 30, a network of 18 low-cost PurpleAir PA-II outdoor monitors (PA-II-SD; PurpleAir Inc.) was deployed across the Galicia region. We selected firefighter stations across Galicia, where the sensors were installed outside the station ensuring unimpaired airflow around them and with a nearby electrical power source. The PurpleAir monitors determine $PM_{2.5}$ concentrations with a ≤10 second time resolution using 2

Plantower sensors (referred to as channels A and B) in parallel for quality control. The 2-minute data were averaged to 1-hour values.

To evaluate the performance of the monitors, an intercomparison of 1-h averaged $PM_{2.5}$ concentrations between PurpleAir and EU-reference equivalent data (Grimm180 laser spectrometer calibrated against EU-reference gravimetric measurements) was conducted during a 1-month period at the Barcelona – Palau Reial urban air quality monitoring station prior to the field campaign. The intercomparison was repeated after the end of the field campaign. In addition, inter-unit variability was also assessed to determine the consistency between monitors.

Finally, tests on different data validation and calibration methods was conducted, aiming to identify the most optimal data processing protocol for the geographical region (NW Spain) and the main targeted emission source (wildfires).

2.2.4 Back-trajectory calculations and data analysis

Air parcel back-trajectories were calculated using HYSPLIT (Stein et al., 2015) with the GFS 0.25-degree meteorological data set. Five-day back-trajectories with hourly endpoints were calculated for each of the 18 receptor sites, at 750 (meters above ground level (magl), for every hour between June and August 2022.

To assess the impacts of wildfire emissions, source apportionment models were applied to $PM_{2.5}$ data collected by a network of 18 low-cost PurpleAir monitors. Source apportionment methods based on statistical evaluation of $PM_{2.5}$ data at receptor sites were utilized. Among these, Positive Matrix Factorization (PMF), implemented by EPA PMF V5, was employed to conduct an Empirical Orthogonal Function (EOF) analysis). In aerosol research, receptor modeling by PMF is widely used for source attribution, which has also been linked with back-trajectory analysis (Zhou et al., 2004). Prior studies (Kim and Hopke, 2005; Zhang et al., 2020) have used the representation of air masses to identify the origin of pollutants reaching a given receptor. PMF can be considered as an alternative approach to implementing EOF analysis, particularly when applied to source apportionment tasks since it provides quantitative results. Typical EOF analyses are eigenvector based with mean-centering and normalization using standard deviations that is actually an unweighted least-squares fit in a standardized space. Given that the desired endpoints in our work are quantitative assessments of the fire impacts, PMF provides them through an explicit weighted least-squares formalism. EOF analysis is frequently used in atmospheric science to decompose a space-time field into spatial patterns (Hannachi et al., 2007) and describe their temporal variability. EOFs extract qualitative information from temporal and spatial data by calculating orthogonal vectors of linear combinations of the original variables. They present the maximum variance contained in the original data (Wilks, 2005). While EOFs are traditionally used for climate and meteorological studies, they may also be used to explore spatial patterns or dominant modes of variability in an air quality dataset with multiple pollutant sources (Henry, 1997a,b,c; Chueinta et al., 2004). Using this conceptual framework, the methodology involves utilizing PMF to perform an EOF analysis to determine the spatial distribution of air pollutants.

3. Results and discussion

3.1 BC and $PM_{2.5}$ exposures during wildland fires and prescribed burns from portable monitors

3.1.1 $PM_{2.5}$ exposures

During a 3-year study period, 114 individual $PM_{2.5}$ exposure datasets were collected, encompassing wildfires and two periods of prescribed burns (PB1 and PB2). The mean $PM_{2.5}$ concentrations across the three scenarios were similar, ranging from 110 $PM_{2.5}$µg/m^3 for PB1 to 152 $PM_{2.5}$µg/m^2 for wildfires (WF). The standard deviation of PB2 was higher due to the varying proportion of extinguishing tasks and mop-up tasks recorded.

On average, mop-up tasks produced significant mean $PM_{2.5}$ emissions, with 1-minute $PM_{2.5}$ peak exposure concentrations reaching up to 1,190 µg/m^3. Other activities reported, which were associated with lower exposure concentrations, included truck driving (on average 28 µg$PM_{2.5}$/m^3), operations at the command center (23 $PM_{2.5}$µg/m^3), and exposure from research staff (36 $PM_{2.5}$µg/m^3).

During wildfires, $PM_{2.5}$ exposure concentrations varied significantly across tasks. The lowest mean concentration, 11 µg/m^3, was observed during the post-fire inspection perimeter task. This was followed by perimeter inspection, smoke column monitoring, and hotspot control (36 µg/m^3), and mop-up tasks at 71 µg/m^3. The highest mean concentration was monitored during direct attack firefighting (333 µg/m^3). Additional datasets collected during wildfires, where task-specific information was unavailable, showed a range of concentrations similar to those described above, with a mean of 179 µg/m^3 (Figure 3).

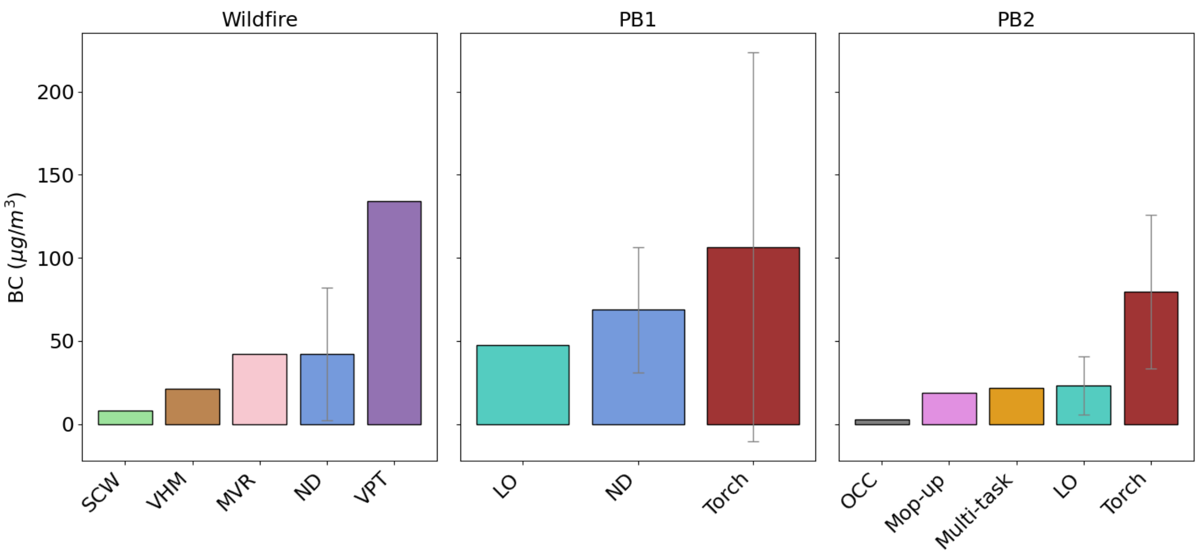

Figure 3. Mean $PM_{2.5}$ exposure concentrations during wildfires and prescribed burns (PB1 and PB2). Abbreviations are defined as follows: Post-inspec: Post-fire inspection; Perim check: Perimeter inspection, monitoring tasks, control of smoke columns, and hotspot control; Mop-up tasks; ND: No data, Direct attack firefighting; Nozzle: Discharging – nozzle; OCC: Operational command center; Driver: truck driving; Research s.: Research staff; LO: Line operator; Torch: Torchers (modified from Gili et al., 2024b).

3.1.2 BC exposures

A total of 67 BC exposure records were gathered during the study period. The average BC concentrations ranged from 47 µg/m³ for wildfires (WF) to 82 µg/m³ for PB1. The higher average BC levels observed in PB1 compared to wildfires may reflect the use of drip torches fueled by a gasoil-gasoline mixture during prescribed burns. BC concentrations in PB2 were similar to those of wildfires, though peak levels during prescribed burns reached an absolute maximum of 4,521 µg/m³, 1.4 times higher than the peak concentrations observed in wildfires. While the observed differences may suggest higher peak exposures during prescribed burns, it is important to note that only 8 wildfire records were available, so the results should be interpreted with caution due to the limited data from wildfires. This limitation stems from the challenges of collecting data during actual wildfires, such as their unpredictable nature, the need for quick action, limited time for response and extreme conditions.

In terms of BC exposure by task (Figure 4), considerable variability was observed. For example, vehicle tracking during fire response and burn operations resulted in an average of 134 µg/m³, while movements involving vehicles, chainsaws, and manual tools for line establishment averaged 42 µg/m³. However, the small sample size for wildfires makes it difficult to draw definitive conclusions. For prescribed burns, particularly PB2, the highest BC concentrations were recorded for torchers, followed by line operators.

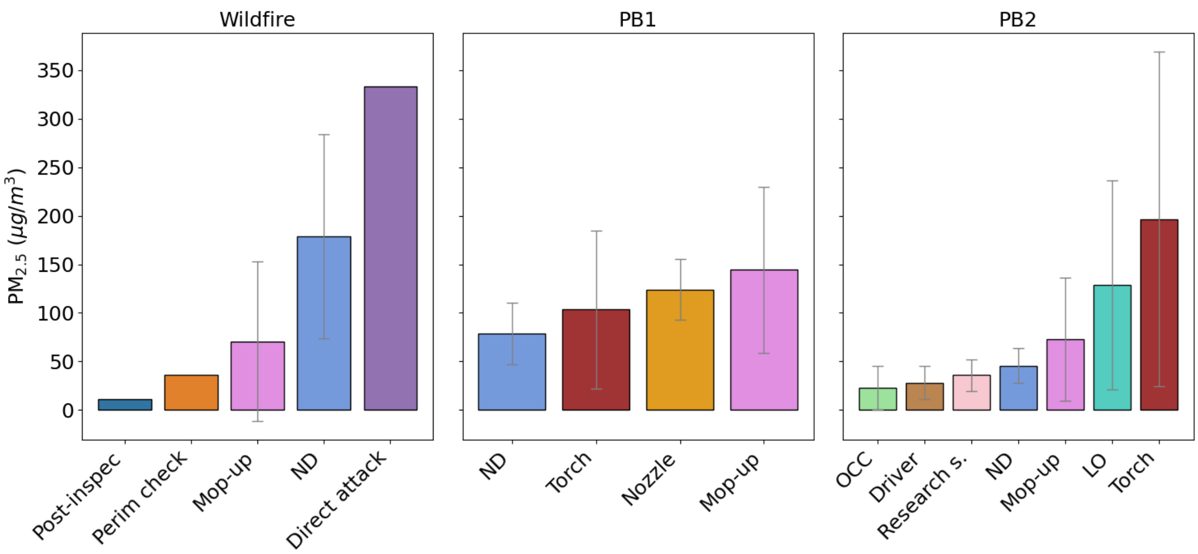

Figure 4. Mean BC exposure concentrations of other firefighting activities. Abbreviations are defined as follows: SCW: Saw Crew Work; VHM: Vehicle Mobility and Driver Tasks; MVR: Movement with Vehicle and Chainsaw Operations; ND: No Data; VPT: Vehicle Patrol and Burn Operations; LO: Line Operator; Mop-up: Mop-up- tasks; Torch: Torcher; OCC: Operational command center, Multi-task: Multi firefighting task (modified from Gili et al., 2024b).

3.1.2.1 Source apportionment

Source apportionment models were applied to the BC datasets based on the two primary exposure profiles: torchers and line operators. Results showed that, on average, $PM_{2.5}$ exposures concentrations were similar for both line operators (129 ± 196 µg/m^3) and torchers (165 ± 207 µg/m^3).

Differences in BC exposure may be attributed to the different tasks performed and associated exposure to emissions sources, such as biomass burning and fossil fuel combustion. On average, line operators were exposed to 61 % of BC_{bb} and 39 % of BC_{ff}, while torchers had a dominant exposure to BC_{ff} (77 %) compared to BC_{bb} (23 %). This suggests that the use of drip torches significantly contributed to BC from fossil fuel combustion. Specifically, the exposure to BC_{ff} for torchers were 8 times higher than those for line operators, highlighting the substantial influence of drip torch use in fire ignition. In contrast, the ratio of $PM_{2.5}$ exposure between torchers and line operators was only 1.3, as expected, since line operators are more exposed to biomass burning smoke containing organic carbon and potentially soil dust particles. This latter exposure is influenced by the resuspension of particles during perimeter monitoring, where manual tools are used to control fire spread, generating suspended dust.

3.2 Air pollution data series from static sensors

3.2.1 Evaluation of wildfires impacts in Galicia

The detailed results of this study may be found in Gili et al. (2024). In July, air quality analysis indicated that north-westerly (NW) back-trajectories contributed significantly to elevated particulate matter (PM) levels, with concentrations surpassing 300 µg/m³ (1-hour mean) at monitoring station PA2, likely due to the impact of the wildfire (WF_1) in Folgoso do Courel (Figure 5b). Additionally, southeastern (SE) back trajectories were linked to high PM concentrations—exceeding 250 µg/m³—associated with fires in Carballeda de Valdeorras (WF_2) and Vilariño de Conso (WF_3) (Figures 5a, 5c). Overall, the impact of wildfires was evident, with mean $PM_{2.5}$ concentrations showing an increase of 36 µg/m³ over the background level of 14 µg/m³.

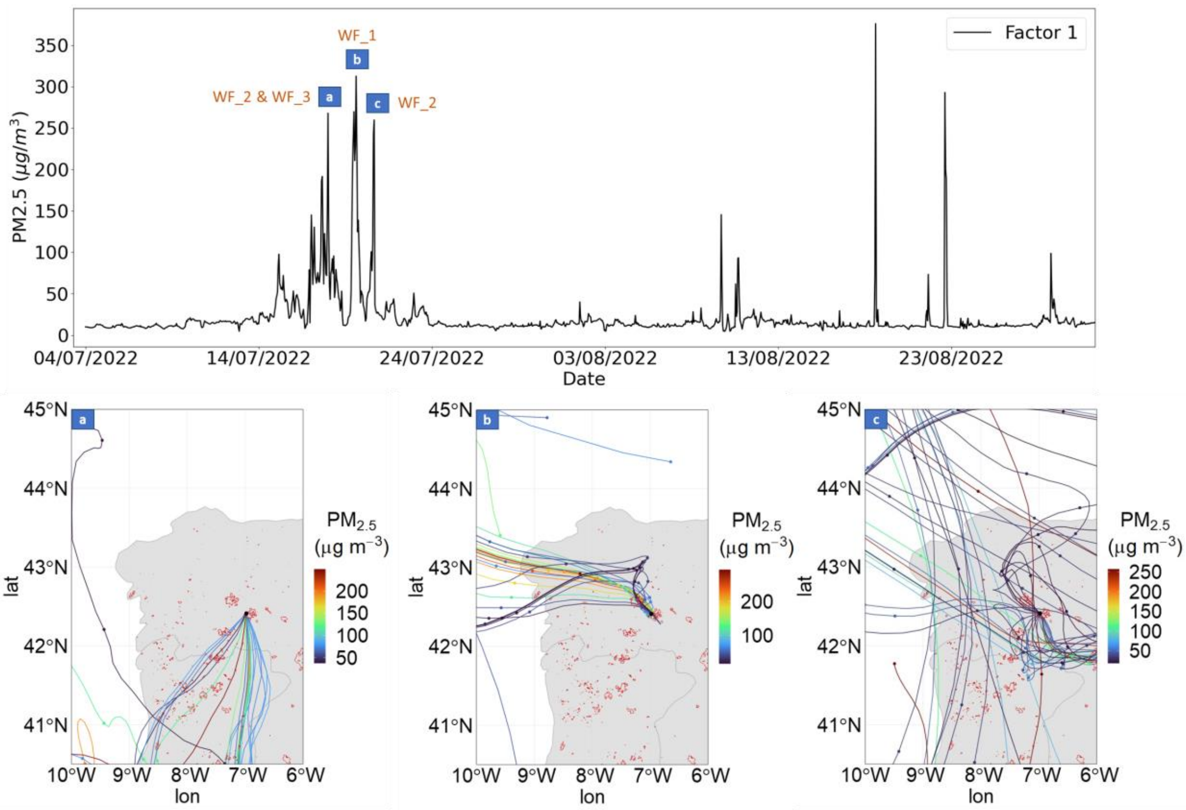

Figure 5. Time series plot of contributions associated with the $PM_{2.5}$ measured at PA2 (top) alongside the corresponding back-trajectory analysis (a, b, c) (bottom).

Between July 15 and 18, 2022, elevated particulate matter concentrations were observed at monitors PA14, PA16, PA18 and PA19, driven by air masses carrying smoke plumes from wildfires in Folgoso do Courel (WF_1), Carballeda de Valdeorras (WF_2), and Vilariño do Conso (WF_3) (Figures 6a, 6b, 6c). On July 19, a notable shift in wind direction allowed for atmospheric cleansing, temporarily reducing pollution levels. However, by July 21, the reappearance of south-southeastern winds likely reintroduced smoke-laden air masses from these fires, resulting in potential $PM_{2.5}$ concentrations of up to 75 µg/m³. These wildfire events collectively raised mean $PM_{2.5}$ concentrations by 36 µg/m³ above the baseline level of 24 µg/m³.

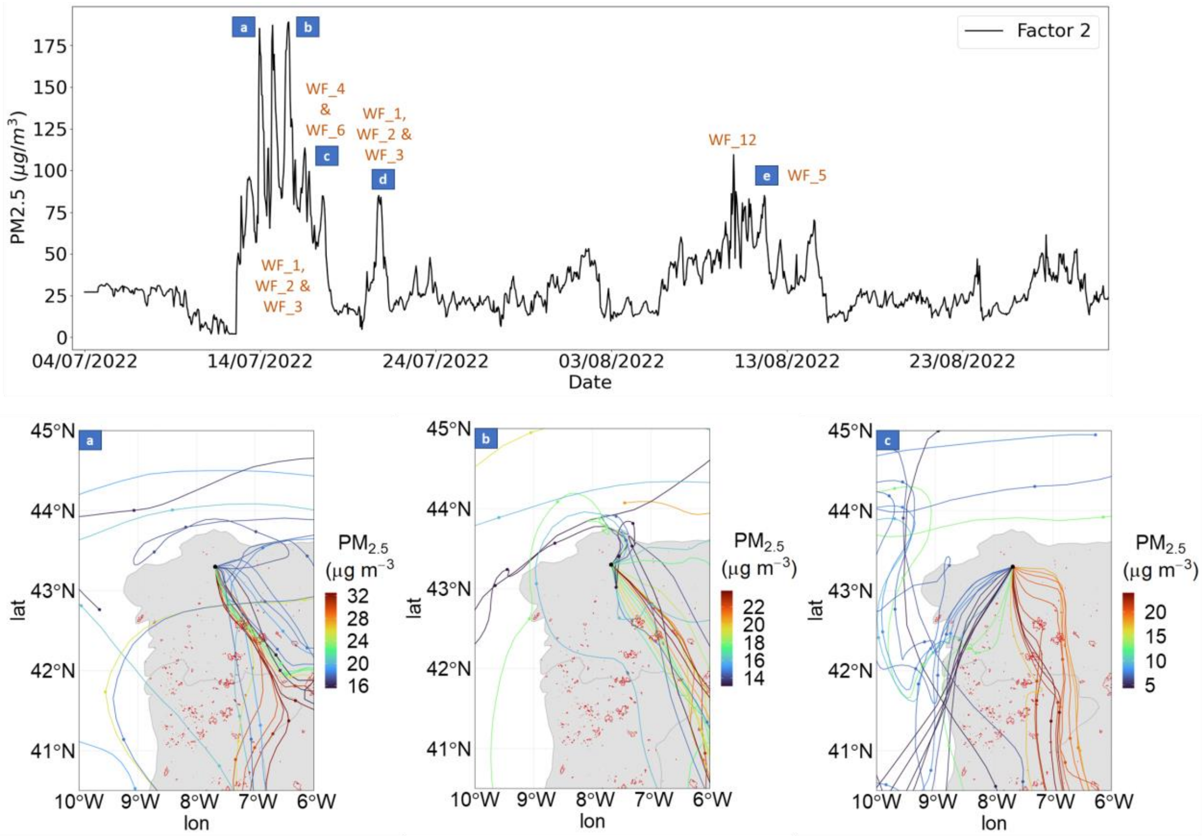

Figure 6. Time series plot of contributions associated with the $PM_{2.5}$ measured at PA14 (top) alongside the corresponding back-trajectory analysis (a, b, c) (bottom).

On July 13, elevated PM concentrations monitored at PA4, PA5, PA6, PA15, PA17, and PA22 were likely influenced by emissions from the Melón (WF_20) and Ribadavia (WF_22) wildfires, as air masses originating from the southwest carried smoke from these events (Figure 7a). Additionally, northeast back trajectories pointed to smoke transport from the Folgoso do Courel wildfire (WF_1) to these monitoring sites (Figure 7c). The impact of wildfires is marked by a mean $PM_{2.5}$ increase of 63 µg/m³ over a baseline of 34 µg/m³, with peak concentrations reaching 435 µg/m³.

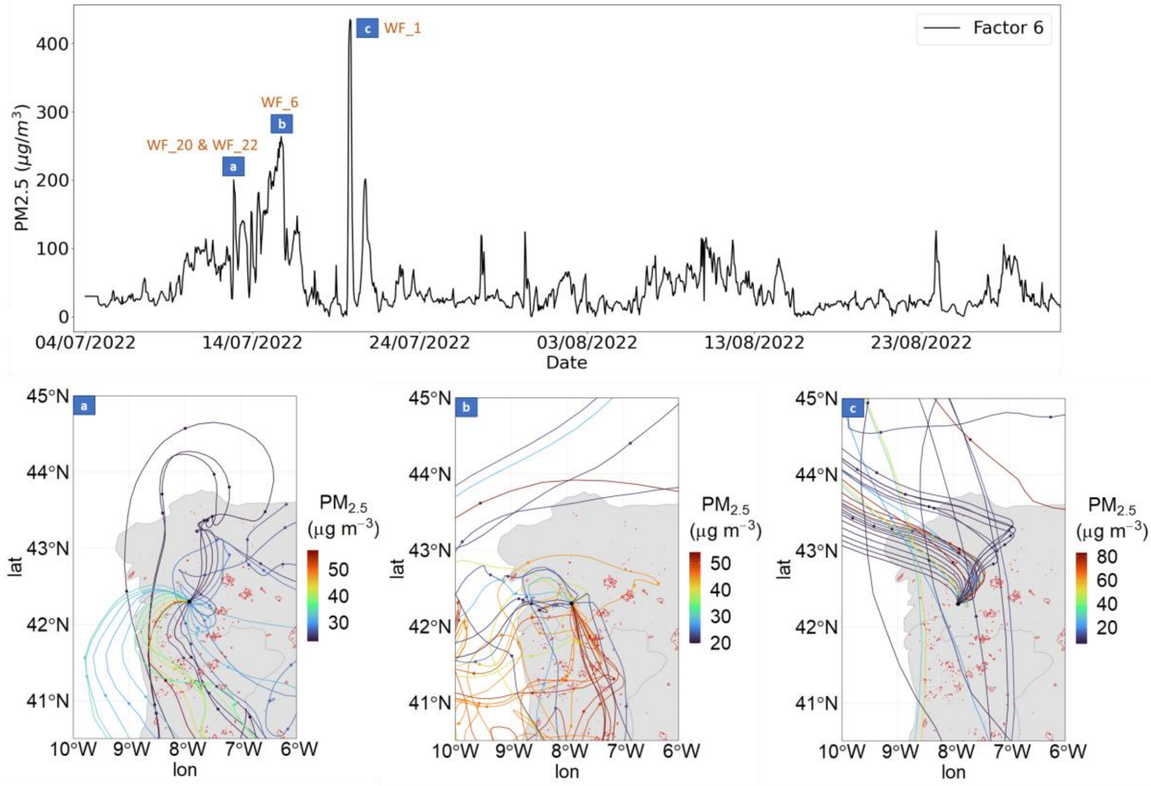

Figure 7. Time series plot of contributions associated with the $PM_{2.5}$ measured at PA4 (top) alongside the corresponding back-trajectory analysis (a, b, c) (bottom).

On August 3, the highest concentration recorded at monitor PA8 was likely linked to a local source, as the back trajectories showed significant divergence (Figure 8). Additionally, PA8 was probably affected by emissions from the Lobeira wildfire on August 24, 2022. The overall impact of wildfires resulted in a 24 µg/m³ increase in mean $PM_{2.5}$ concentrations over the baseline level of 19 µg/m³.

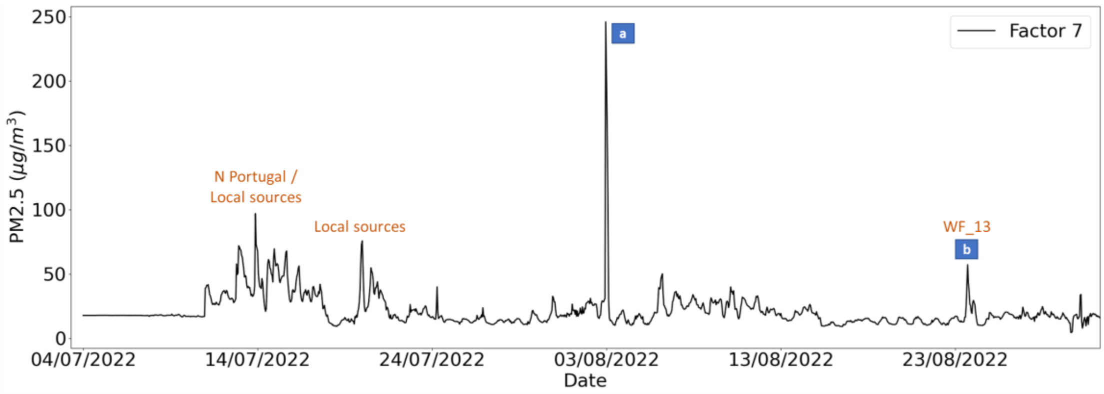

Figure 8. Time series plot of contributions associated with the $PM_{2.5}$ measured at PA8.

Between July 16 and 18, 2022, south-southeasterly back trajectories passing through the Vilariño do Conso wildfire (WF_3) region likely contributed to $PM_{2.5}$ concentrations reaching up to 150 µg/m³ monitored at PA3 (Figures 9a, 9b). On July 20, emissions from WF_1 may have influenced PA3, as air masses from the northeast of the sensor site brought higher concentrations, resulting in the highest values recorded by PA3 (Figure 9c). The overall impact of wildfires led to a 25 µg/m³ increase in mean $PM_{2.5}$ concentrations compared to the baseline level of 19 µg/m³.

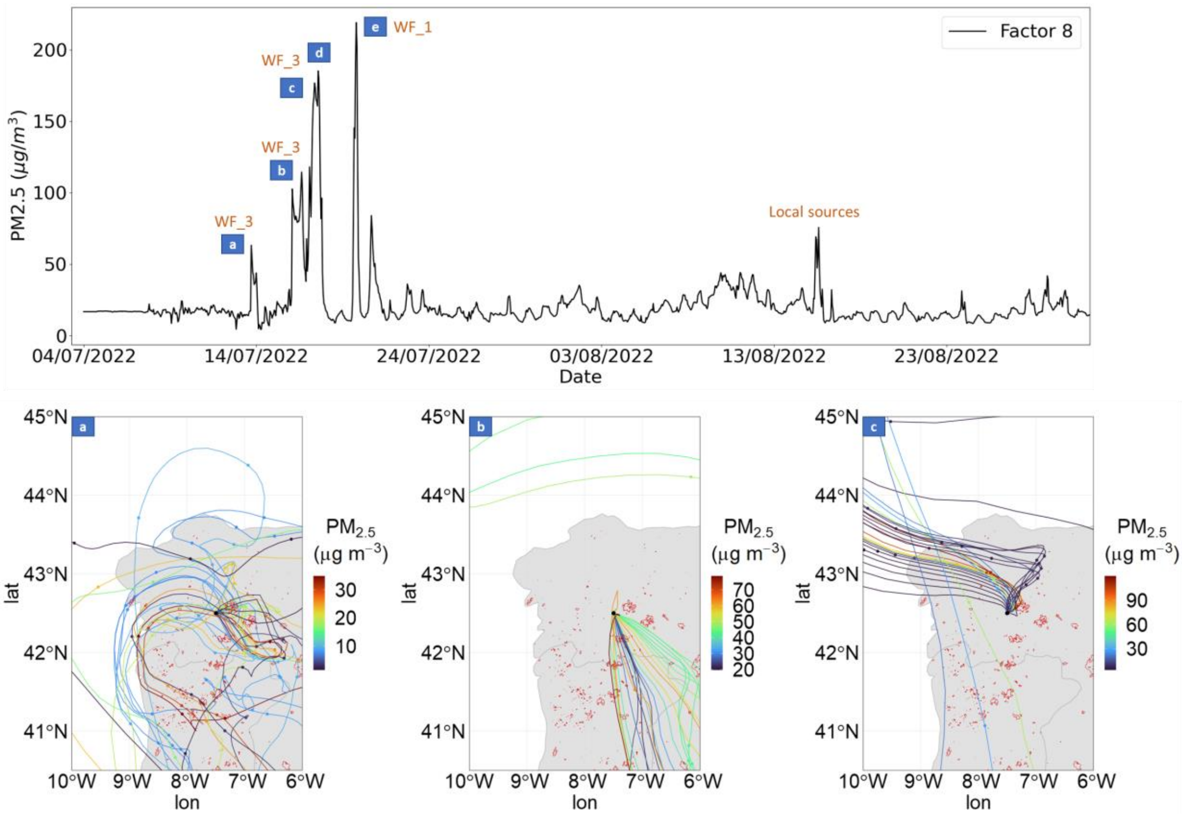

Figure 9. Time series plot of contributions associated with the $PM_{2.5}$ measured at PA3 (top) alongside the corresponding back-trajectory analysis (a, b, c) (bottom).

4. Technology Readiness Level (TRL) of Key Findings

The IA5.7, which focuses on quantifying firefighter exposure to wildfire smoke and assessing its impacts on air quality, has advanced from TRL 6 to TRL 7 by demonstrating its readiness in operational environments. This progress has been solidified through extensive testing in real-world scenarios, including active wildfires between 2022 and 2024. Portable monitors reliably captured exposure data for firefighters under diverse and challenging conditions, while static monitors deployed in Galicia, provided robust ambient air quality data during wildfire events. These systems demonstrated high accuracy and reliability, validated through calibration with EU-reference instruments and adjustments tailored to wildfire-specific aerosols. Furthermore, the collected data have been integrated into practical applications, enabling the development of decision-support systems for firefighting operations and air quality management.

5. Conclusions

The increasing frequency and intensity of wildfires, driven by changes in climate and land-use, pose significant risks to both human health and the environment. This study aimed to deepen our understanding of the types and sources of aerosols, particularly Particulate Matter ($PM_{2.5}$) and Black Carbon (BC), generated during wildfires and prescribed burns, which is crucial for exposure management and mitigation. **Key findings indicate that human exposure to combustion aerosols ($PM_{2.5}$ and BC) was notable and comparable in both prescribed burns and wildfires**. For instance, mean $PM_{2.5}$ concentrations were 152 µg/m³ during wildfires and ranged between 110-149 µg/m³ during prescribed burns. **This similarity suggests that prescribed burns can serve as useful proxies for wildfires in exposure studies, simplifying aerosol monitoring in experimental settings**.

Wildfires, however, resulted in higher overall $PM_{2.5}$ doses compared to prescribed burns, due to longer exposure durations. Although peak $PM_{2.5}$ concentrations were higher during prescribed burns, the duration of wildfires led to greater total exposure. For BC, prescribed burns showed higher peak concentrations, while **mop-up tasks, involving soil disturbance during firefighting activities, were identified as an unexpected contributor to increased $PM_{2.5}$ exposure, particularly among line operators**. These tasks stirred up mineral aerosols, with BC accounting for 62 % of $PM_{2.5}$ exposure for torch operators and only 22 % for line operators, highlighting the role of soil re-suspension in specific firefighting activities.

Additionally, source apportionment analysis revealed distinct exposure patterns between firefighter roles, with drip torch operators exposed predominantly to BC from fire-fronts (77 %) while **line operators had more balanced exposure between BC from fire-**

fronts and background sources. **These findings emphasize the need to assess specific firefighting tasks in terms of aerosol exposure risk**.

Source apportionment of wildfire emissions contributing to $PM_{2.5}$ concentrations was performed using Positive Matrix Factorization (PMF) combined with back-trajectory analysis. **Wildfires were found to increase background $PM_{2.5}$ levels by an average of 21-39 μg/m³ over 5-10 days, reaching up to 63 μg/m³ and maximum hourly peak concentrations of 435 μg/m³**. These results emphasize the extensive reach of wildfire emissions and their variability depending on the fire's size and location.

The study also confirmed the effectiveness of portable monitors and multi-wavelength aethalometers in assessing wildfire emissions and human exposure in real-time. These tools enabled source apportionment and provided high-quality data for spatial and temporal analysis, such as identifying pollution sources during major wildfires and smaller fires that impacted nearby areas.

Overall, these findings underscore the importance of real-time exposure monitoring and advanced tools in identifying and mitigating the health and environmental impacts of wildfires. The data also hold promise for epidemiological assessments, helping to inform effective public health strategies in the face of a global wildfire crisis.

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